SELECTION OF APPROPRIATE BIOREACTOR TECHNOLOGY BASED ON SPACE-SAVING ECONOMY FOR WASTEWATER TREATMENT

THESIS SUBMITTED
BY

BHASKAR SENGUPTA

DOCTOR OF PHILOSOPHY (ENGINEERING)

DEPARTMENT OF CIVIL ENGINEERING,
FACULTY COUNCIL OF ENGINEERING & TECHNOLOGY
JADAVPUR UNIVERSITY
KOLKATA, INDIA

2024

JADAVPUR UNIVERSITY

Kolkata – 700032, India

Index No. 149/19/E

1. **Title of the thesis:**
   Selection of appropriate bioreactor technology based on space saving economy for wastewater treatment.

2. **Name, Designation & Institution of the Supervisor/s:**

Dr. Abhisek Roy
Assistant Professor, Department of Civil Engineering
Jadavpur University, Kolkata – 700 032, India
Mob: +91 8013189845; Email: aroy.civil@jadavpuruniversity.in

and

Dr. Somnath Mukherjee
Professor, Department of Civil Engineering,
Heritage Institute of Technology, Kolkata – 700 032, India
Mob: +91 74392 60339; Email: mukherjeesomnath19@gmail.com

3. **List of Publications**

   i. **Sengupta, B.,** and Mukherjee, S. (2023). "Development of cost functions for biological treatment by membrane bioreactor". *Global NEST Journal*, Vol- 25, Issue 8, page-146–155, https://doi.org/10.30955/gnj.004537.

   ii. **Sengupta, B.,** and Mukherjee, S. (2023). "Integrated Cost Functions for Biological Treatment by Moving Bed Biofilm Reactor in Wastewater Treatment Plant". Journal of Institute of Engineers India Series A, Springer Nature Publication, Vol - 104, page 895–911, https://doi.org/10.1007/s40030-023-00751-8.

   iii. **Sengupta, B.**, Roy, A., and Mukherjee, S. (2024). "Development of cost functions for wastewater treatment by sequential batch reactor". Journal of Environmental Engineering and Landscape Management, Vol-32, Issue – 4, page 339–356, https://doi.org/10.3846/jeelm.2024.22305.

4. List of Patents: Nil

5. List of Presentations in National / International/ Conferences/ Workshops :

i. **Sengupta, B., and Mukherjee, S.** "Development of Cost Functions for Construction of Wastewater Treatment Plant with State-of-the-Art Technology". International conference on "Emerging Technology and Management Trends in Environment and Sustainability (EMTES 2022)", Budge Budge Institute of Technology, 29th – 30th November, 2022.

ii. Sengupta, B., and Mukherjee, S. "Importance of Cost Functions for Biological Treatment of Wastewater". 3rd International Conference on "Advanced Technologies for Industrial Pollution Control (ATIPC 2022)", Indian Institute of Engineering Science and Technology, Shibpur, 21st – 23rd December, 2022.

iii. Sengupta, B., Roy, A. and Mukherjee, S. "Development of 3-D Surface Cost Response Maps to Forecast Rapid Cost for Biological Treatment of Wastewater by Moving Bed Biofilm Reactor". International Conference on "Pollution Control For Clean Environment (ICPCCE-2023)", Indian Institute of Technology, Bhubaneswar, 15th – 16th December, 2023.

iv. Sengupta, B., Roy, A. and Mukherjee, S. "Methodology for Development of Cost Response Maps for Membrane Bioreactor". International Conference on "Sustainable Advanced Technologies for Environmental Management (SATEM-2023)", Indian Institute of Engineering Science and Technology, Shibpur, 20th – 22nd December, 2023.

PROFORMA – 1

"Statement of Originality"

I ________Bhaskar Sengupta________ registered on ____18th June 2019 do hereby declare that this thesis entitled "Selection of appropriate bioreactor technology based on space saving economy for wastewater treatment" contains literature survey and original research work done by the undersigned candidate as part of Doctoral studies.

All information in this thesis have been obtained and presented in accordance with existing academic rules and ethical conduct. I declare that, as required by these rules and conduct, I have fully cited and referred all materials and results that are not original to this work.

I also declare that I have checked this thesis as per the "Policy on Anti Plagiarism, Jadavpur University, 2019", and the level of similarity as checked by iThenticate software is ___2___ %.

Bhaskar Sengupta

Signature of Candidate:

Date : 06 07 2024

Certified by Supervisor(s):

(Signature with date, seal)

Abhisek Roy
06/07/24

....

Dr. Abhisek Roy

(Abhisek Roy
06/07/24)

Assistant Professor,
Department of Civil Engineering
Jadavpur University,
Kolkata – 700 032, India
Mob: +91 8013189845;
Email: aroy.civil@jadavpuruniversity.in

Assistant Professor
Department of Civil Engineering
Jadavpur University
Kolkata-700 032

06/07/24

....

Dr. Somnath Mukherjee

Professor,
Department of Civil Engineering,
Heritage Institute of Technology,
Kolkata – 700 032, India
Mob: +91 74392 60339;
Email: mukherjeesomnath19@gmail.com

DR. ABHISEK ROY
B.E.-Civil (J.U.); M.E.-Civil (J.U.)
Ph.D. (Engineering) (J.U.)
Assistant Professor
Department of Civil Engineering
Jadavpur University (J.U.)
M.: 8013189845 / 8017500578

CERTIFICATE FROM THE SUPERVISORS

This is to certify that the thesis entitled "**Selection of appropriate bioreactor technology based on space saving economy for wastewater treatment**" was submitted by **Shri Bhaskar Sengupta**, who got his name registered on 18th June, 2019, index no. **149/19/E**, for the award of **Ph.D. (Engineering)** degree of **Jadavpur University** is absolutely based upon his own work under the supervision of Dr. Abhisek Roy and Prof. Somnath Mukherjee and that neither his thesis nor any part of the thesis has been submitted for any degree or any other academic award anywhere before.

Signature of the Supervisor
and date with Office Seal

Abhisek Roy 06/08/2024

Dr. Abhisek Roy

Assistant Professor
Department of Civil Engineering
Jadavpur University
Kolkata-700 032

Assistant Professor,
Department of Civil Engineering
Jadavpur University,
Kolkata – 700 032, India
Mob: +91 8013189845;
Email: aroy.civil@jadavpuruniversity.in

Dr. Somnath Mukherjee

Professor,
Department of Civil Engineering,
Heritage Institute of Technology,
Kolkata – 700 032, India
Mob: +91 74392 60339;
Email: mukherjeesomnath19@gmail.com

DECLARATION

I declare that the work described in this thesis is entirely my own. No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or institute. Any help or source information, which has been availed in the thesis, has been duly acknowledged.

Bhaskar Sengupta
06.07.2024
……………………………………………

Bhaskar Sengupta
Index No. – 149/19/E
Department of Civil Engineering,
Jadavpur University

ACKNOWLEDGMENTS

It is indeed my greatest pleasure to acknowledge my heartfelt gratitude to all my mentors, peers and well-wishers who have directly and indirectly contributed towards the successful completion of my thesis. It may not be possible to thank each one of them individually but I shall try my best to do the same.

I would like to express my sincerest thanks and gratitude to my supervisors ***Dr. Abhisek Roy, Assistant Professor, Department of Civil Engineering*** *and* ***Prof. Somnath Mukherjee, Professor, Department of Civil Engineering, Heritage Institute of Technology*** *for their unwavering guidance and help, without whose consistent support this thesis would not have seen the light of the present day.*

Special thanks are due to all the ***Faculty Members*** *and* ***Staff Members*** *of* ***Jadavpur University, Environmental Engg Division, Civil Engineering Department,*** *for supporting me during my Ph.D work at this esteemed Institution.*

Bhaskar Sengupta
06 07 2021
(Bhaskar Sengupta)

Jadavpur University

CONTENTS

Chapters

Appendices

List of Abbreviation

Abbreviated form		**Full form**
APE	:	Absolute Percentage Error
ASP	:	Activated sludge process
BOD	:	Biochemical oxygen demand
CAPEX	:	Total bare construction cost
COD	:	Chemical oxygen demand
EA	:	Extended Aeration
FAB	:	Fluidized Aerobic Bio-Reactor
GOI	:	Government of India
MAPE	:	Mean Absolute Percentage Error
MBBR	:	Moving Bed Biological Reactor
MBR	:	Membrane bio-reactor
MLSS	:	Mixed liquor suspended solids
MLVSS	:	Mixed liquor volatile suspended solids
MoEF	:	Ministry of Environment & Forests
O&M	:	Operation and maintenance
OP	:	Oxidation Pond
OPEX	:	Levelized cost based on energy requirement, operation, and maintenance for 25 years of life of WWTP
R^2	:	Determination coefficient
SBR	:	Sequential batch reactor
TSS	:	Total suspended solids
UASB	:	Up-flow Anaerobic Sludge Blanket
WSP	:	Waste Stabilization Pond
WWTP	:	Wastewater treatment plant
WWTPs	:	Wastewater treatment plants

Abstract

A wastewater treatment plant (WWTP) is a crucial infrastructure that requires careful planning and the selection of cost-effective treatment technologies for successful implementation. Urban planners often necessitate available data or published information for evaluation of costs of WWTPs for various capacities and technologies, as well as the land area and energy requirements for operation. Municipal authorities, tenderers, contractors, and other stakeholders aim to select appropriate WWTP technologies that balance economic and fiscal considerations targeting to award of the job.

It has been noticed through detailed survey of literature that most of the researches in the relevant area were undertaken in connection with cost functions and indices for the construction and operation of WWTPs, primarily aiming for rapid cost estimation and commercial comparisons among various conventional technologies. These studies typically utilize cost data collected from sources for technologies such as continuously mixed activated sludge, oxidation ditches, and aerated lagoons.

In response to this gap, our research initiative aims to develop cost functions and 3-D cost response maps for rapid estimation of WWTP costs using MBR, MBBR, and SBR technologies, without reliance on historical or collected data.

In the present investigation an effort has been endeavoured for development of cost functions for WWTP with recent MBR, MBBR and SBR technologies with due consideration of cost of land acquisition. The approach is based on engineering design and cost estimation rather than use of historic and available cost database from elsewhere. The study includes detail process design, estimation of bill of quantities and cost estimation as per published schedule of rates are the base for development of the cost functions as well as cost response maps and sensitivity study for the cost functions developed. This approach is envisaged to be appropriate and reliable for cost comparison among MBR, MBBR and SBR technologies with reference to planning for installation of WWTP. Research in this new domain will surely add value to the set of tools available for selection of technology to be used for a WWTP, particularly for decision makers and bidders.

The study involved designing and estimating using a developed model, followed by optimization through regression techniques, with the following objectives:

a) Develop cost functions for wastewater treatment plants (WWTPs) employing MBR, MBBR, and SBR technologies, based on an inlet BOD load of 250 g/m^3, a standard practice in municipal sectors.

b) Create 3-D cost response maps to estimate the costs of WWTPs using MBR, MBBR, and SBR technologies at varying capacities and inlet BOD loads. This aimed to analyze cost variations relative to deviations from the standard inlet BOD load.

c) Perform sensitivity analysis on the developed cost functions for WWTPs utilizing MBR, MBBR, and SBR technologies, specifically focusing on an inlet BOD load of 250 g/m^3.

Cost functions developed for capacity wise three different groups of WWTPs with MBR, MBBR & SBR technologies may be used for accurate forecast level cost estimation as applicable in India.

3-D cost response maps have been developed with applicable engineering design criteria and do not include any historic reference. These maps will predict overall cost inclusive of capital, operation and maintenance expenditure for WWTPs with MBR technology within the specified ranges of capacity and inlet BOD.

Sensitivity analysis has also been carried out and validated to facilitate world-wide use of cost functions developed for BOD removal at inlet BOD load of 250 g / m^3.

CHAPTER - 1:

INTRODUCTION

1.0 Introduction

This chapter discusses the introductory issues of the present research.

In recent times, the discharge of contaminated urban wastewater containing various contaminants has become a major cause of water pollution and triggered a big challenge to engineers and scientists including the professionals engaged in alleviating the problem.. This issue is largely due to extensive urban development, city expansion, rapid industrialization with new technologies, the use of advanced materials, and other factors. Approximately 80 percent of wastewater worldwide is released untreated into various surface water bodies which are used as water resource [1]. This practice eventually has detrimental effects on aquatic biodiversity and disrupts interconnected food chains including ecological system.

India is currently experiencing rapid urbanization with high elevated structure for residence, which has presented significant challenges for local governments and urban planners. One major challenge is the scientific and economic management of waste treatment and discharge of treated wastewater in economic way keeping in view of a constraint of scarcity of priceless land

Industrial and human activities release vast amounts of wastewater daily into ponds, canals, and rivers. This wastewater, with high levels of organic content measured as BOD and COD, depletes oxygen and deteriorates the water quality.

Since rivers are a major source of water supply, the Central Government of India has launched various initiatives, such as the Namami Ganga Project, Ganga Action Plan etc to protect urban environments from pollution. The primary focus of these initiatives is to safeguard water quality as drinking water source depletes considerably. Plans have been made to construct various types and sizes of wastewater treatment plants (WWTPs) at multiple locations along both sides of the Ganga and other rivers. A budget of ₹1,41,678 crore (or 18,400 million USD) has been allocated for urban sanitation from 2021 to 2026 [2], with numerous WWTPs expected to be built in the coming years.

A WWTP is a crucial infrastructure that requires careful planning and the selection of cost-effective treatment technologies for successful implementation. Urban planners often necessitate available data or published information for evaluation of costs of WWTPs for various capacities and technologies, as well as the land area and energy requirements for operation. Municipal authorities, tenderers, contractors, and other stakeholders aim to select appropriate WWTP technologies that balance economic and fiscal considerations targeting to award of the job.

Several technologies are available for wastewater treatment. In addition to conventional methods, new technologies have emerged over the earlier decades. Sequential Batch Reactor (SBR) and Moving Bed Biological Reactor (MBBR) are notable options for secondary treatment. Another advanced option is the Membrane Bio-Reactor (MBR), which is considered one of the more advanced processes.

Table 1 provides information on the use of different technologies in wastewater treatment plants (WWTPs) across India for reference [3]:

Table 1: Different technologies in WWTPs

Sl. No.	**Technology**	**Capacity in mld**	**Number of WWTPs**
1	ASP	9486	321
2	Extended Aeration (EA)	474	30
3	SBR	10638	490
4	Moving Bed Biological Reactor (MBBR)	2032	201
5	Fluidised Aerobic Bio-Reactor (FAB)	242	21
6	Up-flow Anaerobic Sludge Blanket (UASB)	3562	76
7	Waste Stabilization Pond (WSP)	789	67
8	Oxidation Pond (OP)	460	61
9	Any Other	8497	364

The space required for constructing wastewater treatment plants (WWTPs) is a major concern when selecting appropriate biological treatment technologies. Population densities have increased significantly in many urban communities over recent years, making the availability of vacant land for WWTP construction a major constraint. Even where vacant land is available, local residents often object to the construction of WWTPs nearby. Therefore, modern WWTPs need to be designed to require less space than those built with conventional technologies in the past, facilitating easier land acquisition. This will help to foster with the constraint addressed above and construct WWTP within limited space.

Figure 1 illustrates the land area requirements for various wastewater treatment technologies [4].

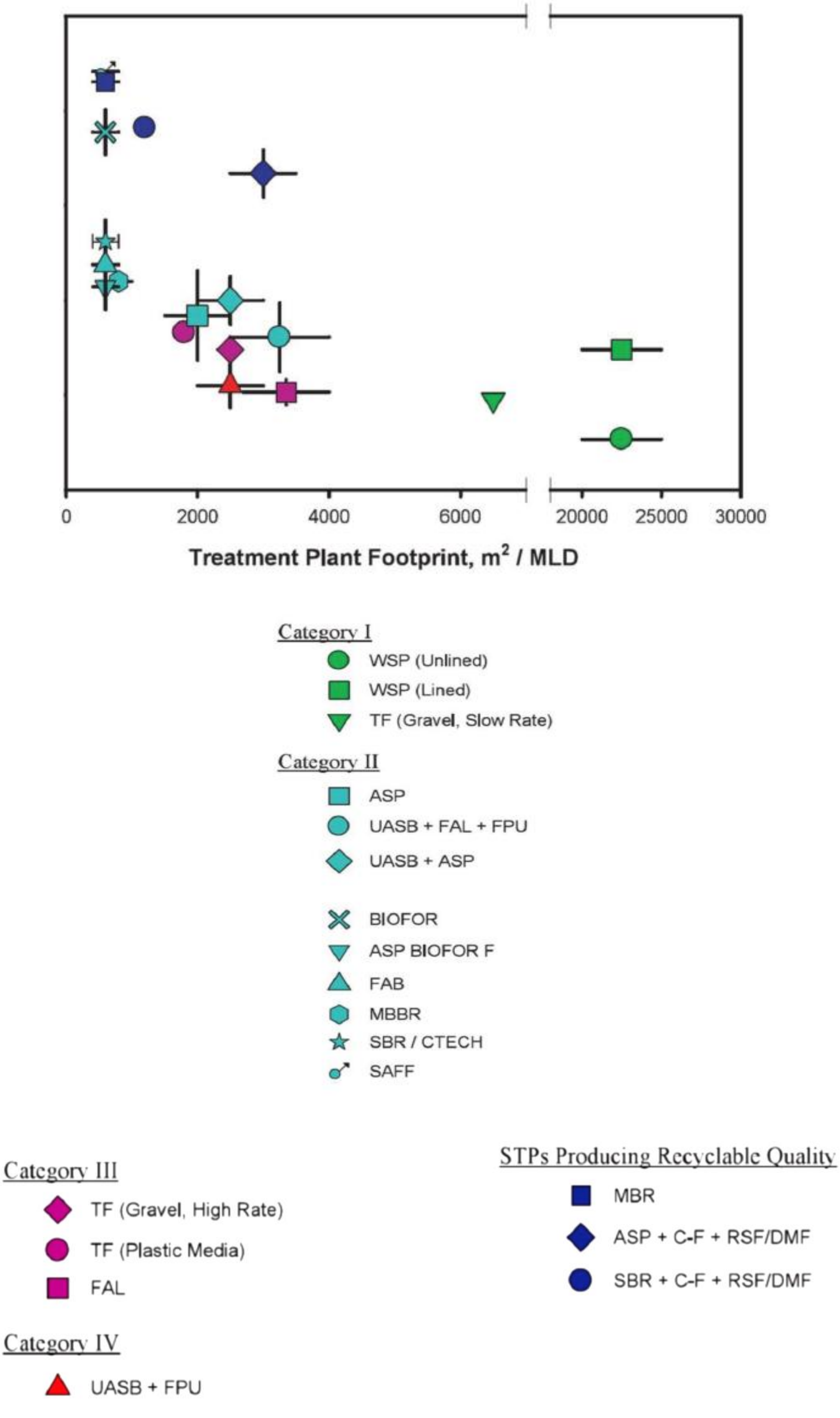


Figure 1: Requirement of plan area for use of various wastewater treatment technologies

The figure above indicates that the area required for WWTPs ranges from 0.2 to 1.0 hectares per million litres per day (MLD) depending on the technology used, with the exception of WSP. It shows that technologies such as MBBR and SBR have smaller footprints compared to ASP. The MBR technology also requires less area than conventional systems since it eliminates the need for primary and secondary clarifiers. Many urban local bodies in India have begun adopting MBBR, SBR, and MBR technologies to reduce land acquisition requirements, optimize operation and maintenance (O&M) costs, and improve the quality of treated wastewater.

For effective planning of WWTP construction using one of the space-saving technologies, it is essential to adopt a rational approach for rapid and accurate cost estimation (forecast-level estimation) for technologies like MBR, MBBR, and SBR. This shall ensure site-specific economic evaluation, comparison and selection of the most suitable one among MBR, MBBR, and SBR technologies for a particular project. Inviting budgetary bids from reputed contractors for these technologies may not be a suitable method for this evaluation. As previously discussed, there are numerous traditional and advanced wastewater treatment technologies available. Contractors often propose alternatives based on their experience, which may include technologies other than MBR, MBBR, and SBR. Some proposals might seem cost-effective, while they may be energy-intensive or require more space despite being attractive from an energy consumption standpoint. There are several challenges in evaluating proposals for WWTP construction submitted by contractors. EPC contractors often advocate for systems or technologies as available with them without applying an unbiased and rational approach to technology selection. Some stakeholders rely on historical data and documentation available to them. Additionally, the availability and cost of land are significant issues that may not always be given due consideration by contractors.

Scrutinizing and selecting the most suitable treatment technology for a specific project is a complex, challenging, and time-consuming task. Currently, there is no published or widely accepted rational method or tool found available for evaluating these tasks. Therefore, there is a genuine need to develop a rational design as well as cost estimation approach or tool and establish criteria for selecting the appropriate WWTP technology to ensure techno-commercial acceptance by project owners or urban authorities. An engineering approach for scrutiny of economic aspects may be the use of appropriate cost functions derived based on standard engineering design rationale, cost estimation for construction as well as requirement of space, operation and maintenance. Such approach will enable the stakeholders to conduct techno-economic analysis and select the most suitable technology encompassing all concerned aspects for a particular project. Against this backdrop, a research investigation has been conducted to develop and establish the methodologies for assessment and selection of the most suitable WWTP technology among

MBR, MBBR, and SBR through realistic engineering and cost evaluations using process design and estimation algorithms.

The primary objective of this research is to formulate rational cost functions and generate cost response maps to assess the economic aspects of space-saving wastewater treatment technologies (MBR, MBBR, and SBR).

Further the cost for a project is dependent upon the location-specific as well as time-specific rates. For universal use, unit cost co-efficients functions are envisaged to be developed through sensitivity study so that the stakeholders across the globe may use these functions for economic evaluation among MBR, MBBR, and SBR technologies based on location-specific rates at any point of time.

The results derived by use of cost functions developed through this research are envisaged to be reconciled by feedbacks from reputable EPC contractors to ensure suitability for application of developed cost functions.

1.1 Limitation of earlier research studies

It has been noticed through detailed survey of literature that most of the researches undertaken in connection with cost functions and indices for the construction and operation of WWTPs, primarily aimed for rapid cost estimation and commercial comparisons among mainly various conventional technologies such as continuously mixed activated sludge, oxidation ditches, and aerated lagoons. Further these studies typically utilized historical cost data collected from various sources.

It is an important concern that cost for WWTPs designed for specific capacities will be responsive for variation in inlet BOD levels. Despite extensive literature surveys over the past five decades, there appears to be a gap in publications regarding the research on development of 3-D response maps or any other tool for rapid cost estimation of WWTPs to take into account the impact of variation of inlet BOD level at a specific capacity.

Further the cost functions available as addressed above for few conventional technologies are based on country specific historical rates relevant at the point of time of construction and therefore these are not suitable for use in respect of future applications in other geographies. Universal cost functions for application in other geographies at any point of time are not found reported in literature for either conventional technologies or MBR, MBBR, and SBR technologies.

In response to above gaps and constraints, this research initiative aims to develop cost functions, 3-D cost response maps and cost co-efficient functions through sensitivity study for rapid estimation of WWTP costs using MBR, MBBR, and SBR technologies, without necessity for use of any historical or collected data.

1.2 Rationality of the Research

Economic analysis is necessary and plays a crucial role in selecting the optimal treatment technology for WWTPs among space-saving options like MBR, MBBR, and SBR, considering capital costs, land requirements, and operation and maintenance (O&M) expenses.

A significant challenge in planning WWTPs with advanced space-saving technologies is accurately estimating construction and O&M costs, and evaluating the associated benefits. Detailed design of various components is necessary for precise construction cost estimation, a process that demands time, expertise, and engineering judgment. At the planning stage, such detailed exercises are time consuming and sometimes may not be feasible. Therefore, WWTP cost estimates often rely on rule-of-thumb methods, such as cost per million litres per day (MLD) of wastewater flow, leading to inaccuracies and potential cost and time overruns during construction.

To facilitate quick and reliable estimation of WWTP construction and O&M costs, cost functions (where cost is dependent on capacity for a selected design inlet BOD load), cost response maps (where cost varies with capacity and inlet BOD load) and unit cost co-efficient functions (for universal use) are invaluable tools. This research aims to develop and apply these methodologies or tools for economic evaluation of well-established space-saving wastewater treatment processes (MBR, MBBR, and SBR) using optimization techniques.

1.3 Justification of Research Study

In many of the studies conducted earlier in the developed countries, the cost functions have been developed based on historic data collected on the cost of WWTPs constructed in different years from different local authorities and in few cases subsequently updating these data with cost indices. However, in India, detailed costs of WWTPs including technology, process hook-up, subsoil specifics, and component-wise breakdowns in integrated way are not typically published. Currently, there are no authenticated and published cost functions specifically tailored for predicting the costs of WWTPs of varying capacities and technologies in India. Available data usually only includes awarded contractor costs, sometimes with O&M expenses. Cost functions and response maps are crucial tools for estimating both capital and O&M costs of WWTPs. However, developing cost functions and cost response maps using historical data may introduce inaccuracies.

Given that WWTP components vary significantly with different technologies, specific cost functions and response maps are necessary for each treatment technology type.

Considering the substantial investment required for WWTP construction and the challenges in securing adequate space, there is a true need for research to develop accurate cost functions and cost response maps (to take into account the variation in inlet BOD level) specifically tailored for space-saving technologies like MBR, MBBR and SBR.

Further it is also important to develop tools for cost estimation for WWTPs with MBR, MBBR and SBR technologies which are suitable for use at any place across the globe other than India at any point of time. Development of unit rate co-efficient functions for MBR, MBBR and SBR technologies may fulfil this objective.

These tools would greatly benefit engineers and urban planners in generating realistic estimates and effectively allocating budgets for WWTP projects with MBR, MBBR and SBR technologies.

1.4 Hypothesis of Research Study

The hypotheses proposed for the development of cost functions and cost response maps as well as sensitivity analysis to explore unit cost co-efficient functions (which relate capacity to co-efficients of unit costs of various items) for WWTP using MBR, MBBR, and SBR technologies are as follows:

- The research study aims to remove BOD from wastewater.
- The costs of biological treatment systems generally decrease with increase in capacity. Therefore, biological treatment systems have been categorized capacity wise in three groups viz. small, medium and large.

  The cost of a WWTP depends on characteristics of raw wastewater, quality of treated wastewater, civil structure, electro-mechanical components and space requirements.
- The characteristics of raw wastewater depend on rate of water supply and pollution load per capita.

  Development of cost functions have been made based on inlet BOD load of 250 g/m^3 which is adopted as a standard design practice in municipal sector.

  However, the inlet BOD in wastewater may vary case to case in actual scenario. Six different BOD contents have been selected for the research study to develop 3-D cost response maps for cost estimation at any capacity as well as inlet BOD within the ranges adopted.

  Further sensitivity analysis has been carried out to derive the functions, which relate capacity to co-efficients of unit costs of various items required for the construction of WWTPs using MBR, MBBR, and SBR technologies with an inlet BOD load of 250 mg/l based on developed mathematical models to ensure universal application of the functions at any time.
- Characteristics of treated wastewater have been envisaged as specified by the Ministry of Environment & Forests of the Government of India.

- The process design rationale of biological treatment with MBR, MBBR and SBR technologies have been adopted as per guidelines addressed in standard and classical references.
- Mathematical models have been developed for design and estimation in Microsoft EXCEL environment for each of MBR, MBBR and SBR technologies based on above and published algorithms for quantity estimation.
- Development of cost functions for each of MBR, MBBR and SBR technologies:

Data sets have been generated for different groups in terms of capacities and respective overall costs inclusive of costs of land, construction and operation as well as maintenance by means of models developed in Microsoft Excel. Regression analysis of data have been carried out in Microsoft EXCEL based on trend lines (viz., exponential, linear, logarithmic, polynomial and power) to determine the relationship between capacity and respective overall cost for the treatment envisaged. Polynomial, logarithmic, power and exponential regression analyses did not reveal a significant increase in the R^2 value and introduced complexity. Therefore, only linear regression results and the respective equations as cost functions have been reported throughout the thesis. Validation of cost function derived has been carried out based on determination of Mean Absolute Percentage Error (MAPE) and 95 % Confidence Interval.

- Development of cost response maps for each of MBR, MBBR and SBR technologies:
- Project Costs inclusive of costs for land, civil items, electro-mechanical items, operation and maintenance at different capacities and levels of BOD concentration in raw wastewater have been worked out by use of the developed model. The results have been analysed through least square methods with regression technique based on trend lines as addressed above. As mentioned earlier, polynomial, logarithmic, power and exponential regression analyses did not yield a significant increase in the R^2 value and proposed complexity to the

functions. Therefore, only linear regression results and the respective equations as cost functions are reported throughout the thesis to depict the nature of relationship between overall cost and inlet BOD. Validation of cost function derived has been carried out based on determination of MAPE and 95 % Confidence Interval. The data sets for variation of costs with change in input level BOD in raw wastewater for different capacities as predicted from most appropriate cost response functions are modelled in 3-D environment to develop a surface map and contour map for each of MBR, MBBR and SBR technologies.

- Sensitivity analysis of developed cost functions for WWTPs with MBR, MBBR and SBR technologies:

To ensure global applicability, the functions which relate capacity to co-efficients of unit costs of various items for the construction of WWTPs using MBR, MBBR, and SBR technologies with an inlet BOD load of 250 mg/l, have been derived using developed mathematical models. Regression analysis has been performed on datasets for each range of MBR, MBBR, and SBR technologies using five different functions (exponential, linear, logarithmic, polynomial, and power). However, for simplicity and easy application, linear function curves of unit cost coefficients for various items have been adopted for use.

1.5 Originality or Novelty of Research Study

The gaps in earlier research studies as addressed under cl. no. 1.1 relate to issues as follows:

- Non-availability of rational cost functions which enable rapid cost estimations for WWTPs with MBR, MBBR, and SBR technologies in Indian Scenario,
- Non-availability of tool to assess the implications on cost of WWTPs with the above technologies in connection with variation of inlet BOD level
- Non-availability of functions which may be used for rapid cost estimations for WWTPs with MBR, MBBR, and SBR technologies at any place over the universe at any point of time.

The originality or novelty of this research study is endowed with the approach for development of a tool for basic engineering as well as cost estimations for WWTPs with MBR, MBBR, and SBR technologies to further cast several rational cost functions and cost response maps.

Cost estimation will be based on rational scheduled unit costs for various items for specific year and location (the year 2021 in India for this research). and not on historical cost data.

Such approach enables derivations and development of rational functions for cost estimations of WWTPs with above technologies (designed for operation over a 25-year period for BOD removal) across a wide capacity range, assuming an inlet BOD load of 250 g/m^3.

Response maps will be developed for cost estimation of WWTPs with due consideration of variable BOD levels ranging from 100 g/m^3 to 250 g/m^3, the variation which is common in practice.

Rational cost functions and cost response maps are extremely beneficial in respect of decision-making processes involving vendors and plant owners when awarding contracts. This study is focused on space-saving technologies to manage the space constraints in urban areas.

Sensitivity analysis of these cost functions will also be carried out since unit costs for various components used for development of cost functions can fluctuate over time and across different geographical locations. The functions derived through sensitivity analysis are considered highly engineered and practical for application across various locations within any country.

Thus, this novel research study will surely make available the set of tools developed based on rational engineering approach to the community of decision makers and bidders for selection of technology among MBR, MBBR, and SBR in respect of construction and operation of WWTPs.No such exercise has been attempted earlier, neither found in literature.

Organization of Research Thesis to be submitted

The content of the thesis has been organized with eight (8) chapters which are enumerated below

Chapter 1 focuses on introduction, the need for the study.

Chapter 2 presents the review of literature pertaining to the salient features of wastewater treatment plants based on space saving technologies, design features, cost estimation, development of cost function and selection of technology.

Chapter 3 illustrates objectives, scope and novelty of the research study.

Chapter 4 presents the methodologies adopted for the design of WWTPs, cost estimation, development of cost function and cost response maps, validation and economic analysis.

Chapter 5 includes results and discussions, presents the data sets, developed cost functions, cost response maps and the results of economic analysis in the selection of technology.

Chapter 6 presents the summary of the study and conclusion arrived from the study for the selection of technology.

CHAPTER – 2:

REVIEW OF LITERATURE

2.0 Review of pertinent literature

This chapter provides a brief overview of space-saving treatment technologies and summarizes the findings from available and published literature relevant to the subject investigation.

2.1 Brief description of space saving treatment technologies

MBR Technology

MBR technology combines the activated sludge process with membrane separation. Typically, low-pressure membranes are used, which can be submerged in the reactor itself or placed in a separate chamber to facilitate the separation of solids from liquids. This process eliminates the need for primary sedimentation tanks, final sedimentation tanks, and disinfection facilities. A schematic of the MBR Process Cycle is presented in Figure 2.

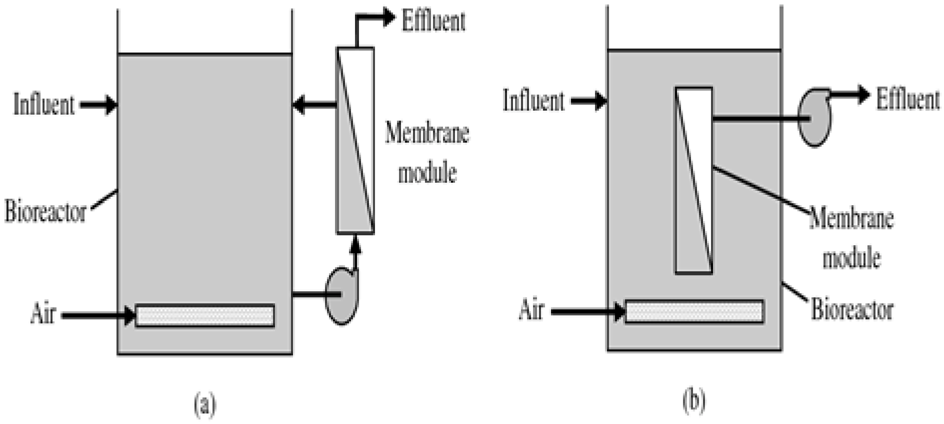


Figure 2: MBR Process Cycle

A typical arrangement for membranes is furnished in Figure 3.

Figure 3: View of MBR Membranes

Treatment of wastewater using MBR produces high-quality treated water, making it an effective option for meeting industrial water supply needs. MBR technology integrates the activated sludge process with membrane filtration, eliminating the need for primary and secondary clarifiers required in conventional ASP. This reduction in infrastructure lowers the space requirements for WWTP installation. MBR technology has broad applications in both municipal and industrial wastewater treatment.

In many cases, MBR technology is considered a preferential wastewater treatment technology over ASP, the conventional technology used for an extended period. MBR is seen as a significant innovation because it does not require a secondary clarifier, thereby eliminating the need for a large space. Suitable for both municipal and industrial wastewater treatment, MBR technology integrates a conventional biological treatment system with membrane filtration, forming a hybrid bioreactor. The use of MBR technology offers several advantages over ASP, including:

- Superior quality of treated effluent
- Higher volumetric loading rates
- Reduced hydraulic retention times
- Extended solid retention times
- Nitrification and Denitrification due to higher solid retention times and high bacterial removal efficiency.

The use of membrane filtration in MBR technology eliminates the need for secondary clarifiers, significantly reducing the required plant area. However, MBR technology has some limitations, such as higher energy consumption and associated costs, membrane fouling issues, and high maintenance costs due to the periodic replacement of membranes.

MBBR Technology

In this process, a tank similar to that used in an ASP is provided for biological reactions. MBBR technology utilizes carrier media made of polymeric material, on which microorganisms attach. The carrier media is kept in suspension by air supply in aerobic processes or by mechanical agitation in anoxic or anaerobic processes. A sieve is provided at the exit of the MBBR to retain the carrier media within the system.

This technology includes a primary clarifier upstream of the MBBR and also requires a secondary clarifier. However, there is no need to recycle activated sludge back to the MBBR inlet, as an adequate population of microorganisms is maintained within the MBBR due to the presence of carrier media and the biofilms attached to it. A schematic for the MBBR Process Cycle is provided in Figure 4.

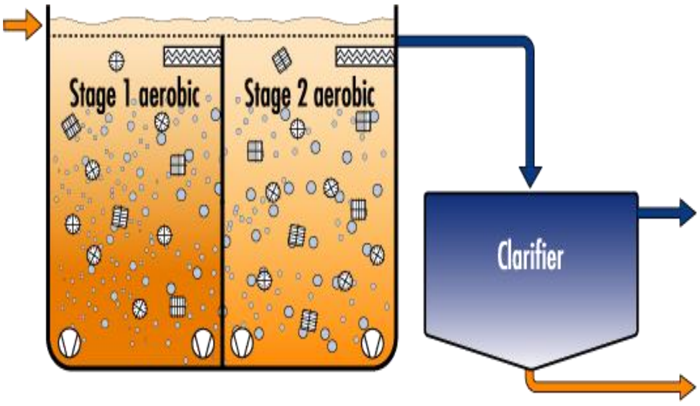


Figure 4: Schematic for MBBR Process Cycle

A typical view of MBBR media is presented in Figure 5.

Figure 5: Typical View of MBBR media

MBBR technology utilizes specialized carriers that offer surfaces conducive to biofilm growth. Typically, these carriers are constructed from high-density polyethylene (HDPE), with a density of approximately 0.9 g/cm³. The aeration system ensures the carriers are continuously circulated within the biological reactor, facilitating sufficient contact between the wastewater and the biomass on the carriers. Key advantages of MBBR technology are outlined below:

- Reactor is compact in nature and thus saves space.
- Expansion is simple and may be achieved by increase in quantity carriers.
- Satisfactory operation even in case of high level of biological load.
- Easy maintenance
- MBBR is not susceptible to toxic shock.
- MBBR does not call for the return activated sludge.
- MBBR provides high sludge retention time and therefore enables the nitrification.

SBR Technology

SBR is an advancement of the ASP. Unlike ASP, which requires a primary clarifier, an aeration tank, and a secondary clarifier for wastewater treatment, SBR conducts aeration and settling sequentially within a single tank. This eliminates the need for primary clarifiers. At least two SBR basins are necessary for parallel operation, ensuring that while one is in the aeration phase, the other is in the settling phase, allowing for subsequent decantation of the supernatant.

A schematic for SBR Process Cycle is presented in Figure 6:

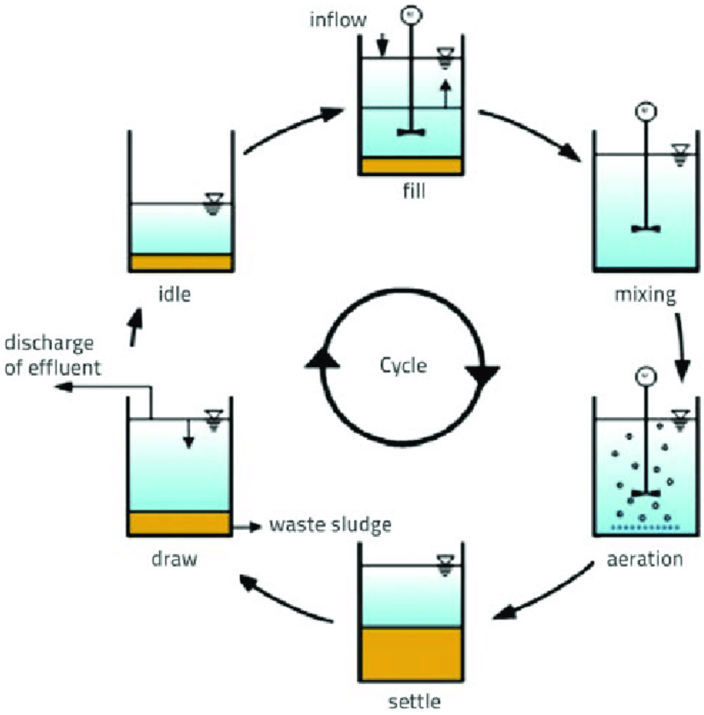


Figure 6: Schematic for SBR Process Cycle

Major benefits which may be achieved by use of SBRs are furnished below:

- Primary clarification, biological treatment and secondary clarification take place in single chamber.
- Wide flexibility for smooth operation and control.
- Requirement of minimal area for installation.
- Significant reduction with reference to requirement of capital cost due to elimination of primary and secondary clarifiers and other equipment.

2.2 Synopsis of the reviewed literature

Numerous studies on the application of MBR, MBBR, and SBR technologies in WWTPs [5 – 227] have been reviewed. Here is a concise overview of the findings:

Addressing the challenges of sustainable development in the 21st century includes tackling issues such as water scarcity and wastewater management. Global water usage has risen significantly over the past century, with projected demands reaching approximately 6000 km3/y by 2050. Consequently, anthropogenic activities are expected to generate large volumes of wastewater with elevated concentrations of biochemical oxygen demand (BOD) and chemical oxygen demand (COD).

Efficiently managing large volumes of wastewater involves employing various techniques encompassing physical, chemical, and biological treatments, often combined for enhanced effectiveness. Over recent decades, the development of technologies like the moving bed biofilm reactor (MBBR) and membrane bioreactor (MBR) has catalyzed extensive research in wastewater treatment. Research in MBR and MBBR has gained significant traction, leading to substantial advancements in these systems. MBBR processes, notably, offer a promising advantage by reducing space requirements. However, in cases involving high-strength wastewater, MBBR alone may not consistently meet stringent discharge standards. Conversely, MBR is valued for its compact footprint and efficient removal of organic matter and suspended solids, although membrane fouling remains a critical concern when treating high-strength wastewater.

Several researchers have published review papers summarizing the performance, identifying research gaps, and detailing recent advancements in MBBR and MBR, which have been reviewed for relevance to this study.

The sequencing batch reactor (SBR) represents a variant of the activated sludge system characterized by batch or intermittent operation. It offers an appealing alternative to conventional activated sludge processes due to its lower cost and smaller footprint. The SBR operates on a fill-and-draw principle, integrating biological reactions and solids-liquid separation within a single vessel. Unlike conventional continuous flow activated sludge systems, the SBR conducts treatment in a sequential time-based sequence. A significant advantage of this approach is its flexibility to adjust phase durations and cycle numbers based on varying inputs and desired treatment outcomes.

Based on literature review related to the current investigation, it is evident that numerous studies over the past fifty years have focused on developing cost functions to estimate both construction and operational expenses of wastewater treatment plants (WWTPs). The primary aim of these endeavours has been to economically analyze various alternative treatment technologies.

Below, relevant publications have been reviewed, and summaries of these investigations are provided for quick reference:

Shah and Reid (1970) formulated mathematical models for cost functions associated with wastewater treatment plants (WWTP) after surveying 563 plants across 48 states in the US [228]. Their study utilized collected data to develop regression equations that calculated unit construction costs, taking into account design flow and a variable denoted as 'PE,' which incorporated average waste inlet flow and biological oxygen demand (BOD). They observed that economies of scale exert a notable influence on the unit construction costs of different secondary treatment systems.

In 1976, the USEPA analyzed tendered price data for the construction of wastewater treatment plants (WWTP) and formulated two cost curves: one for new secondary plants and another for upgrades from primary to secondary treatment [229]. Drawing from bid data collected from EPA regional offices, the study categorized and analyzed it using linear regression methods. A comparison between the developed cost curves and the costs estimated in the EPA guide for secondary treatment revealed that bid costs were 1 to 2.5 times higher than the guide's predictions. This discovery underscored that the bid data reflected a significantly lesser economy of scale compared to what the guide had initially projected.

Qasim et al. (1992) presented generalized equations for evaluating costs across various categories including construction, operation, and maintenance of water treatment plants [230]. They developed equations specifically for chlorine storage, ozone generation, liquid alum feed, dry alum feed, polymer feed, lime feed, potassium permanganate feed, sulfuric acid feed, sodium hydroxide feed, and ferric sulfate feed.

Vanrolleghem et al. (1996) emphasized the necessity of developing cost functions for the design and operation of wastewater treatment plants (WWTPs) [231]. They presented a comprehensive framework for formulating and assessing a decision support index. This index facilitates the evaluation of both design considerations and operational strategies during the planning stages of new WWTPs, as well as for enhancing existing plant operations. The authors advocated spatial and temporal optimizations to enhance the functionality of this approach, providing examples in their paper to illustrate its application.

Gillot et al. (1999) discussed investment cost functions tailored for oxidation ditches and outlined several fixed and variable operating cost functions to estimate the total cost of wastewater treatment systems [232]. They emphasized that when constructing a new WWTP or expanding an existing one, various treatment options can be evaluated using a cost index. The authors noted two key observations:

a) Cost indices often focus solely on investment or specific operating costs, which can be limiting.

b) Time-dependent characteristics of wastewater are often overlooked, leading to inflated cost estimates when large safety factors are applied.

Their study introduced an economic index derived from cost functions covering both construction and variable operation and maintenance (O&M) costs throughout the project's lifespan. They highlighted the benefits of simulation in cost estimation and underscored the need for a standardized cost criterion for comparing different treatment alternatives in WWTP design and operation. Gillot et al. recommended including variable O&M costs in cost evaluations to accurately assess control strategies developed through dynamic modeling and simulation.

Tsagarakis et al. (2003) formulated cost functions to assess land requirements, construction costs, and operation and maintenance (O&M) expenses for activated sludge systems based on a survey conducted in Greece [233]. This paper scrutinizes economic data from existing municipal wastewater treatment plants (MWTPs) in Greece, utilizing a dataset that includes land usage and cost data modelled as $y = a*(x^b)$, with calculated coefficients a and b. Specific equations for costs and land use were developed for different systems, considering manpower and energy as significant cost components during operation.

The study also conducted a life cycle analysis (LCA) of WWTPs, highlighting the most suitable technologies for specific cases. Conventional activated sludge systems were found to be less cost-effective under conditions of high energy costs, low automation, and operation at low food-to-microorganisms (F/M) ratios. In contrast, waste stabilization ponds appeared cost-effective with minimal earthworks and careful consideration of land costs.

Gratziou et al. (2006) conducted a comparative analysis of total costs among several small-scale wastewater treatment systems, calculating construction and operation costs based on established cost functions from literature [234]. They developed unit capacity functions for a forty-year operating period for each system investigated, which included Oxidation Ditch, Rotating Biological Contactor, Sequential Batch Reactor, Subsurface Constructed Wetland Systems, Trickling Filter, and Waste Stabilization Ponds.

The study accounted for various cost components such as construction materials (including civil and electro-mechanical equipment), energy consumption, chemical usage, manpower, maintenance, and land value. Total and individual costs were expressed as functions of inlet flow. The authors found that annual operation and maintenance costs, as well as total costs encompassing construction, maintenance, and forty years of operation, could be represented by equations of the form $a + b*Q + c*Q^2$, where Q is the inlet flow rate. Energy costs were linearly related to flow rate, expressed as $a + b*Q$. The coefficients (a, b, c) were summarized in tables provided in the study.

Positive economies of scale were observed across all treatment alternatives, particularly pronounced for capacities up to 5,000 equivalent populations. Natural treatment methods for wastewater emerged as the least expensive option within the study's range of equivalent populations. The choice of treatment method, from least to most expensive, was shown to be influenced by plant capacity.

Friedler & Pisanty (2006) developed cost functions by analyzing the construction costs of 55 wastewater treatment plants (WWTPs) built in Israel [235]. Their study focused on examining the cost-performance relationships based on data from these WWTPs.

The authors proposed exponential regression equations that express construction costs for secondary treatment, advanced secondary treatment, and advanced treatment as functions of design flow. They observed that the power coefficients tend to increase with higher treatment levels, indicating that economies of scale diminish as treatment complexity rises.

A review of cost distribution among construction components revealed significant decreases in civil item costs with increasing design flow, while proportional costs for electro-mechanical equipment rose. Costs for electricity and control did not show sensitivity to design flow. The study noted a shift in cost significance from civil items to electro-mechanical components as WWTP size increased.

Regarding operation and maintenance (O&M) costs, the study found them to be more sensitive to the required treatment level rather than construction costs, often ranging 20% to 70% higher than relative construction costs depending on the treatment requirements.

Nogueira et al. (2007) formulated cost functions for energy-saving wastewater treatment technologies using power law relationships, where costs are inversely proportional to the population served [236].

Their study focused on natural processes for wastewater treatment, which are inherently energy-saving and promote sustainable management with low investment and operational costs, often with minimal or zero energy consumption. Cost functions were developed to estimate the investment required for construction and operation of wastewater treatment plants (WWTPs) employing these energy-saving technologies.

The derived cost functions indicated that costs decrease as the population served increases. For WWTPs utilizing various energy-saving treatment alternatives, the investment for construction and operation ranged from 400 euros per population equivalent to 200 euros per population equivalent. Annual operation costs were estimated between 70 euros per population equivalent to 20 euros per population equivalent, particularly for populations ranging from 50 to 250 population equivalents.

Sato et al. (2007) developed cost functions for capital expenditure, operation, maintenance, and land requirements based on data collected from various reports and field visits in India, focusing on up-flow anaerobic sludge blanket (UASB) and waste stabilization pond (WSP) systems [237].

Their study evaluated the total annual costs, including capital and operation and maintenance (O&M) costs, associated with operating UASB and WSP systems in India. They compared these systems with activated sludge process (ASP) and biological aerated filter (BAF) systems based on their ability to remove chemical oxygen demand (COD) and their total annual costs considering different annual interest rates and land prices.

The study found that capital and O&M costs per unit size of UASB or WSP systems followed a first-order relationship with treatment capacity. Analyzing the cost-effectiveness of organic removal and capital or O&M costs across various sewage treatment systems at different annual interest rates, the study concluded that, for the Indian context, UASB systems could offer the most suitable balance between expenses and treatment efficiency.

Papadopoulos et al. (2007) gathered data on land requirements, construction costs, and operation and maintenance expenses from existing wastewater treatment facilities. They developed twelve equations using ordinary least squares (OLS) and fuzzy linear regression methods [238].

The study focused on analyzing cost data from municipal wastewater treatment plants (WWTPs) in Greece, collected through on-site visits. The data encompassed information on the land size needed and costs associated with constructing and maintaining natural wastewater treatment systems.

Equations of the form ln $Y_i = A_{0i} + A_{1i}$ ln X_i (where A and Y are vectors of fuzzy numbers and X is a matrix of independent variables) were derived using both OLS and fuzzy linear regression techniques. Mean absolute error and root mean square error were employed to compare the accuracy of OLS versus fuzzy estimations. In most cases, the study found that OLS provided slightly more accurate estimates compared to fuzzy linear regression for these specific datasets.

Dysert (2008) emphasized the significance of parametric cost models as crucial resources for early cost estimation [239]. The paper highlights that the methodology for preparing a cost estimate varies based on the project's level of definition. During the initial stages of a project, preliminary cost estimates are essential to guide decision-making by authorities regarding further project development. This process involves selecting the most appropriate technology from various alternatives tailored to site-specific conditions.

The concept of parametric estimating is central to this approach. Parametric cost estimating models serve as valuable tools for generating conceptual estimates when detailed technical information is not yet available for a comprehensive cost estimation. The paper outlines the concept of parametric estimating and provides insights into the steps involved in creating a parametric estimating model.

Singhirunnusorn and Stenstrom (2010) proposed cost functions for activated sludge, oxidation ditches, aerated lagoons, and waste stabilization ponds to evaluate land, construction, operation, and maintenance costs of wastewater treatment plants (WWTPs) in Thailand, based on data collected from several municipal WWTPs [240].

The authors analyzed economic indices relevant to Thailand for determining optimal and suitable technologies in WWTPs. They evaluated these indices based on land requirements, construction costs, and operation and maintenance (O&M) costs obtained from 53 municipal WWTPs through questionnaire surveys and secondary research. Using regression analysis, they developed economic indicator models specific to activated sludge, oxidation ditches, aerated lagoons, and waste stabilization ponds.

The study found that construction costs and land requirements were correlated with design capacity and followed a power regression form ($y = a*x^b$). O&M costs were related to actual flow rate and followed a linear regression form ($y = a + b*x$). Based on these models, economic indicators for each technology were calculated and compared across different scenarios.

Key findings included that waste stabilization ponds required significantly larger land areas compared to other technologies of similar size ranges. Activated sludge systems were identified as the most expensive across all size ranges, with the cost difference between activated sludge and other processes increasing with plant capacities. Oxidation ditches were noted for higher annual O&M costs compared to other technologies studied.

Hernandez-Sancho et al. (2011) developed a series of cost functions for different wastewater treatment technologies based on data collected from 341 WWTPs in Spain [241].

Their methodology aims to provide clarity on the cost structure of WWTP technologies, which can be valuable for planning new WWTPs. Unlike existing models that primarily base treatment costs on plant capacity, this study introduces a novel approach. It focuses on deriving cost functions based on the most influential variables within the treatment process, such as pollutant removal efficiency and the age of the WWTP. This approach allows for an assessment of economies of scale concerning these variables.

These cost functions enable a detailed economic comparison of various treatment technologies, aiding in the planning of new WWTPs and water reuse projects. The research aimed to establish a comprehensive cost model using statistical insights derived from a sample of 341 WWTPs, enhancing understanding and decision-making in wastewater treatment infrastructure development.

Yengejeh et al. (2014) conducted a study comparing various sewage treatment processes based on their costs, as documented [242].

The authors highlighted the critical importance of water resources, particularly in light of changing climatic conditions threatening water availability in many countries. They emphasized that constructing sewage treatment plants is essential for urban improvement plans to prevent water source pollution and promote sewage reuse. However, they noted a lack of awareness regarding the economic aspects, costs, and benefits of these plans, leading to suboptimal investments and outcomes.

The study compared several sewage treatment methods suitable for both hot and dry climates. It determined per capita costs for different processes and prepared comparative diagrams and economic benefit analyses to establish cost-benefit indices for potential investors. Financial calculations were conducted in Euro, aiming to provide comprehensive insights for informed decision-making and efficient allocation of financial resources in sewage treatment infrastructure.

Pannirselvam and Gopalakrishnan (2015) compiled cost records from thirty operational wastewater treatment plants (WWTPs) constructed using conventional activated sludge technology. They adjusted the cost data to the base year of 2014 using verified construction cost indices and developed cost functions through regression analysis [243].

The study aimed to establish cost functions for estimating the expenses of sewage treatment plants during the planning stages, facilitating informed technology selection. The authors gathered cost data from thirty existing WWTPs built with activated sludge process (ASP) technology and normalized them to 2014 using reliable construction cost indices. Regression analysis was conducted in Microsoft Excel to establish unit cost versus capacity relationships, selecting equations with determination coefficients close to unity as the preferred cost functions.

To validate these cost functions, the authors applied them to calculate costs for small, medium, and large capacity ranges, comparing the results with actual WWTP costs. They computed Absolute Percentage Error (APE) for each WWTP and Mean Absolute Percentage Error (MAPE) as the average of APE values across the three capacity groups. The MAPE values were found to be 3.22%, 7.72%, and 2.35% for small, medium, and large capacity groups, respectively, all within 10%, indicating highly accurate cost predictions. Additionally, polynomial, logarithmic, and power functions were identified as the best-fit equations for different capacity groups based on their analysis.

Koul and John (2015) conducted a Life Cycle Cost analysis of Up-flow Anaerobic Sludge Blanket Reactor (UASBR), Sequencing Batch Reactor (SBR), and Moving Bed Biofilm Reactor (MBBR) using data collected from various plants [244].

The study addresses the wide availability of wastewater treatment plants (WWTPs) employing different technologies, each claiming varying levels of performance efficiency and suitability. However, these claims often lack a standardized basis for comparison, especially when evaluating plants in isolation. This paper proposes a life cycle cost-based approach to evaluate the performance of WWTPs using UASBR, SBR, and MBBR technologies operating under similar conditions.

The authors concluded that life cycle cost analysis serves as a valuable tool for comparing WWTPs. Their analysis indicated that UASBR technology was the most suitable for treatment, followed by MBBR and SBR, based on their comprehensive evaluation of operational costs and efficiencies over the plants' life cycles.

Panaitescu et al. (2015) employed various cost functions sourced from literature to estimate fixed and variable operating costs of wastewater treatment plants (WWTPs), aiming to analyze the influence of influent characteristics on costs and explore economic aspects [245].

The study utilized the present value method to determine the total costs of WWTPs. Annual operation and maintenance costs for each process were discounted to present value and added to the investment costs to calculate the current net value. Generally, WWTP costs are categorized into investment costs and operating costs, with the latter further classified as stable (routine operation, maintenance, and power consumption) or variable (chemicals, sludge treatment and disposal, effluent charges). Cost functions were applied to evaluate preliminary cost estimates, assisting decision-makers in selecting among different alternatives during the early project phases.

The authors calculated operational costs to benchmark various optimization scenarios. They used statistical formulas and graphical representations to analyze the impact of influent characteristics on economic costs, focusing on investment cost functions, fixed operational costs, and variable operational costs for WWTPs. Their findings suggested that constructing larger plants becomes more economical as maximum loading rates are approached.

The study recommended implementing these cost functions into software tools for integrated evaluation of plant design and behaviour simulation, enhancing decision-making processes in WWTP development and optimization.

Jafarinejad (2016) utilized CapdetWorks to estimate costs and conduct a comparative analysis of conventional activated sludge (CAS), extended aeration activated sludge (EAAS), and sequencing batch reactor (SBR) technologies for a wastewater treatment plant (WWTP) in Tehran [246].

The study emphasized the importance of economic modelling and cost estimation in designing, constructing, and forecasting the future financial requirements of WWTPs. Three configurations—CAS, EAAS, and SBR—were evaluated for their total project construction costs, operation and maintenance costs, material and chemical costs, energy costs, and amortization costs at the Tehran WWTP. Additionally, the study investigated the impact of mixed liquor suspended solids (MLSS) levels on WWTP costs.

The findings indicated that increasing MLSS levels reduced total project construction costs and material costs for WWTPs using EAAS and CAS technologies, highlighting the economic implications of MLSS management in wastewater treatment processes.

Gautam et al. (2017) conducted a comparative analysis of several wastewater treatment technologies including MBR, MBBR, SBR, Extended Aeration, and Submerged Aerobic Fixed Film processes using data from small-sized Sewage Treatment Plants (STPs) in India. They derived cost functions for capital investment, electro-mechanical equipment, electricity, operation, and maintenance costs based on their findings [247].

The study focused on identifying cost-efficient technologies for wastewater treatment applicable to small-sized STPs in India. Emphasizing compliance with pollution control guidelines set by national authorities, the research highlighted the economic considerations of wastewater treatment technologies aimed at making treated wastewater suitable for reuse. Various technologies such as Extended Aeration (EA), Moving Bed Biofilm Reactor (MBBR), Membrane Bioreactor (MBR), Submerged Aerobic Fixed Film (SAFF), and Sequential Batch Reactor (SBR) were analyzed, with a particular focus on their operation and maintenance costs (O&M).

The findings indicated that SBR emerged as the most cost-effective treatment technology, while MBR was identified as the most expensive among the options considered. This comparative assessment provides insights into selecting suitable wastewater treatment technologies based on economic feasibility and operational efficiency for small-scale applications in India.

Doherty (2017) compiled life cycle cost data from various sources encompassing wastewater treatment systems of different sizes, loading capacities, discharge limits, and sludge disposal methodologies. Through analysis, it was observed that systems capable of reducing energy and chemical requirements tend to exhibit greater economic viability [248].

The study aimed to introduce a performance assessment methodology and toolkit for wastewater treatment plants (WWTPs). This methodology was applied across several WWTPs with diverse characteristics over an extended period. The toolkit, developed as part of this study, was disseminated to key stakeholders for testing and feedback. Stakeholder input highlighted the need for enhancements in methodology, key performance indicator (KPI) calculation, result presentation, and applicability across various WWTP configurations.

Feedback from stakeholders also emphasized the potential integration of this methodology into the national WWTP management system in Ireland. The developed decision support tool proved effective in identifying comparable WWTPs based on regulatory compliance data, facilitating benchmarking and comparison. Its application was successfully tested across operational and licensed WWTPs in Ireland, offering a streamlined alternative to manual identification methods for similar groups of WWTPs.

Sekandari (2019) conducted an evaluation to determine the most economical sewage treatment scheme among an integrated anaerobic-aerobic sewage treatment plant (IA-ATP), waste stabilization pond (WSP), and complete-mix activated return sludge sewage treatment plant (ARSTP) for an average sewage flow rate of 9.379 million liters per day [249].

Cost estimation plays a crucial role in the development and assessment of sewage treatment plants. This study compared the project costs and annual operation and maintenance (O&M) costs of IA-ATP against WSP and ARSTP. For an average sewage flow with BOD and SS concentrations of 350 mg/L and 360 mg/L, respectively, IA-ATP was found to have project costs approximately 14% and 34% lower than ARSTP and WSP, respectively. Additionally, the annual O&M costs of ARSTP were significantly higher than

IA-ATP and WSP by approximately 109%.

The per unit cost of sewage treatment in IA-ATP was estimated at USD 1.10 per cubic meter, whereas for ARSTP and WSP, it was USD 1.36 per cubic meter and USD 1.46 per cubic meter, respectively. Based on these findings, IA-ATP emerged as the most cost-effective sewage treatment scheme for the specified study area.

Acampa et al. (2019) conducted a study to estimate the construction costs of an urban wastewater treatment plant (WWTP) with a capacity of less than 50,000 Population Equivalent (PE). The cost estimation employed two methods: synthetic cost estimation for civil works and multiple linear regression for electromechanical components. Their findings indicated that increasing the size of the WWTP resulted in higher economic benefits for populations ranging from 5,000 to 10,000 PE, with diminishing returns beyond this range [250].

The study aimed to assess the economic feasibility of constructing an urban WWTP suitable for up to 50,000 PE and to provide insights for planning new WWTPs. They proposed a methodology based on cost functions developed as follows:

Estimation of civil costs using synthetic methods and electromechanical equipment costs using multiple linear regression. These functions establish mathematical relationships between construction costs and population equivalents. It was observed that significant economic benefits accrue from scaling up WWTP size within the population equivalent range of 5,000 to 10,000. However, further increases in size were found to offer diminishing economic returns.

Arif et al. (2020) utilized economic modelling to compare the cost-effectiveness of three wastewater treatment plants (WWTPs): conventional activated sludge without denitrification (CAS), conventional activated sludge with pre-denitrification (CAS-N), and membrane bioreactor (MBR). They employed Capdet Works simulation software to analyze these alternatives for an average flow rate of 30 million liters per day (mld) [251].

The study aimed to highlight the advantages of employing economic modelling in selecting the most cost-effective treatment scheme among the aforementioned WWTP technologies. CapdetWorks (v.3) was used to calculate the present worth costs for each alternative and evaluate their unit costs at Tikrit WWTP. The results indicated that the present worth cost of MBR technology exceeded that of CAS and CAS-N by approximately 57% and 42%, respectively. Additionally, the unit costs were determined as \$0.2/m3 for CAS, \$0.27/m3 for CAS-N, and \$0.43/m3 for MBR. The lower cost of CAS reflects its reduced removal efficiencies compared to CAS-N and MBR. Economic modelling was underscored as beneficial for comparing relative costs among treatment alternatives, aiding in informed engineering decisions for selecting appropriate treatment technologies.

Altin et al. (2020) made an investigation to find out the costs of operation for an urban WWTP since such costs are important for planning of construction of WWTPs. The design flow rate for the plant was around 34000 m^3/day and activated sludge reactor was installed for biological treatment of wastewater [252].

The costs for consumption of electricity, the chemicals used, repair as well as maintenance were calculated based on equipment data and operating hours for each individual equipment. The study was made to calculate the costs on daily, monthly and yearly basis. Based on calculated data, average treatment costs per unit volume of wastewater and unit pollution load were determined.

It was observed that cost for electricity consumption was more than 40 % of the total operating costs. This might be due to the size of the plant which was medium. The operation cost of activated sludge reactor was the highest among all other units. The energy requirement per m^3 of treated wastewater worked out as 0.88 kilowatt-hour and the same per kg of COD as 2.22 kilowatt-hour. These data were reconciled with earlier researches and found compatible.

Karolinczak et al. (2020) addressed that construction of a subsurface vertical flow constructed wetland (SS-VF) for treatment septage reduces pollution load to significant extent and undertook an optimization study to investigate the cost economy for treatment of septage through SS-VF in advance of it's feed to WWTP for biological treatment [253].

The model developed for optimization was based on power functions. The fraction of septage stream fed to SS-VF was envisaged as the decision parameter. The criteria for optimization were minimum cost for treatment of part of septage through SS-VF and thereafter biological treatment in WWTP.

The results from the study were validated in respect of rural WWTPs which are small in size. It was established that it is prudent to treat complete septage by SS-VF bed as primary treatment for rural WWTPs. However, it was concluded that SS-VF for primary treatment of septage is not cost-economic for urban WWTPs since acquisition of land for construction of SS-VF is cost-prohibitive.

Ozgun et al. (2021) made a study to determine unit capital expenditure and unit operation & maintenance expenditure based on analysis of expenditure data collected from sixteen WWTPs located at Istanbul [254].

Unit capital expenditure as worked out for primary treatment was in the range of 0.009 – 0.0134 euro per m^3 and the same for tertiary treatment was in the range of 0.045 – 0.063 euro per m^3.

Unit O&M expenditure had the range of 0.004 – 0.018 euro per m^3 for primary treatment and the range of 0.056 – 0.098 euro per m^3 for tertiary treatment.

It was concluded that capital expenditure for primary treatment is almost around 60 % of overall expenditure, whereas the same for tertiary treatment is around 40 % of overall expenditure.

It was recommended that cost functions developed through this study may be used to undertake economic assessment for construction of new WWTPs and management of already installed WWTPs.

Rivera (2022) conducted research for establishment of approaches beneficial for administrative authorities of WWTPs to reduce the costs for disinfection. Urban areas experience a steady growth in population and as a consequence a steady increase in wastewater generated. Process of disinfection of wastewater is energy intensive and has a significant cost impact with reference to increase in quantity of wastewater. He collected data through interviews with few municipalities at Florida who took initiatives to bring down the costs for disinfection of wastewater [255].

It was revealed that the municipalities who had been able to control the costs for disinfection of wastewater used ‘Define, Measure, Analyse, Improve and Control’ approaches.

It was recommended to go for automated disinfection system to control and reduce cost reduction in disinfection processes. Further, the use of a ‘Supervisory Control and Data Acquisition’ system has also been addressed which would provide the facility for adjustments for best utilization of resource.

Rathore et al. (2022) made a study with technologies - Activated Sludge Process, Biological Filtration and Oxygenated Reactor, Moving Bed Bio Reactor and Up-flow Anaerobic Sludge Blanket to explore the most economic option under given set of conditions. All data for treatment of wastewater @ 1.0 million litre per day were compared to arrive at resolution. Costs for energy costs and requirement for area were also taken into consideration [256].

Life Cycle Cost Analysis based on present value method were carried out with due consideration of capital expenditure, operation and maintenance expenditure, energy expenditure, replacement expenditure and salvage value. Various cost data for each of the technologies were collected from literature & other sources.

It was concluded that Up-flow Anaerobic Sludge Blanket is a preferred option where availability of land is not an issue related to cost and quality of treated wastewater is not a statutory concern. If quality of treated wastewater is an issue but not the availability of space, Activated Sludge Process is economic option. Where space is a concern, Biological Filtration and Oxygenated Reactor is recommended as a choice for treatment. Where space is limited, Moving Bed Bio Reactor may be an option. However, this study has presented that capital and maintenance costs for Moving Bed Bio Reactor are high.

Maziotis and Molinos-Senante (2023) undertook a study with three objectives - determination of eco-efficiency for more than 100 WWTPs by use of ‘Efficiency Analysis Tree’ technique, calculations of reduction achieved in operation expenditure for eco-efficient WWTPs and estimation of optimum levels of expenditure for operation as well as GHG emissions for WWTPs [257].

Linear programming as well as machine learning were adopted in the study to avoid the constraints connected with non-parametric approaches followed in earlier relevant studies.

It was revealed from the study that the costs and GHG emissions are functions of suspended solids and organic matter removed in WWTPs. The average eco-efficiency as estimated was less than o.4 which signifies that the set of WWTPs could reduce expenditure by more than 0.3 euro and more than 0.1 kg of carbon di-oxide for each m^3 of wastewater. Except very few WWTPs explored as eco-efficient, majority had the scope to reduce expenditure for operation as well as GHG emissions.

Sayyad et al. (2024) made a study to compare the costs estimated for inlet chamber, screen chambers, grit chambers, and distribution chamber of a sewage treatment plant (capacity 63 million litres per day) by use of conventional approach and BIM software. Detail drawings of the above the units were collected from the plant as reference for further use in respect of this cost estimation study [258].

In conventional method, the length, breadth, and height of each unit addressed above were considered as per the concerned drawings collected. The quantities of concrete, steel, brickwork, plinth, wall, plaster, paint and railing were estimated to find out the bill of quantities and respective costs as well as overall cost by use of unit rates.

For estimation by use of BIM software, Revit was used to develop 3-D model of the above units. Quantities and costs were extracted from the software. The comparative study revealed that the difference of quantities in respect of various items varies from (-) 3.48 % to (+) 0.41 %. Cost estimated by use of BIM was 1.12 % more than that estimated by use of conventional method.

K. Limbore and Dr. R. D. Shinde (2024) carried out a comprehensive study for planning, design, and implementation of a WWTP in conjunction with sewerage, with special emphasis to operation and maintenance issues. The study was based on both qualitative and quantitative analysis. Extensive review of literature review made to study available methodologies and practices adopted for planning and management of WWTPs and sewerage [259].

Qualitative analysis was conducted through interviews with domain experts, policy-makers, and stakeholders involved to collect feedbacks with reference to typical challenges and resolutions. Quantitative analysis included surveys administered to plant operators and local authorities for collection of efficiency data, quality data and maintenance details. Qualitative data was analyzed by thematic method and quantitative data by statistical methods to develop themes and expressions.

A case study on Vasai Virar City in Maharashtra was made for validation of research findings. It was concluded that the HDD method for installation of HDPE pipelines is a costlier option than open cut method employed for the RCC sewer pipeline. However, the advantages for HDD method include lesser expenses for restoration of roads and a longer life for HDPE pipelines.

Variations of cost for different components were also studied. With reference to the year 2013, most of the components experienced a cost inflation of 12.34% in 2021 and the cost further increased in 2023. Cost for operation & maintenance costs had significant increase of around 26 % in 2021 and a spike to around 42 % in 2023.

2.3 Critical review of pertinent literature

Summary of key findings from review:

From the literature review, it has been noted that in the history of the last 50 years, several studies are being carried out in connection with the development of cost functions and cost indices for the construction and operation of WWTPs. The intent behind such efforts was the economic analysis of ubiquitous alternative treatment technologies. A summary is addressed below for the key findings:

In 1970, cost functions for WWTPs were developed based on the feedback survey of various plants located in 48 states in the United States. USEPA in 1976 analysed collected construction bid data for WWTPs and developed two cost curves - one for new secondary treatment systems and the other for upgradation of plants from primary to secondary treatment system. In 1992 generalised equations were developed for estimation of cost in different categories for water treatment plants. Cost functions derived for WWTPs with oxidation ditches were published in 1999. In 2003 at Greece, cost functions were developed based on data survey to assess requirements for land, construction and O&M for WWTPs with activated sludge systems. Three years later, cost functions were formulated by analysis of the costs of few constructed WWTPs in Israel. Next year, cost functions for capital cost, operation, maintenance and land requirements were published based on collected data for UASB and WSP. In 2010, functions based on data collected from Thailand were reported to assess cost of WWTPs with activated sludge, oxidation ditches, aerated lagoons, and waste stabilization ponds. Next year, a set of cost functions for

WWTPs with different technologies were formulated based on collected data in Spain. In 2015, cost functions were published based on collected cost records for few constructed WWTPs with conventional activated sludge technology. In the same year, life cycle cost analysis for UASB, SBR and MBBR based on collected data from different plants was reported. A comparative analysis of the costs for conventional ASP, EA-activated sludge and SBR technologies by use of CapdetWorks in 2016. Next year, a comparative scrutiny among MBR, MBBR, SBR, EA and submerged aerobic fixed film process was made in India and cost functions for capital, electro-mechanical, electricity, operation and maintenance were derived from collected data. In 2020, an investigation was made to find out the costs of operation for WWTP with activated sludge reactor since such costs are important for planning of construction of same kind of WWTPs. A study was made in 2021 to determine unit capital expenditure and unit operation & maintenance expenditure based on analysis of expenditure data collected at Istanbul. Another study was made in 2022 with technologies - Activated Sludge Process, Biological Filtration and Oxygenated Reactor, Moving Bed Bio Reactor and Up-flow Anaerobic Sludge Blanket to explore the most economic option under given set of conditions. A comparative study was made in 2024 on the costs estimated for inlet chamber, screen chambers, grit chambers, and distribution chamber of a sewage treatment plant by use of conventional approach and BIM software. In the same year, a comprehensive study was undertaken for planning, design, and implementation of a WWTP in conjunction with sewerage, with special emphasis to operation and maintenance issues.

Research gaps and limitations:

The above summary reveals that major studies carried out in connection with development of cost functions and indices for rapid cost estimation of WWTPs were mainly with various conventional technologies.

Most studies derived cost functions for land, construction, operation, and maintenance of WWTPs from region-specific historical cost data obtained from existing sources or published documents. Some studies utilized CapdetWorks software to compare costs among conventional technologies based on specific inflow rates. However, newer technologies such as MBR, MBBR, and SBR have not been adequately considered in these studies.

The literature concerning the selection of appropriate wastewater treatment technology based on engineering economics and applicable issues in India is found to be limited. Very few studies did focus on cost issues for WWTPs, employing space-saving technologies like MBR, MBBR, and SBR, which are specifically relevant to Indian conditions.

It is acknowledged that the construction of WWTPs based on conventional technologies or natural pond systems requires large plots of land, which are increasingly scarce in dense urban areas. Adoption of WWTPs utilizing space-saving technologies is a prudent solution to this constraint.

Cost for WWTPs designed for specific capacities will be responsive for variation in inlet BOD levels. No published literature has been noticed on development of 3-D response maps or any other tool to assess cost variation of WWTPs with variation of inlet BOD level at a specific capacity.

Further the cost functions published in literature are based on country specific historical rates relevant at specific points of time and therefore may not be prudent for use even with due consideration of cost indices in other geographies. Universal cost functions for application in other geographies at any point of time are not found reported in literature.

With above research gap and limitations in background, selecting the most suitable and cost-effective option among space-saving MBR, MBBR, and SBR technologies for wastewater treatment at a particular site poses a significant challenge. Therefore, there is a clear need for an appropriate approach or methodology to accurately forecast and estimate the cost levels of WWTPs employing each of these technologies, ensuring efficient decision-making in wastewater treatment infrastructure planning.

This research initiative is focused on approach to develop cost functions, 3-D cost response maps and unit cost co-efficient functions through sensitivity study for rapid estimation of WWTP costs using MBR, MBBR, and SBR technologies based on rational engineering approach and methods.

CHAPTER – 3:

OBJECTIVE AND SCOPE OF WORK

3.0 Objectives of the research and Scope of the Present Research Investigation

3.1 Objectives of the research

Densities of population in last few years have increased in several urban local communities. Therefore, the availability of large vacant land required for construction of conventional WWTPs in urban areas is always a major constraint. Nowadays, constructions of WWTPs need to be planned such that requirements of areas are much less than those required for WWTPs with conventional technologies used in earlier days. This will help in easier and smooth acquisition of land. As per Figure 1 presented in Chapter – 1, the area requirements for wastewater treatment with technologies such as MBBR and SBR are lower compared to that for ASP. Further, the use of MBR technology eliminates the need for secondary clarifiers, significantly reducing the requirement of area for construction of WWTPs. Use of treatment technologies like MBBR, SBR, and MBR for construction of WWTPs also ensure optimized operation as well as maintenance (O&M) costs, and improve the quality of treated wastewater.

Many urban local bodies in India and abroad have already shifted from conventional to space saving treatment technologies like MBBR, SBR, and MBR to reduce the requirement of land for construction of WWTPs, optimize O&M costs and improve the quality of treated wastewater. Therefore, the selection of most cost-effective technology among MBR, MBBR & SBR for a particular wastewater flow rate is a techno-economic concern and a challenging task.

Based on above, the primary objective of this research has been set to ***formulate cost functions and generate cost response maps to assess the economic aspects of contemporary space-saving wastewater treatment technologies (MBR, MBBR, and SBR).***

3.2 Scope of the Present Research Investigation

The scope of the current research is delineated as follows:

- Process design, including calculations for civil, mechanical, and electrical equipment and accessories, for the primary flow-sheet configurations of WWTPs using membrane bio-reactor (MBR), moving bed bio-reactor (MBBR), and sequential bio-reactor (SBR) technologies, focusing on BOD removal across a wide capacity range, assuming an inlet BOD load of 250 mg/l (adopted as standard practice for municipal waste treatment).

- Development of mathematical models to estimate land, capital, and O&M costs for WWTPs utilizing MBR, MBBR, and SBR technologies.
- Development of cost functions to predict the total cost (comprising CAPEX and OPEX) of WWTPs employing MBR, MBBR, and SBR technologies for BOD removal across a broad range of inlet capacities, assuming an inlet BOD load of 250 mg/l, using data sets generated from the models developed earlier.
- Validation of the aforementioned cost functions through Mean Absolute Percentage Error (MAPE) calculations and 95 % Confidence Interval.
- Development of cost response functions to predict the total cost (including CAPEX and OPEX) of WWTPs utilizing MBR, MBBR, and SBR technologies for BOD removal at varying inlet capacities and fluctuating BOD loads across a wide range, using datasets generated from the models developed previously.
- Validation of the above cost functions using MAPE calculations and 95 % Confidence Interval.
- Development of three-dimensional cost response maps to predict the total cost of WWTPs employing MBR, MBBR, and SBR technologies for BOD removal across a wide range of inlet capacities and varying BOD loads, using datasets generated from the cost response functions developed previously.
- Therefore, this research study aims to develop cost functions that account for varying plant capacities under specific BOD loading conditions, as well as for scenarios involving both variable BOD loading and capacity.

- Sensitivity analysis of the developed cost functions to facilitate rapid cost estimation for WWTPs utilizing MBR, MBBR, and SBR technologies for BOD removal, assuming an inlet BOD load of 250 mg/l.
- Gathering feedback on model-based estimated costs for WWTPs using MBR, MBBR, and SBR technologies from reputable EPC contractors.

Novelty of the Research Study

Given the identified gaps in existing literature, and to establish a systematic approach for rapid cost estimation of WWTPs using space-saving technologies such as MBR, MBBR, and SBR, this novel research initiative aims to develop a streamlined tool for basic engineering and cost assessment. This will be achieved through the creation of cost functions and response maps that provide detailed cost estimates without relying on historical cost data. The developed cost functions will be anchored to specific base year and location unit costs (specifically, the year 2021 in India for this study). Sensitivity analysis of these cost functions will also be conducted, considering that unit costs for various components used in the cost functions can fluctuate over time and across different geographical locations.

The developed cost functions are considered highly relevant, logical, and practical for application across various locations within any country. They are particularly valuable for decision-making processes involving vendors and plant owners when awarding contracts. Emphasis has been placed on space-saving technologies to address typical spatial limitations in urban areas.

In this research study, a series of cost functions has been developed using regression techniques to estimate capital costs, energy requirements, and operational and maintenance costs over a 25-year period for BOD removal across a wide capacity range, assuming an inlet BOD load of 250 g/m^3. These derived cost functions will be invaluable for conducting comparative assessments of available technologies for the construction of new WWTPs moving forward.

A comparable approach has been applied, taking into account variable BOD levels ranging from 100 g/m^3 to 250 g/m^3, which are commonly observed in many locations. Using regression techniques, a set of 3-D cost response maps has also been developed for estimating capital costs, energy requirements, and operational and maintenance costs over 25 years. These 3-D cost response maps are expected to provide significant value in evaluating the effectiveness of MBR, MBBR, and SBR technologies for the construction of new WWTPs where wastewater inlet BOD levels range from 100 g/m^3 to 250 g/m^3.

Additionally, sensitivity analyses were conducted on the cost functions developed for each of MBR, MBBR, and SBR technologies. Based on these analyses, the cost functions have been restructured to reflect capacity variations and specific unit costs for each item. These item-specific cost functions are expected to be practical and applicable globally, regardless of location and time.

The methods and procedures outlined above represent the novel contributions of this research study.

Limitations of the Research Study

This research study is focused as follows for rapid estimation of WWTP costs using MBR, MBBR, and SBR technologies for BOD removal:

- Development of cost functions.
- Development of 3-D cost response maps.
- Development of unit cost co-efficient functions through sensitivity study.

The above functions and maps are based on rational engineering approach and methods. As such, no major engineering limitation is attached for the use of developed cost functions, cost response maps and unit cost co-efficient functions. Positive feedbacks on sample estimated costs for WWTPs with MBR, MBBR, and SBR technologies have also been collected from few Indian contractors.

However, the present research study does not encompass the application of MBR, MBBR, and SBR technologies for nitrification and denitrification.

CHAPTER – 4:

METHODOLOGY

4.0 Methodology

This chapter outlines the rationale behind the WWTP design, cost estimation, development of cost functions, creation of cost response maps, sensitivity analysis of developed cost functions, and their validations.

4.1 Capacity Ranges

The concept of economy of scale applies to WWTPs, where typically the unit cost decreases as the capacity increases. In this study, WWTPs have been categorized into multiple capacity groups: small (0.5 – 5.0 MLD), medium (5.0 – 50.0 MLD), and large (50.0 – 150.0 MLD).

4.2 Design Input Quality of Wastewater

The characteristics of raw wastewater are influenced by the rate of water supply and the pollution load per capita. According to the "Manual on Sewerage and Sewage Treatment Systems," 2013 published by the Central Public Health and Environmental Engineering Organization in collaboration with JICA, the design inlet wastewater concentrations presented in Table 2 have been adopted for the design of municipal WWTPs. These concentrations are based on a water supply rate of 135 liters per capita per day.

Table 2: Conventional Inlet wastewater characteristics

Impurities	**Unit**	**Content**
BOD (biochemical oxygen demand)	g / m^3	250.00
COD (chemical oxygen demand)	g / m^3	425.00
TSS (total suspended solids)	g / m^3	375.00

The first phase of the research involved developing cost functions for BOD removal across a wide capacity range, based on an inlet BOD load of 250 mg/l as specified in Table 2. This inlet BOD load is a standard practice commonly used for municipal waste treatment and is typically referenced in government or public tenders.

However, the cost of a WWTP can vary significantly depending on the BOD content in the wastewater. In practical scenarios, the BOD levels in inlet wastewater can differ from one location to another. In the second phase of the research, cost response functions and cost response maps were developed using six different BOD concentrations (100 mg/l, 130 mg/l, 160 mg/l, 190 mg/l, 220 mg/l, and 250 mg/l), while maintaining a consistent BOD to COD ratio across all cases.

4.3 Design Quality of Treated Wastewater

The criteria set by the Ministry of Environment & Forests (MoEF) of the Government of India (GOI) have been adopted as the standard for treated water quality. These criteria are listed below for quick reference:

Table 3: Design treated wastewater quality

Parameters	Value	Unit
Biological oxygen demand (BOD) - design limit	10.00	g / m^3
Total suspended solids (TSS)	10.00	g / m^3

The requirements for the characteristics of treated wastewater are legally mandated and must be adhered to in all circumstances.

4.4 Design Rationales

The design principles formulated for biological treatment in MBR, MBBR, and SBR-based WWTPs are outlined in Table 3 [252].

Table 4: Design rationales as adopted for biological treatment in WWTPs

Parameters	Value	Unit
Peak factor	2.25	
Lean Factor	0.45	
Thickener overflow return as fraction of plant flow	0.15	
BOD in thickener overflow return	500.00	g / m^3
Centrate from sludge dewatering as fraction of plant flow	0.0060	
BOD in centrate from sludge dewatering return	380.00	g / m^3

Table 4: Design rationales as adopted for biological treatment in WWTPs (continued)

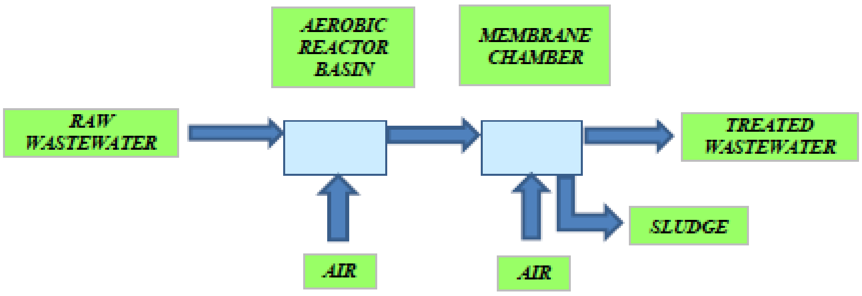
Parameters	**Value**	**Unit**
BOD_u / VSS	1.42	g BOD / g VSS
BOD_5 / BOD_u	0.67	
Kinetic parameters for BOD removal:		
Reference temperature for kinetic parameters	20.00	deg C
Half Velocity Constant	20.00	g bs COD / m^3
Maximum specific bacterial growth rate	6.00	(g VSS / g VSS) / d
Endogenous Decay Co-efficient	0.06	(g VSS / g VSS) / d
True Yield Co-efficient	0.3125	g VSS / g b COD
	0.5000	g VSS / g BOD
Fraction of biomass that remains as cell debris	0.15	
θ values:		
Temperature activity co-efficient for Ks	1.00	
Temperature activity co-efficient for µm	1.07	
Temperature activity co-efficient for kd	1.04	
Other data:		
Design temperature of reactor basin	12.00	^{o}C
Design MLSS for MBR	8000.00	g / m^3
Design MLSS for MBBR	5000.00	g / m^3
Design MLSS for SBR	4000.00	g / m^3
Ratio of VSS to TSS	0.70	
Design MLVSS for MBR	5600.00	g / m^3
Design MLVSS for MBBR	3500.00	g / m^3
Design MLVSS for SBR	2800.00	g / m^3
Percentage clean water oxygen transfer efficiency (for fine bubble ceramic diffusers)	35.00	%
Elevation at site	9.00	m
Atmospheric pressure at elevation of site	95.60	kPa
Effective liquid depth in reactor basin	4.07	m
Point of air release for ceramic diffusers from bottom of reactor basin	0.50	m

Table 4: Design rationales as adopted for biological treatment in WWTPs (continued)

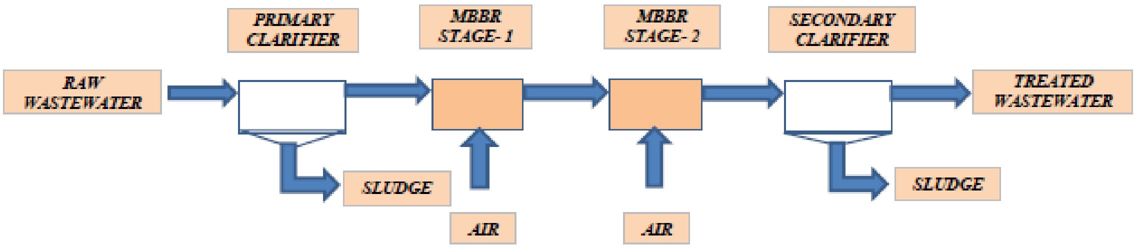
Parameters	**Value**	**Unit**
Standard temperature	20.00	ºC
Concentration of dissolved oxygen at standard temperature & pressure of 101325 N/m^2	9.08	g / m^3
Aeration α factor for BOD removal	0.50	
Salinity & surface tension correction factor for both conditions i. e. BOD removal	0.95	
Diffuser fouling factor	0.90	
Percentage (by weight) of oxygen in air	23.20	%
Density of air	1.20	kg / m^3
Oxygen transfer efficiency	8.00	%
Factor of safety	2.00	
Oxygen consumption	1.42	mg / mg of cell

4.5 Flow diagrams for WWTPs with space saving technologies

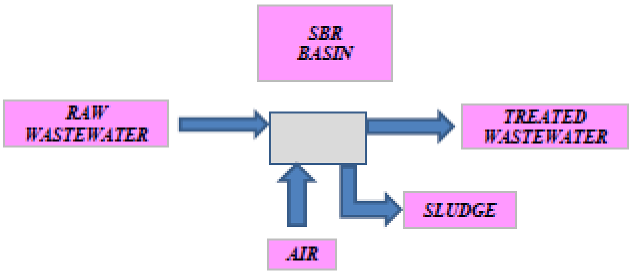
Below are flow diagrams for MBR, MBBR, and SBR-based WWTPs, illustrating the equipment and accessories requirements specific to each technology:



FLOW DIAGRAM FOR WWTP WITH MBR



FLOW DIAGRAM FOR WWTP WITH MBBR



FLOW DIAGRAM FOR WWTP WITH SBR

4.6 Components of WWTPs considered for cost estimation

The initial treatment system for wastewater typically includes a screen chamber and grit chamber upstream of secondary treatment. The systems for sludge collection and treatment remain largely unchanged regardless of the secondary treatment technology employed. The costs associated with these treatment systems for a specific WWTP capacity are generally consistent and not influenced by the choice of secondary treatment technology.

In practice, the selection of a specific secondary treatment technology, along with its required equipment, will primarily determine the capital, operational, and maintenance costs of the WWTP. Therefore, costs other than those related to secondary treatment of wastewater do not need to be considered when comparing and assessing cost efficiency for the construction of new WWTPs. It is economically prudent to base comparisons on alternative technologies solely for secondary treatment.

In this research study, the development of cost functions and subsequent creation of 3-D maps are based on detailed engineering and cost estimates.

The major equipment and accessories as required for MBR based WWTP:

a) Reaction Basins & Accessories
b) Membrane Chambers & Accessories
c) Mixed Liquor Recirculation Pumps and Pump-House
d) Blowers and Blower Building

Primary Clarifiers and Secondary Clarifiers are not required for WWTPs with MBR.

The major equipment and accessories as required for MBBR based WWTP:

a) Primary Clarifiers
b) Primary Clarifier Sludge Sump
c) Primary Clarifier Sludge Transfer Pumps & Pump-House
d) Reaction Basins & Accessories (in two stage)
e) Reactor Basin Waste Transfer Pumps and Pump-House

f) Secondary Clarifiers
g) Secondary Clarifier Sludge Sump
h) Secondary Clarifier Sludge Transfer Pumps & Pump-House
i) Blowers and Blower Building

The major equipment and accessories as required for SBR based WWTP:

a) Reaction Basins along with accessories.
b) Waste Transfer Pumps for Reactor Basin
c) Waste Transfer Pump-House for Reactor Basin
d) Blowers
e) Blower Building

Clarifiers (both primary as well as secondary) are not required for SBR based WWTPs.

4.7 Design, detailing and cost estimation

Three models for design and estimation have been developed using Microsoft Excel spreadsheets: one for MBR-based WWTPs, another for MBBR-based WWTPs, and the third for SBR-based WWTPs. Each model incorporates input parameters such as the quality of wastewater before treatment, desired treated wastewater quality, and other relevant design parameters outlined previously. Standard engineering procedures [260] have been integrated into each model to determine the sizes of various equipment required for biological wastewater treatment.

Algorithms similar to those outlined in CAPDET – USEPA [261] have been employed in each model to select the number of treatment streams for specific capacities and to calculate the bill of quantities for items such as basins with diffused aeration, pumping systems, and blowers. Furthermore, costs for biological treatment in MBR, MBBR, and SBR-based WWTPs across different inlet capacities have been estimated using each respective model. These estimates are based on schedule of rates for scheduled components of civil works [262] and quotations gathered for non-scheduled items such as mechanical and electrical components. Each model includes a contingency to cover additional costs for process control, piping, painting, etc.

Each model is designed to perform the following functions:

a) Process design and sizing of major equipment and accessories based on adopted design criteria.
b) Preparation of a bill of quantities for the construction of individual equipment.
c) Estimation of civil works costs (including earthwork, in-place reinforced concrete walls, in-place reinforced concrete slabs, and in-place handrails) for each major equipment item.
d) Estimation of costs for non-scheduled mechanical and electrical equipment, including applicable accessories, based on vendor quotations.
e) Determination of space requirements for the installation of WWTPs using respective technologies.
f) Calculation of operation and maintenance costs for a period of twenty-five years.
g) Calculation of capital expenditure (CAPEX) and operational expenditure (OPEX) for energy consumption, operation, and maintenance over the 25-year lifespan of the WWTP. The cost of land required for installing the entire system is also integrated into the model.

The developed model necessitates input data including the WWTP's design capacity in million liters per day (mld), concentrations of BOD_5 and SS in raw wastewater, and the design specifications for treated effluent BOD_5 and SS. Its purpose is to forecast the comprehensive cost (including CAPEX, OPEX, and necessary land, with the base year set as 2021) for technology-specific WWTPs designed for biological treatment.

Process design, estimation of bill of quantities for the designed components and respective comprehensive costs for designed components have been estimated by means of the developed models addressed above.

For WWTPs with each of the MBR, MBBR & SBR technologies, design and comprehensive cost estimations have been made at each of the capacities in mld for three groups conforming the standard practices as follows: for small group - 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5 & 5.0; for medium group - 5.0, 10.0, 15.0, 20.0, 25.0, 30.0, 35.0, 40.0, 45.0 & 50.0 and for large group - 50.0, 60.0, 70.0, 80.0, 90.0, 100.0, 110.0, 120.0, 130.0, 140.0 & 150.0.

Regression analysis of data sets [the capacities of WWTPs and integrated overall respective costs for biological treatment in WWTPs] for each group of each of MBR, MBBR & SBR technologies has been made based on five different functions (viz., exponential, linear, logarithmic, polynomial and power) to determine the applicable cost function for each case.

The cost functions have been validated by comparing the predicted values with the respective estimated costs. To assess the accuracy of the predicted costs based on determined cost functions, MAPE (Mean Absolute Percentage Error) and 95 % Confidence Interval have been determined and reviewed.

MAPE is calculated as follows:

$$\mathbf{MAPE = \sum \{(|A-F|/A)*100\}/N}$$

Where A= Estimated cost, F= Forecasted cost by use of cost function as determined, N= Number of elements in the data set.

The value of MAPE corresponds to the accuracy of prediction as follows:

Table5: Interpretation of MAPE

MAPE	Interpretation
< 10	Accurate forecasting result
10 -20	Good forecasting result
20 - 50	Reasonable forecasting result
> 50	Inaccurate forecasting result

Confidence interval is calculated as follows:

$$\text{Confidence interval} = \mathbf{X \pm Z*(s/\sqrt{n})}$$

Where:

- X is the mean
- Z is the chosen Z-value (1.96 for 95%)

- s is the standard error
- n is the sample size

Development of several functions and their validations have been carried out for the categories as follows:

a) Development of cost functions for wastewater treatment plants (WWTPs) with MBR, MBBR, and SBR technologies in three capacity groups, based on an inlet BOD load of 250 g/m^3 which is a standard design base for municipal WWTPs.

b) Developments of distinguished cost functions to generate 3-D cost response maps for estimation of the costs of WWTPs using MBR, MBBR, and SBR technologies at varying capacities and inlet BOD loads.

   Assessment for change in cost of a wastewater treatment plant (WWTP) with variation in inlet BOD levels is important and an economic concern. The developed model has been used for design as well as estimation of the bill of quantities and costs for each of capacities (5 mld for small group, 50 mld for medium group and 150 mld for large group) and inlet BOD (100 mg/l, 130 mg/l, 160 mg/l, 190 mg/l, 220 mg/l, and 250 mg/l for each capacity) for each of the MBR, MBBR & SBR technologies.

   The cost response curves with BOD along abscissa and total costs of WWTPs along ordinate for each of 5 mld, 50 mld and 150 mld capacities have been developed for each of MBR, MBBR & SBR technologies.

   The datasets of costs of each selected capacity with changes in inlet BOD for each of MBR, MBBR & SBR technologies have been used to create cost response surface maps and contour maps in a 3-D environment.

c) Development of co-efficient functions related to unit costs of various items based on sensitivity analysis of cost functions developed for WWTPs with MBR, MBBR, and SBR technologies and based on an inlet BOD load of 250 g/m^3.

   Cost functions developed to predict the overall cost of WWTPs using MBR, MBBR, and SBR technologies for BOD removal at any inlet capacity (within a wide range) are based on unit costs of various items applicable for the year 2021. These unit costs are sensitive to time as well as geographic territories.

To ensure novelty and universal application, the functions which relate capacity to co-efficients of unit costs of various items for the construction of WWTPs using MBR, MBBR, and SBR technologies with an inlet BOD load of 250 mg/l, have been determined by application of developed mathematical models and presented in this thesis.

The co-efficient functions as determined for respective unit costs have been validated with reference to estimated total bare construction cost and estimated levelized cost of 25 years of operation for selected specific capacities with unit cost base in India at year 2021.

CHAPTER – 5:

RESULTS AND DISCUSSIONS

5.0 Results and Discussions

The study involved designing and estimating using a developed model, followed by optimization through regression techniques, with the following objectives:

a) Develop cost functions for wastewater treatment plants (WWTPs) employing MBR, MBBR, and SBR technologies, based on an inlet BOD load of 250 g/m3, a standard practice in municipal sectors.

b) Create 3-D cost response maps to estimate the costs of WWTPs using MBR, MBBR, and SBR technologies at varying capacities and inlet BOD loads. This aimed to analyze cost variations relative to deviations from the standard inlet BOD load.

c) Perform sensitivity analysis on the developed cost functions with reference to unit costs of various items for WWTPs utilizing MBR, MBBR, and SBR technologies, specifically focusing on an inlet BOD load of 250 g/m^3.

The results are discussed sequentially, starting with the findings related to the cost functions, followed by insights from the 3-D cost response maps and sensitivity analysis..

5.1 Development of cost functions for WWTPs with MBR, MBBR and SBR technologies

The process involved designing and estimating bill of quantities for components using a developed model for MBR, MBBR, and SBR technologies in wastewater treatment. Design and estimation were conducted across various capacities in million liters per day (mld) for WWTPs as follows: small group (0.5 to 5.0 mld), medium group (5.0 to 50.0 mld), and large group (50.0 to 150.0 mld).

Appendices I to III summarize the data for small, medium, and large group WWTPs with MBR. Appendices IV to VI provide data summaries for WWTPs with MBBR, and Appendices VII to IX for WWTPs with SBR.

Regression analysis was performed on the datasets (WWTP capacities and corresponding costs for biological treatment) using five functions: exponential, linear, logarithmic, polynomial, and power. Polynomial, logarithmic, power and exponential regression analyses did not result in a significant increase in the R^2 value and introduced greater complexity to the models. Therefore, only linear regression results and the respective equations as cost functions are reported throughout the thesis. Cost curves were then plotted with WWTP capacities (mld) on the X-axis and biological treatment costs (in crore ₹) on the Y-axis for MBR, MBBR, and SBR technologies. Figure 7 illustrates the total cost (in crores) of MBBR, MBR, and SBR technologies plotted against flow (in MLD) for small-scale WWTPs (ranging from 0.5 to 5 MLD).

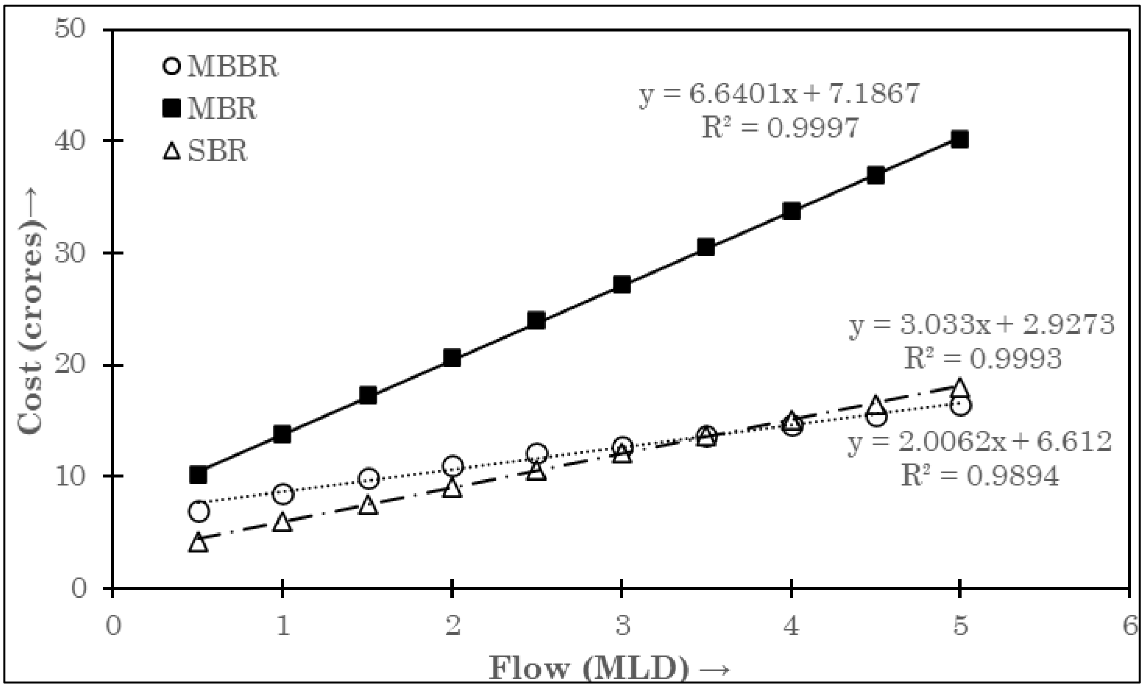


Figure 7: Cost Curve for Small Range WWTPs with MBR, MBBR, SBR

In Figure 7, it can be observed that as the flow increases, the total cost also increases, which aligns with expectations. It is evident that in this flow range, the total cost is generally higher for MBR technology. For MBBR and SBR technologies, the costs are approximately similar. Up to a design flow of 3.5 MLD, the cost of MBBR technology is slightly higher compared to SBR technology; however, beyond this point, the cost of SBR technology becomes significantly higher. The cost data were plotted using linear regression. For MBR and SBR technologies, the coefficient of determination (R^2) values exceeds 0.999, while for MBBR, the R^2 value is over 0.98 (refer to Appendices I, IV & VII). These high R^2 values indicate a close fit of the data to the regression line. Therefore, this curve can be utilized to predict the total cost of WWTPs across a flow range from 0.5 MLD to 5 MLD, eliminating the need for detailed cost estimation.

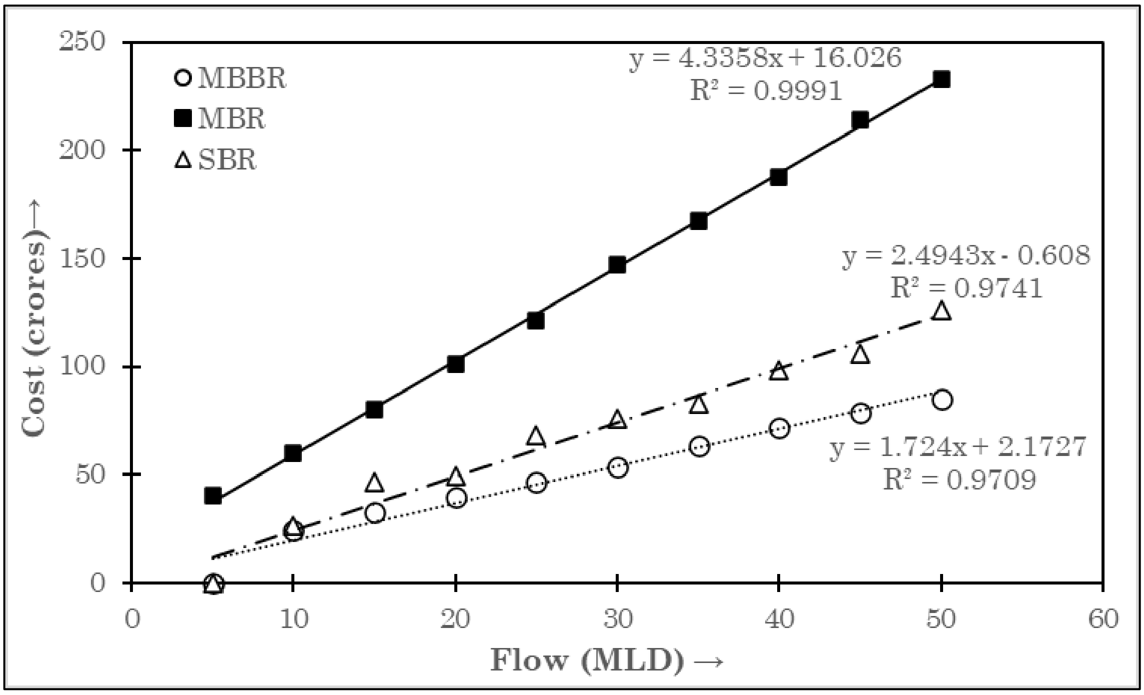


Figure 8: Cost Curve for Medium Range WWTPs with MBR, MBBR, SBR

Figure 8 reveals that in this flow range, the total cost tends to be higher for MBR technology compared to SBR and then MBBR technologies. The slope of the MBR regression line is steeper than that of SBR and MBBR, indicating a greater increase in total cost per MLD flow for MBR, followed by SBR, and then MBBR. The cost data were analyzed using linear regression. The R^2 value for MBR technology exceeds 0.999, while for MBBR and SBR technologies, it is above 0.97 (refer to Appendices II, V & VIII). These high R^2 values demonstrate a strong fit of the data to the regression lines. Thus, this curve can be effectively used to predict the total cost of WWTPs across a flow range from 5 MLD to 50 MLD, offering a reliable alternative to detailed cost estimation.

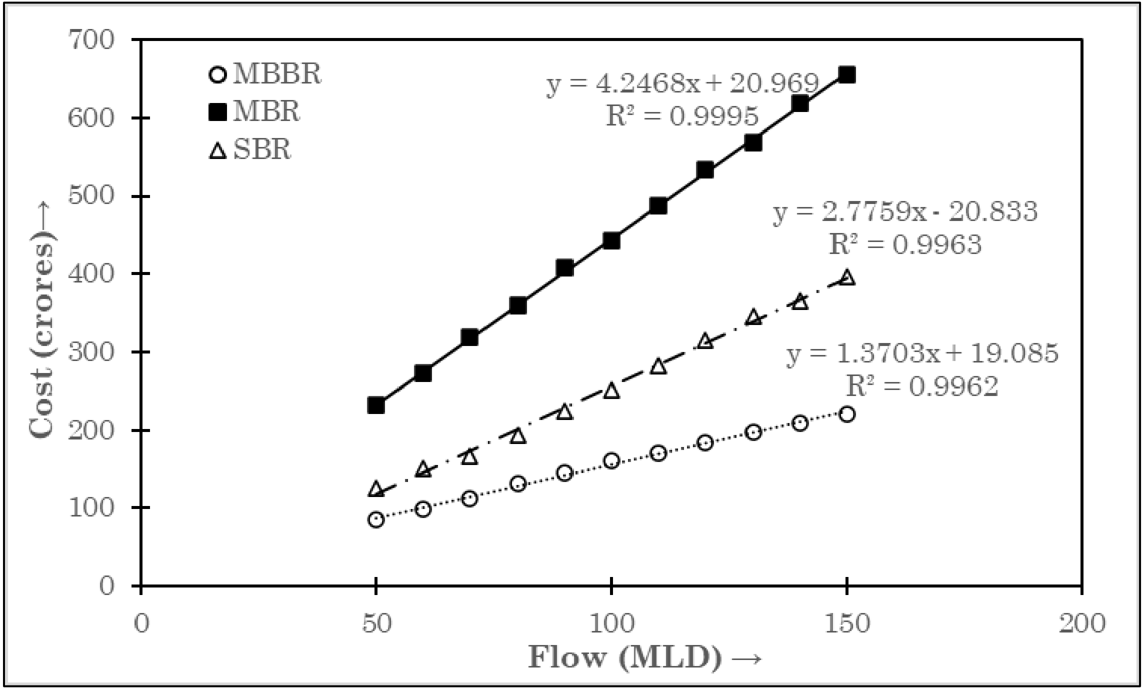


Figure 9: Cost Curve for Large Range WWTPs with MBR, MBBR, SBR

Figure 9 shows that within this flow range, the total cost tends to be higher for MBR technology compared to SBR and then MBBR technologies. The MBR regression line has a steeper slope than those of SBR and MBBR, indicating a more significant increase in total cost per MLD flow for MBR, followed by SBR, and then MBBR. The cost data were analyzed using linear regression, with all technologies achieving an R^2 value exceeding 0.99 (refer to Appendices III, VI & IX). These high R^2 values indicate a robust fit of the data to the regression lines. Therefore, this curve can reliably predict the total cost of WWTPs across a flow range from 50 MLD to 150 MLD, providing a dependable alternative to detailed cost estimation.

For all the aforementioned technologies, polynomial, logarithmic, power, and exponential regression analyses were also conducted. However, these methods did not result in a significant increase in the R^2 value and introduced greater complexity to the models. Therefore, only linear regression results were reported and plotted throughout the thesis. The cost functions were validated by comparing the predicted values with the respective estimated costs. To assess the accuracy of the predicted costs, MAPE (Mean Absolute Percentage Error) was calculated.

Further 95 % confidence interval for the MAPE has also been calculated for each case.

A summary of cost functions derived, respective values of R^2, MAPE and 95 % confidence intervals for the MAPE are presented hereinafter. The symbols as follows are used to express the cost functions.

C_{SR} - Cost [₹ (in crore)] of a WWTP within small range
Q_{SR} - Input flow rate [in MLD] for a WWTP within small range
C_{MR} - Cost [₹ (in crore)] of a WWTP within medium range
Q_{MR} - Input flow rate [in MLD] for a WWTP within medium range
C_{LR} - Cost [₹ (in crore)] of a WWTP within large range
Q_{LR} - Input flow rate [in MLD] for a WWTP within large range

The cost functions for capacity wise three different groups of WWTPs with MBR are furnished in Table 6 (refer to Appendices I, II & III).

Table 6: Cost Functions for Different Groups of WWTPs with MBR

Description	***Equation***	***Value of R^2***	***Value of MAPE***	***95 % Confidence Interval***
Cost function for small range WWTPs with MBR (0.5 mld – 5 mld)	$C_{SR} = 6.6401*Q_{SR} + 7.1867$	0.9997	0.73	0.16 – 1.29
Cost function for medium range WWTPs with MBR (5 mld – 50 mld)	$C_{MR} = 4.3358*Q_{MR} + 16.026$	0.9991	1.57	0.50 – 2.64
Cost function for large range WWTPs with MBR (50 mld – 150 mld)	$C_{LR} = 4.2468*Q_{LR} + 20.969$	0.9995	0.58	0.37 – 0.79

As presented above, the cost functions for three different capacity groups of WWTPs with MBR are expressed by linear equations. The determination coefficients for the small, medium, and large capacity groups are 0.9997, 0.9991, and 0.9995, respectively. The MAPE values for the small, medium, and large capacity groups are 0.73%, 1.57%, and 0.58%, respectively. In no case did the MAPE value and respective upper limit of 95 % confidence interval exceed 10 %. Thus, it can be concluded that the selection of linear functions is appropriate and applicable for accurate predictions.

The Cost functions derived for different groups of WWTPs with MBBR are furnished in Table 7 (refer to Appendices IV, V & VI).

Table 7: Cost Functions for Different Groups of WWTPs with MBBR

Description	***Equation***	***Value of*** R^2	***Value of MAPE***	***95 % Confidence Interval***
Cost function for small range WWTPs with MBBR (0.5 mld – 5 mld)	$C_{SR} = 2.0062*Q_{SR} + 6.612$	0.9894	2.24	0.60 – 3.87
Cost function for medium range WWTPs with MBBR (5 mld – 50 mld)	$C_{MR} = 1.7240*Q_{MR} + 2.1727$	0.9709	8.70	1.87 – 15.53
Cost function for large range WWTPs with MBBR (50 mld – 150 mld)	$C_{LR} = 1.3703*Q_{LR}+19.085$	0.9962	1.65	1.02 – 2.28

As presented above, the cost functions for three different capacity groups of WWTPs with MBBR are expressed by linear equations. The determination coefficients for the small, medium, and large capacity groups are 0.9894, 0.9709, and 0.9962, respectively. The MAPE values for the small, medium, and large capacity groups are 2.24%, 8.7%, and 1.65%, respectively. In no case did the MAPE value and respective upper limit of 95 % confidence interval exceed 10% except the upper limit of 95 % confidence interval for medium range which is slightly higher. Thus, it can be concluded that the selection of linear functions is appropriate and applicable for more or less accurate predictions.

The Cost functions derived for different groups of WWTPs with SBR are furnished in Table 8 (refer to Appendices VII, VIII & IX).

Table 8: Cost Functions for Different Groups of WWTPs with SBR

Description	*Equation*	*Value of R^2*	*Value of MAPE*	*95 % Confidence Interval*
Cost function for small range WWTPs with SBR (0.5 mld to 5 mld)	$CF_{SR} = 3.0330*Q_{SR} + 2.9273$	0.9993	1.19	0.22 – 2.15
Cost function for medium range WWTPs with SBR (5 mld to 50 mld)	$CF_{MR} = 2.4943*Q_{MR}–0.6080$	0.9741	8.75	2.10 – 15.39
Cost function for large range WWTPs with SBR (50 mld to 150 mld)	$CF_{LR} = 2.7759*Q_{LR} - 20.8330$	0.9963	2.45	1.35 – 3.55

The cost functions for three different capacity groups of WWTPs with SBR are expressed by linear equations, as outlined above. The determination coefficients for the small, medium, and large capacity groups are 0.9993, 0.9741, and 0.9963, respectively. The MAPE values for the small, medium, and large capacity groups are 1.19%, 8.75%, and 2.45%, respectively. In no case did the MAPE value and respective upper limit of 95 % confidence interval exceed 10% except the upper limit of 95 % confidence interval for medium range which is slightly higher. Thus, it can be concluded that selecting linear functions is appropriate and applicable for more or less accurate predictions.

5.2 Development of 3-D cost response maps for WWTPs with MBR, MBBR and SBR technologies

The cost implications for a specific design capacity of a wastewater treatment plant (WWTP) with varying inlet BOD levels are crucial. This section of the research outlines the methodology used to map the cost response of biological treatment using MBR, MBBR, and SBR technologies in a 3-D environment, considering variations in inlet flow rate and inlet BOD. The developed mathematical model has been utilized for comprehensive design and estimation of the bill of quantities and costs, considering capacity and inlet BOD as follows:

Capacity:

The capacities for WWTPs as taken into consideration for this part of the study are as follows:

a) A capacity in low range as 5 mld

b) A capacity in medium range as 50 mld

c) A capacity in large range as 150 mld

Characteristics of raw wastewater:

For this part of the research study, six different BOD contents (100 mg/l, 130 mg/l, 160 mg/l, 190 mg/l, 220 mg/l, and 250 mg/l) were selected for each capacity. However, the BOD to COD ratio was kept constant in all cases. The construction cost, operation and maintenance cost over 25 years, and cost of land, as estimated using the developed model for different capacities and inlet BODs, have been analyzed using the trend line technique. Polynomial, logarithmic, power and exponential regression analyses did not result in a significant increase in the R^2 value compared to those for linear regression. Suitable cost response curves were selected from several available alternatives based on the linear function for ease of application.

This linearity corresponds to value of co-efficient of determination (R^2) for which prediction works out as accurate with MAPE much less than 10 %.

Appendix –X to XII: Summary of data obtained for 5 mld, 50 mld and 150 mld capacity of WWTP with MBR, Appendix –XIII to XV: Summary of data obtained for 5 mld, 50 mld and 150 mld capacity of WWTP with MBBR and Appendix - XVI to XVIII: Summary of data obtained for 5 mld, 50 mld and 150 mld capacity of WWTP with SBR are attached herewith for ready reference.

The cost response curves (which corresponds to value for co-efficient of determination in case of linear function) with BOD [as mg/l] along abscissa and total costs of WWTPs [as ₹ (crore)] along ordinate for each of 5 mld, 50 mld and 150 mld capacities have been constructed for MBR, MBBR & SBR technologies and are shown in Figures 10 through 12.

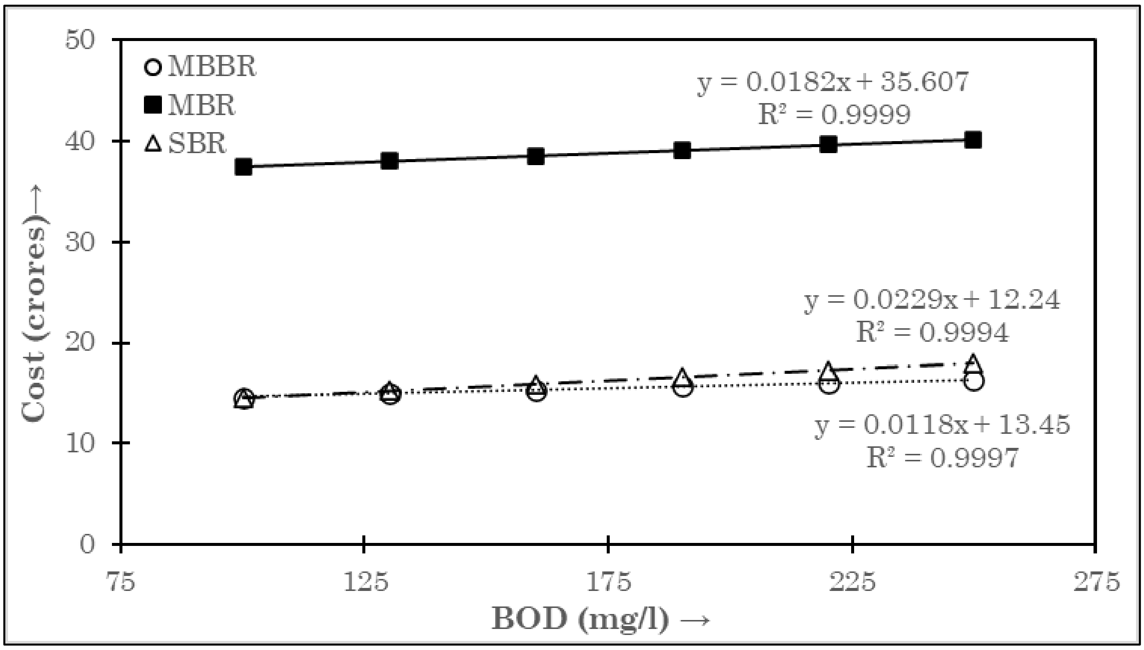


Figure 10: Cost Response Curve for variation in BOD 5 mld WWTP with MBR, MBBR and SBR technologies

In Figure 10, it is evident that as the influent BOD increases, the total cost also rises, which aligns with expectations. Specifically, for a 5 MLD flow rate, the total cost tends to be higher for MBR technology compared to MBBR and SBR technologies, which show similar costs. As the influent BOD concentration increases, the cost of SBR technology slightly surpasses that of MBBR technology. The cost data were plotted using linear regression, and all three curves exhibit minimal slopes, indicating stable total costs across this influent BOD concentration range. The high R^2 values (> 0.999), MAPE (< 0.20) and upper limit of 95 % confidence interval (< 0.25) for all technologies indicate a strong fit of the data to the regression lines (refer to Appendices X, XIII & XVI). Therefore, this curve can be used to predict the total cost of WWTPs across an influent BOD concentration range from 100 mg/l to 250 mg/l for a flow rate of 5 MLD, thereby eliminating the need for detailed cost estimation.

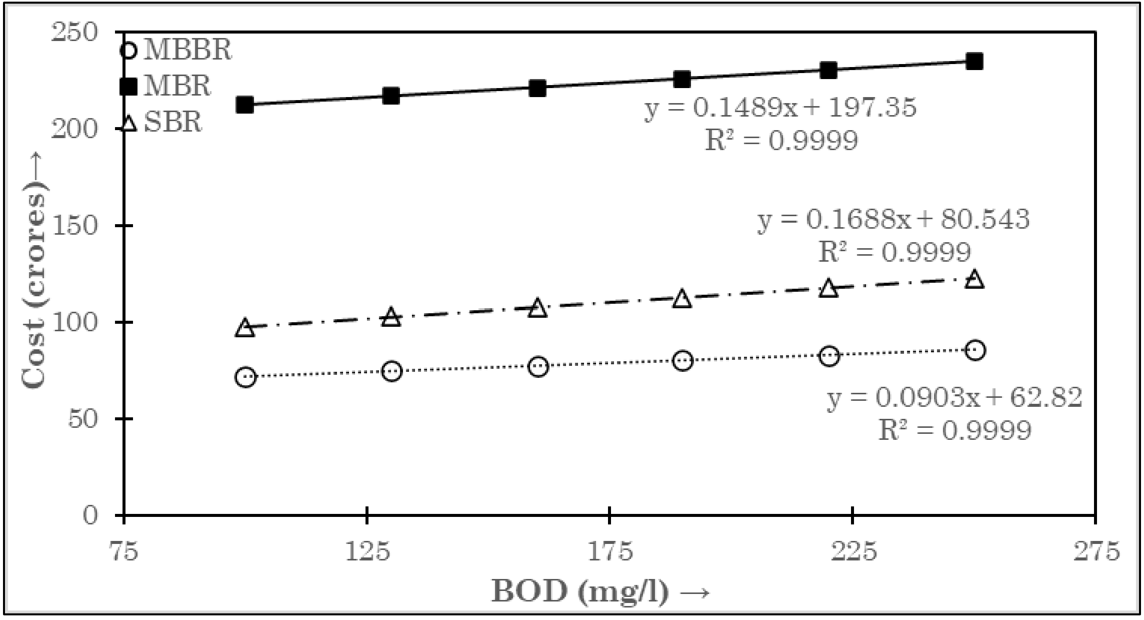


Figure 11: Cost Response Curve for variation in BOD 50 mld WWTP with MBR, MBBR and SBR technologies

Similar observations can also be drawn from Figure 11. Figure 11 shows that within this influent BOD concentration range for a flow rate of 50 MLD, the total cost tends to be higher for MBR technology compared to SBR and then MBBR technologies. The cost data were analyzed using linear regression, and all three curves display minimal slopes, indicating consistent total costs across this influent BOD concentration range. The high R^2 values (> 0.999), MAPE (< 0.10) and upper limit of 95 % confidence interval (< 0.15) for all technologies indicate a robust fit of the data to the regression lines (refer to Appendices XI, XIV & XVII). Therefore, this curve can be utilized to predict the total cost of WWTPs across an influent BOD concentration range from 100 mg/l to 250 mg/l for a flow rate of 50 MLD, thereby eliminating the need for detailed cost estimation.

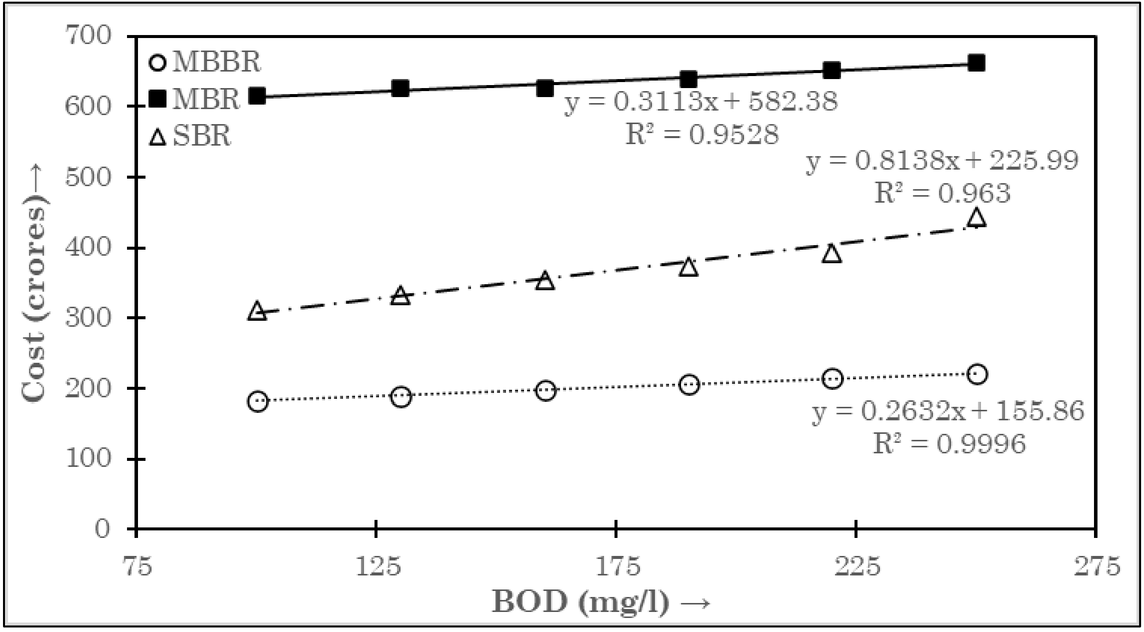


Figure 12: Cost Response Curve for variation in BOD 150 mld WWTP with MBR, MBBR and SBR technologies

Similarly, from Figure 11, it can be observed that within this influent BOD concentration range for a flow rate of 150 MLD, the total cost tends to be higher for MBR technology compared to SBR and then MBBR technologies. The cost data were analyzed using linear regression, and the MBR and MBBR curves display minimal slopes, indicating consistent total costs across this influent BOD concentration range. However, for SBR, the slope is very high, indicating a sharp increase in total cost with influent BOD concentration, even for a constant flow of 150 MLD. The high R^2 values (> 0.999), MAPE (< 1.75) and upper limit of 95 % confidence interval (< 2.70) for all technologies indicate a robust fit of the data to the regression lines (refer to Appendices XII, XV & XVIII).

Therefore, this analysis allows the prediction of total WWTP costs across an influent BOD concentration range from 100 mg/l to 250 mg/l for a flow rate of 150 MLD, eliminating the need for detailed cost estimation. Additionally, these findings underscore the significant impact of influent BOD concentration on total costs for SBR technology at high flow rates, whereas other flow ranges and influent BOD concentrations exhibit stable cost trends.

The validation of cost response functions has been conducted through the estimation of MAPE and 95 % confidence interval. Below is a summary of the derived cost response functions along with their respective values of R^2, MAPE and 95 % confidence interval. The following symbols are used to express the cost response functions:

$C_{R\text{-}5\ mld}$ - Cost [₹ (in crore)] of 5 mld WWTP with MBR

$C_{R\text{-}50\ mld}$ - Cost [₹ (in crore)] of 50 mld WWTP with MBR

$C_{R\text{-}150\ mld}$ - Cost [₹ (in crore)] of 150 mld WWTP with MBR

R^2 - Co-efficient of determination

x - BOD [in mg/l] in raw wastewater

Table 9 presents the identified most suitable cost response functions for WWTP with MBR (refer to Appendices X, XI & XII).

Table 9: Cost Response Functions for WWTP with MBR

Capacity of WWTP with MBR	**Cost Response function**	***Value of R^2***	***Value of MAPE***	***95 % confidence interval***
5 mld	$C_{R\text{-}5\ mld} = 0.0182*x + 35.607$	0.9999	0.03	0.01 – 0.05
50 mld	$C_{R\text{-}50\ mld} =0.1489*x + 197.35$	0.9999	0.03	0.01 – 0.04
150 mld	$C_{R\text{-}150\ mld} =0.3113*x + 582.38$	0.9528	0.47	0.19 – 0.74

The cost versus BOD plots for 5 MLD, 50 MLD, and 150 MLD WWTPs with MBR indicate a linear relationship. Therefore, a linear function has been chosen as the appropriate cost response model for these capacities.

The corresponding R^2 values are 0.9999, 0.9999, and 0.9528 for 5 MLD, 50 MLD, and 150 MLD WWTPs with MBR. The MAPEs for the cost response functions are 0.03%, 0.03%, and 0.47% respectively for 5 MLD, 50 MLD, and 150 MLD. In each case, the MAPE falls within the accurate range (< 10%). 95 % confidence intervals for 5 MLD, 50 MLD, and 150 MLD WWTPs with MBR as worked out are (0.01 – 0.05), (0.01 – 0.04) and (0.19 – 0.74).

Table 10 presents the datasets showing the variation of costs with changes in inlet BOD for 5 MLD, 50 MLD, and 150 MLD WWTPs with MBR.

Table 10: Data Sets for Variation of Costs with Change in inlet BOD for WWTP with MBR

Predicted costs for WWTPs with MBR

BOD REMOVAL							
Capacity in mld	Description	BOD in mg/l	BOD in mg/l	BOD in mg/l	BOD in mg/l	BOD in mg/l	BOD in mg/l
		100.00	130.00	160.00	190.00	220.00	250.00
5	Predicted cost value in Crore ₹ (as per linear cost function)	37.43	37.97	38.52	39.07	39.61	40.16
50	Predicted cost value in Crore ₹ (as per linear cost function)	212.24	216.71	221.17	225.64	230.11	234.58
150	Predicted cost value in Crore ₹ (as per linear cost function)	613.51	622.85	632.19	641.53	650.87	660.21

The datasets mentioned above are utilized in a 3-D environment to create cost response surface maps and contour maps, depicted in Figure 13 and Figure 14.

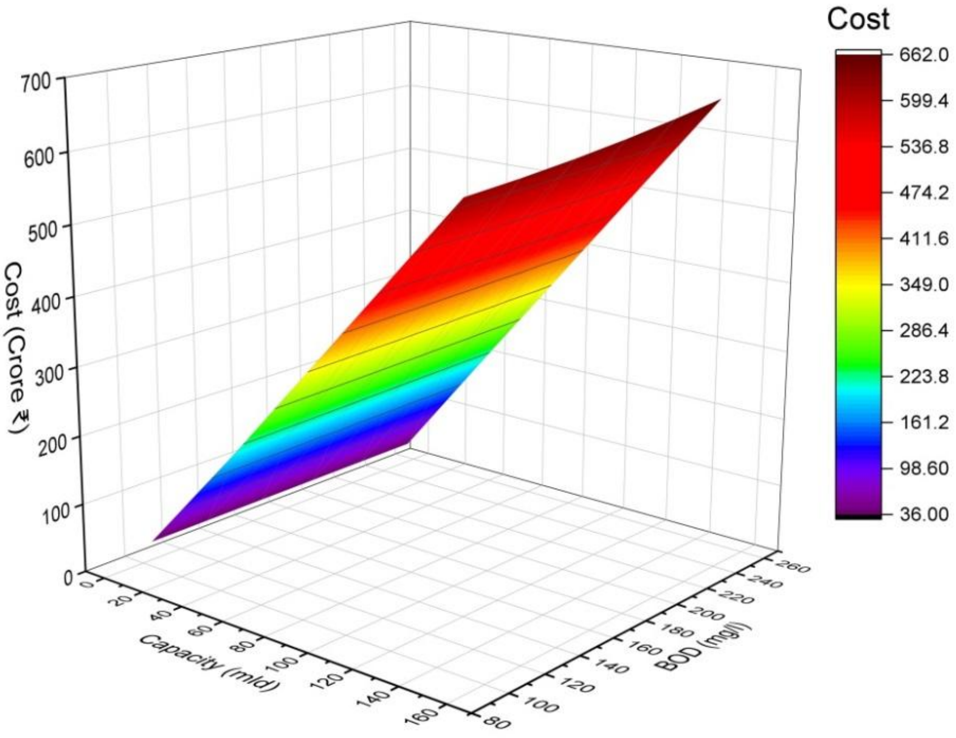


Figure 13: 3-D cost response surface map for WWTP with MBR technology

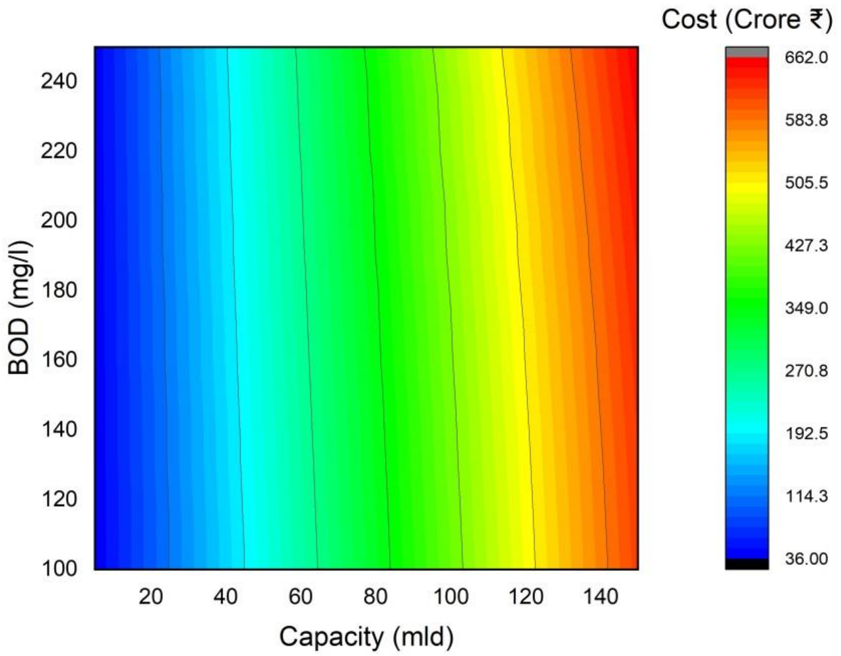


Figure 14: 3-D contour map for WWTP with MBR technology

These maps can be used to quickly predict costs for WWTPs with MBR across a capacity range of 5 to 150 MLD and an inlet BOD range of 100 mg/l to 250 mg/l. From Figure 13 and Figure 14, it is apparent that the cost calculations for MBR technology primarily vary with flow rate. Influent BOD concentration does not significantly impact the overall cost in

MBR technology up to a flow range of 80 MLD. However, when the flow rate exceeds 80 MLD, influent BOD concentration also plays a significant role in determining the total cost.

Table 11 presents the identified most suitable cost response functions for WWTP with MBBR (refer to Appendices XIII, XVI & XV).

Table 11: Cost Response Functions for WWTP with MBBR

Capacity of WWTP with MBBR	**Response function**	***Value of R^2***	***Value of MAPE***	***95 % confidence interval***
5 mld	$C_{R\text{-}5\ mld} = 0.0118*x + 13.45$	0.9997	0.06	0.02 – 0.09
50 mld	$C_{R\text{-}50\ mld} = 0.0903*x + 62.82$	0.9999	0.05	0.01 – 0.10
150 mld	$C_{R\text{-}150\ mld} = 0.2632*x + 155.86$	0.9996	0.11	0.06 – 0.17

Where,

$C_{R\text{-}5\ mld}$ - Cost [₹ (in crore)] of 5 mld WWTP with MBBR

$C_{R\text{-}50\ mld}$ - Cost [₹ (in crore)] of 50 mld WWTP with MBBR

$C_{R\text{-}150\ mld}$ - Cost [₹ (in crore)] of 150 mld WWTP with MBBR

x - BOD [in mg/l] in raw wastewater

For 5 MLD, 50 MLD, and 150 MLD WWTPs with MBBR, the linear function has been chosen as the respective cost response model. The corresponding R^2 values are 0.9997, 0.9999, and 0.9996 for 5 MLD, 50 MLD, and 150 MLD WWTPs with MBBR. The MAPEs for the cost response functions are 0.06%, 0.05%, and 0.11% respectively for 5 MLD, 50 MLD, and 150 MLD. In each case, the MAPE falls within the range of accurate forecasting (< 10%). 95 % confidence intervals for 5 MLD, 50 MLD, and 150 MLD WWTPs with MBBR as worked out are (0.02 – 0.09), (0.01 – 0.10) and (0.06 – 0.17). Table 12 presents the datasets illustrating the variation of costs with changes in BOD in raw wastewater for 5 MLD, 50 MLD, and 150 MLD as predicted from the most appropriate cost response functions.

Table 12: Data Sets for Variation of Costs with Change in inlet BOD for WWTP with MBBR

Predicted costs for WWTPs with MBBR							
BOD REMOVAL							
Capacity in mld	Description	BOD in mg/l	BOD in mg/l	BOD in mg/l	BOD in mg/l	BOD in mg/l	BOD in mg/l
		100.00	130.00	160.00	190.00	220.00	250.00
5	Predicted cost value in Crore ₹ (as per linear cost function)	14.63	14.98	15.34	15.69	16.05	16.40
50	Predicted cost value in Crore ₹ (as per linear cost function)	71.85	74.56	77.27	79.98	82.69	85.40
150	Predicted cost value in Crore ₹ (as per linear cost function)	182.18	190.08	197.97	205.87	213.76	221.66

The datasets mentioned above are employed in a 3-D environment to generate cost response surface maps and contour maps, illustrated in Figure 15 and Figure 16.

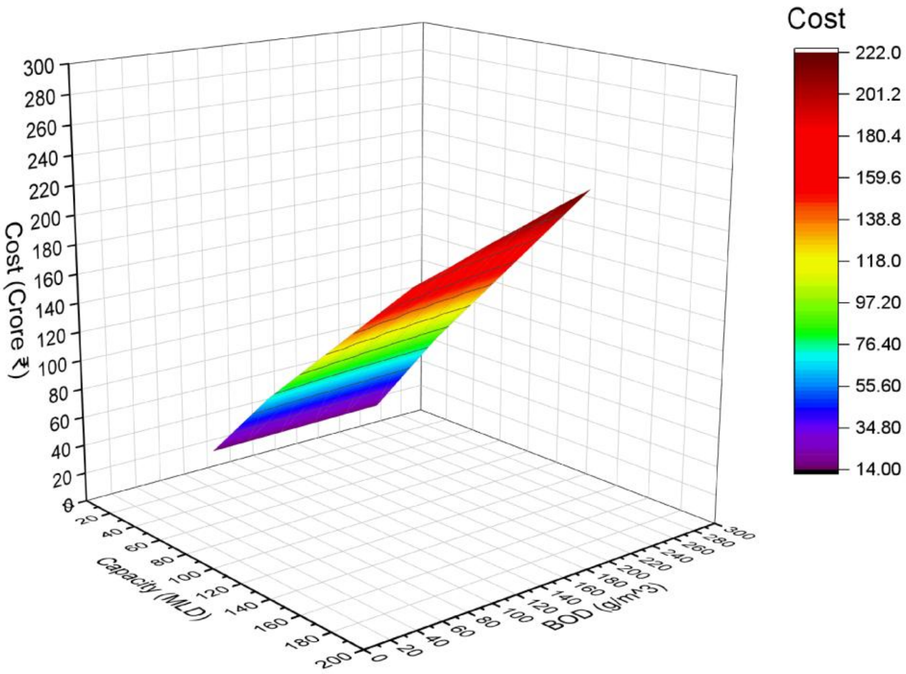


Figure 15: 3-D cost response surface map for WWTP with MBBR technology

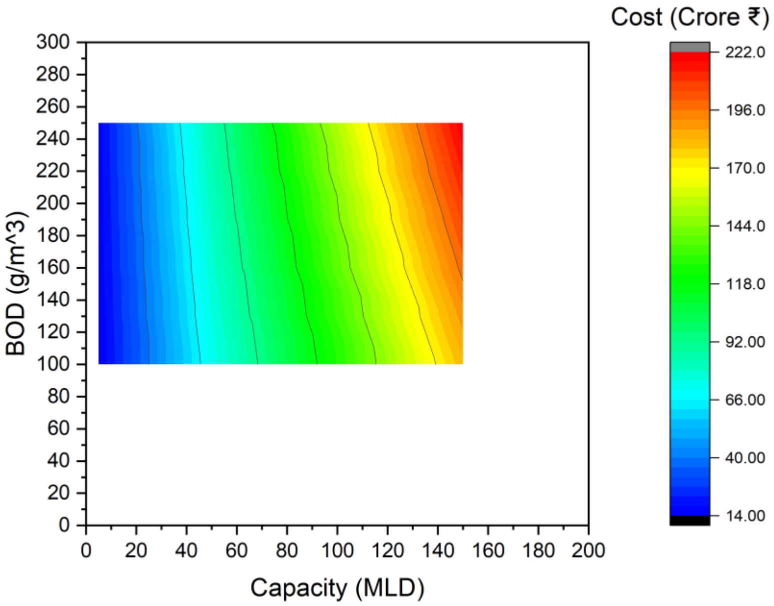


Figure 16: 3-D contour map for WWTP with MBBR technology

These maps facilitate rapid cost predictions for WWTPs using MBBR across a capacity range of 5 to 150 MLD and an inlet BOD range of 100 mg/l to 250 mg/l. From Figure 15 and Figure 16, it is evident that the cost calculations for MBBR technology primarily vary with flow rate. Influent BOD concentration does not significantly impact the overall cost up to a flow range of 50 MLD. However, when the flow rate exceeds 50 MLD, influent BOD concentration also plays a significant role in determining the total cost.

Table 13 presents the identified most suitable cost response functions for WWTP with SBR (refer to Appendices XVI, XVII & XVIII).

Table 13: Cost Response Functions for WWTP with SBR

Capacity of WWTP with SBR	Response function	Value of R^2	Value of MAPE	95 % confidence interval
5 mld	$C_{R\text{-}5\ mld} = 0.0229*x + 12.24$	0.9994	0.17	0.11 – 0.23
50 mld	$C_{R\text{-}50\ mld} = 0.1688*x + 80.543$	0.9999	0.08	0.05 – 0.12
150 mld	$C_{R\text{-}150\ mld} = 0.8138*x + 225.99$	0.9630	1.74	0.82 – 2.65

Where,

$C_{R\text{-}5\ mld}$ - Cost [₹ (in crore)] of 5 mld WWTP with SBR

$C_{R\text{-}50\ mld}$ - Cost [₹ (in crore)] of 50 mld WWTP with SBR

$C_{R\text{-}150\ mld}$ - Cost [₹ (in crore)] of 150 mld WWTP with SBR

R^2 - Co-efficient of determination

x - BOD [in mg/l] in raw wastewater

For 5 MLD, 50 MLD, and 150 MLD WWTPs with SBR, the linear function has been chosen as the respective cost response model.

The corresponding R^2 values are 0.9994, 0.9999, and 0.9630 for 5 MLD, 50 MLD, and 150 MLD WWTPs with SBR. The MAPEs for the cost response functions are 0.17%, 0.08%, and 1.74% respectively for 5 MLD, 50 MLD, and 150 MLD. In each case, the MAPE falls within the range of accurate forecasting (< 10%). 95 % confidence intervals for 5 MLD, 50 MLD, and 150 MLD WWTPs with SBR as worked out are (0.11 – 0.23), (0.05 – 0.12) and (0.82 – 2.65). Table 14 presents the datasets illustrating the variation of costs with changes in inlet BOD for 5 MLD, 50 MLD, and 150 MLD WWTPs with SBR.

Table 14: Data Sets for Variation of Costs with Change in inlet BOD for WWTP with SBR

Predicted costs for WWTPs with SBR							
BOD REMOVAL							
Capacity in mld	Description	BOD in mg/l	BOD in mg/l	BOD in mg/l	BOD in mg/l	BOD in mg/l	BOD in mg/l
		100.00	130.00	160.00	190.00	220.00	250.00
5	Predicted cost value in Crore ₹ (as per linear cost function)	14.53	15.22	15.90	16.59	17.28	17.97
50	Predicted cost value in Crore ₹ (as per linear cost function)	97.42	102.49	107.55	112.62	117.68	122.74
150	Predicted cost value in Crore ₹ (as per linear cost function)	307.37	331.78	356.20	380.61	405.03	429.44

The datasets depicting the variation of costs with changes in BOD in raw wastewater for 5 MLD, 50 MLD, and 150 MLD, as predicted from appropriate cost response functions, are modelled in a 3-D environment to create a surface map and contour map, shown in Figure 17 and Figure 18. Either of these maps can be used to estimate forecasted costs for WWTPs with SBR across a capacity range of 5 to 150 MLD, with inlet BOD content ranging from 100 mg/l to 250 mg/l.

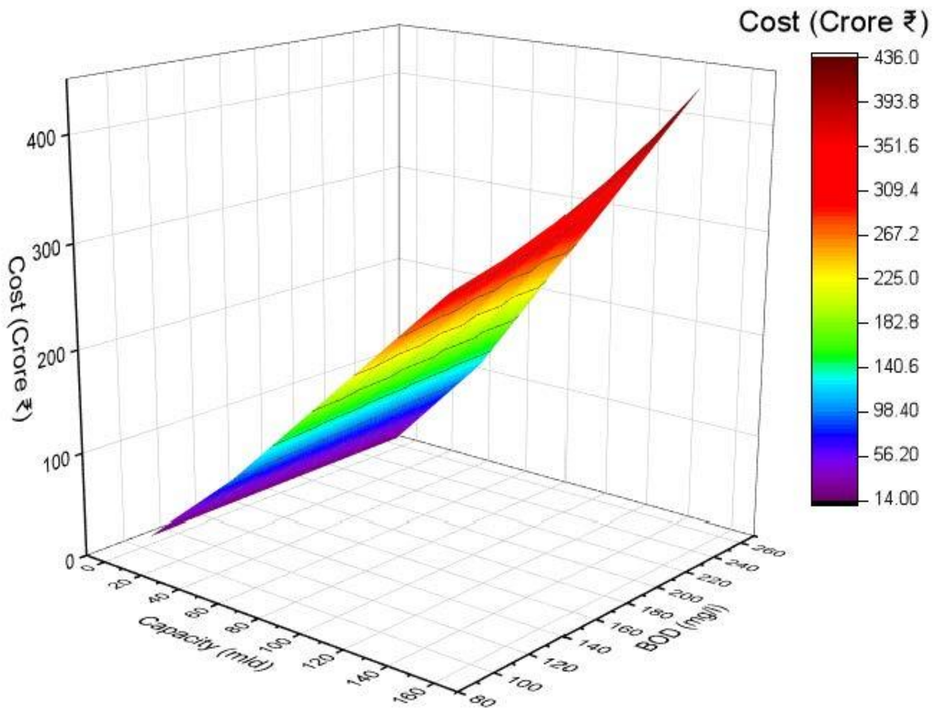


Figure 17: 3-D Cost Response Surface Map for WWTP with SBR technology

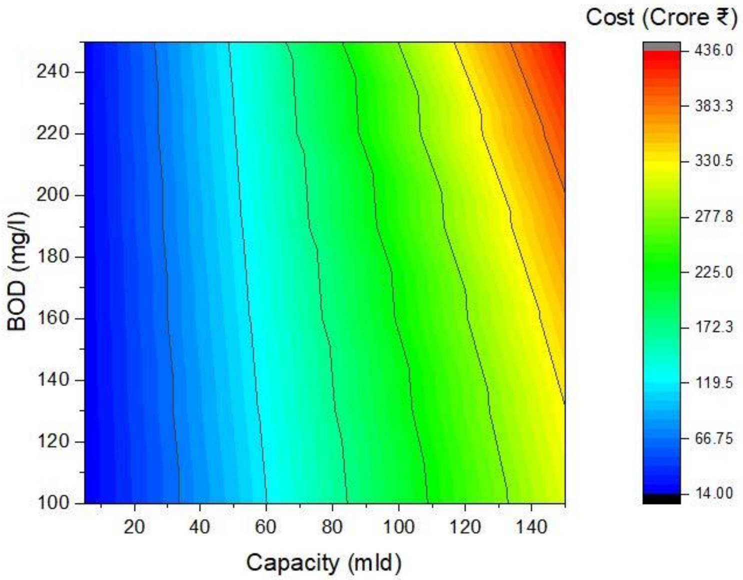


Figure 18: 3-D Contour Map for WWTP with SBR technology

Unlike MBBR and MBR technologies, influent BOD concentration significantly impacts the overall cost above a flow range of 30 MLD. Only at very low flow rates does influent BOD concentration not significantly affect the cost.

5.3 Sensitivity analysis of developed cost functions for WWTPs with MBR, MBBR and SBR technologies

Cost functions have been developed, as discussed earlier in this thesis, to predict the overall cost of WWTPs using MBR, MBBR, and SBR technologies for BOD removal at any inlet capacity (within a wide range) with an inlet BOD load of 250 mg/l. These cost functions are based on unit costs of various items prevalent in India as of the year 2021. Therefore, the cost functions are sensitive to changes in the unit costs of these items over time and may vary with specific locations worldwide. These functions can be used in the future, with adjustments made to account for cost indices applicable to the respective items in India.

To highlight their uniqueness and ensure global applicability, the functions, which relate capacity to co-efficients of unit costs of various items for the construction of WWTPs using MBR, MBBR, and SBR technologies with an inlet BOD load of 250 mg/l, have been derived using developed mathematical models.

Cost of WWTP with any of MBR, MBBR and SBR technologies are determined based on several unit costs for the items as follows:

Items for calculations of total bare construction cost:

a) Cost of total earthwork
b) Cost of total quantity of RCC
c) Cost of total quantity of handrails
d) Cost of houses or buildings
e) Cost of clarifier mechanisms (for MBBR)
f) Cost of blowers
g) Cost of installation man-hours
h) Cost of crane requirements for installation
i) Cost of pumps
j) Cost of diffusers
k) Cost of swing arm diffuser headers
l) Cost of membrane modules (for MBR)
m) Cost of carrier media (for MBBR)

n) Cost of decanters (for SBR)
o) Cost of air piping

Items for calculations of levelized cost for 25 years of operation:

a) Cost of operation and maintenance material costs
b) Cost of energy requirement
c) Cost of operation and maintenance hours
d) Cost of chemicals (for MBR}

For each item mentioned above, the coefficient of unit cost has been determined as a function of WWTP capacity using MBR, MBBR, and SBR technologies.

- The summary of coefficients for small, medium, and large WWTPs using MBR is presented in Appendix XIX to XXI.
- The summary of coefficients for small, medium, and large WWTPs using MBBR is presented in Appendix XXII to XXIV.
- The summary of coefficients for small, medium, and large WWTPs using SBR is presented in Appendix XXV to XXVII.

Regression analysis has been performed on datasets for each range of MBR, MBBR, and SBR technologies using five different functions (exponential, linear, logarithmic, polynomial, and power). However, for simplicity and effective performance, linear function curves of unit cost coefficients for various items were chosen. These curves are plotted with WWTP capacities (in MLD) along the X-axis and unit cost coefficients along the Y-axis for MBR, MBBR, and SBR technologies.

Figures 19 to 38 depict the unit cost co-efficient curves for different items in small-range WWTPs using MBR, MBBR, and SBR technologies.

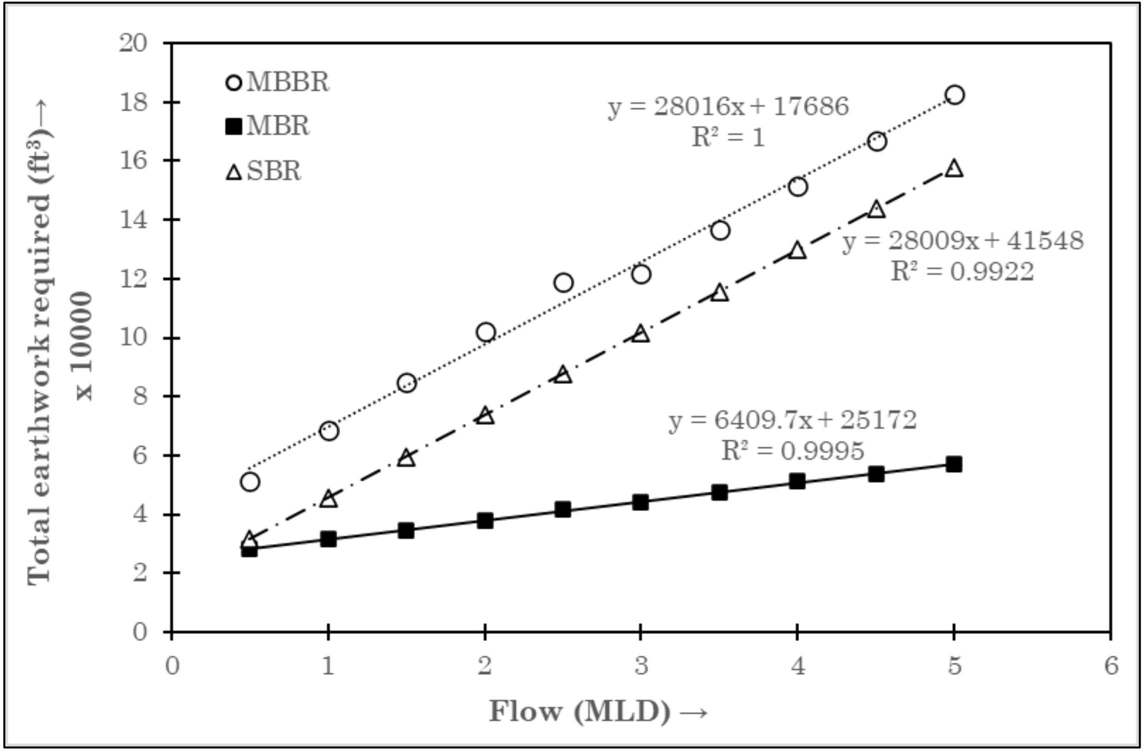


Figure 19: Excavation curve for small range WWTPs with MBR, MBBR and SBR

In Figure 19, it is evident that as the flow increases, the total co-efficient of earthwork in excavation (ft³) also increases, which aligns with expectations. Within this flow range, the total co-efficient of earthwork in excavation (ft³) tends to be higher for MBBR technology compared to SBR technology. Conversely, MBR technologies generally require less total co-efficient of earthwork due to their space-saving design.

The total costs related to earthwork can be calculated by multiplying the total co-efficient of earthwork by the unit rate price specific to the earthwork. The total co-efficient of earthwork data were analyzed using linear regression. For all technologies, the coefficient of determination (R^2) values exceed 0.99, indicating a strong fit of the data to the regression line. Therefore, this curve can be used to predict the total cost of earthwork for WWTPs across a flow range from 0.5 MLD to 5 MLD, eliminating the need for detailed cost estimation.

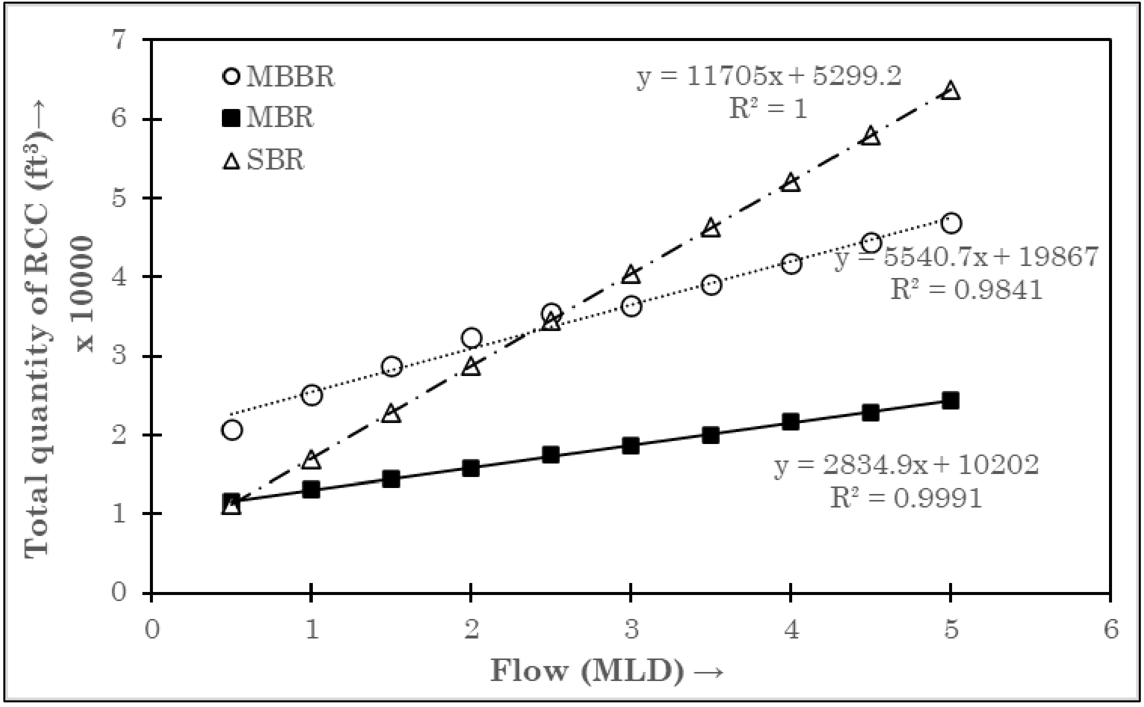


Figure 20: Concrete curve for small range WWTPs with MBR, MBBR and SBR

In Figure 20, it is observed that as the flow increases, the total co-efficient of reinforced cement concrete (RCC) work (ft³) also increases, which aligns with expectations. Within this flow range, the total co-efficient of RCC work tends to be higher for MBBR technology compared to SBR technology up to a flow rate of 2.5 MLD. However, beyond a flow rate of 2.5 MLD, the total co-efficient of RCC work required for SBR exceeds that of MBBR. MBR technologies generally require less total co-efficient of RCC work due to their space-saving design.

The total costs related to RCC can be calculated by multiplying the total co-efficient of RCC by the unit rate price specific to the RCC. The total co-efficient of RCC data was analyzed using linear regression. For all technologies, the R² values exceed 0.98, indicating a strong fit of the data to the regression line. Therefore, this curve can be used to predict the total cost of RCC for WWTPs across a flow range from 0.5 MLD to 5 MLD, eliminating the need for detailed cost estimation.

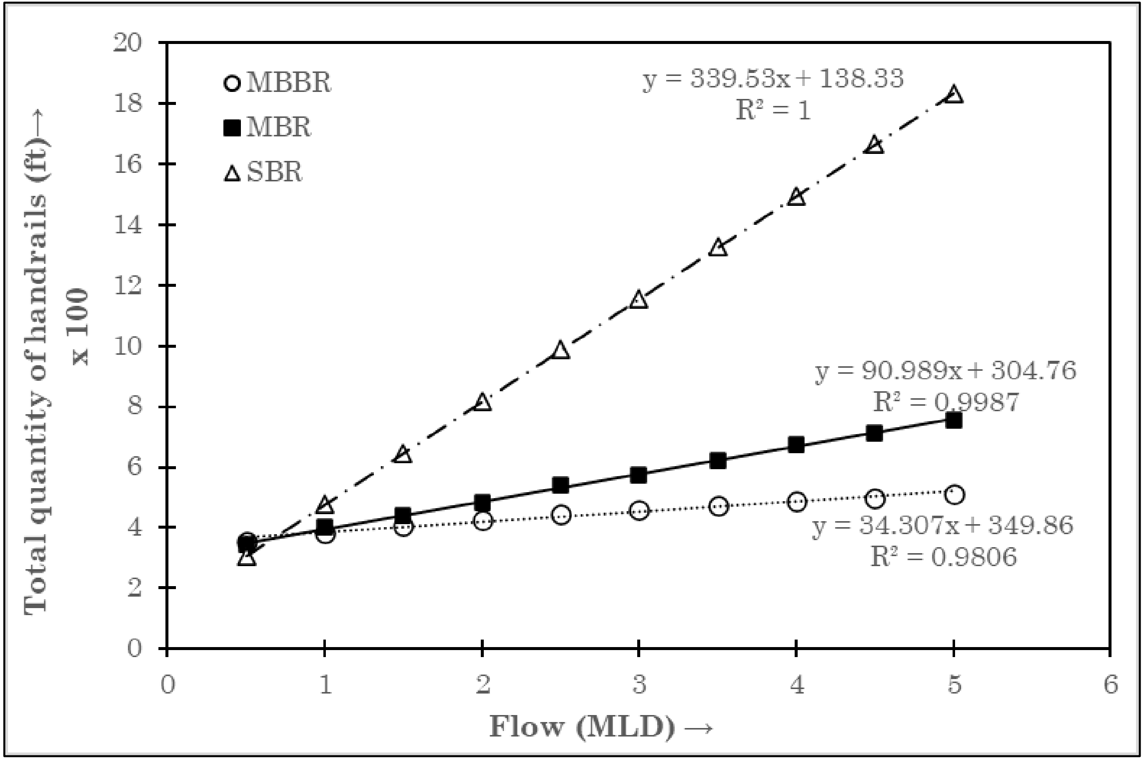


Figure 21: Hand-rail curve for small range WWTPs with MBR, MBBR and SBR

In Figure 21, it is evident that as the flow increases, the total co-efficient of handrails (ft) also increases, which aligns with the hypothesis. Within this flow range, the total co-efficient of handrails tends to be higher for SBR technology followed by MBR technology followed by MBBR technology.

The total costs related to handrails can be calculated by multiplying the total co-efficient of handrails by the unit rate price specific to the handrails. The total co-efficient of handrails was analyzed using linear regression. For all technologies, the R^2 values exceed 0.98, indicating a strong fit of the data to the regression line. Therefore, this curve can be used to predict the total cost of handrails for WWTPs across a flow range from 0.5 MLD to 5 MLD, eliminating the need for detailed cost estimation.

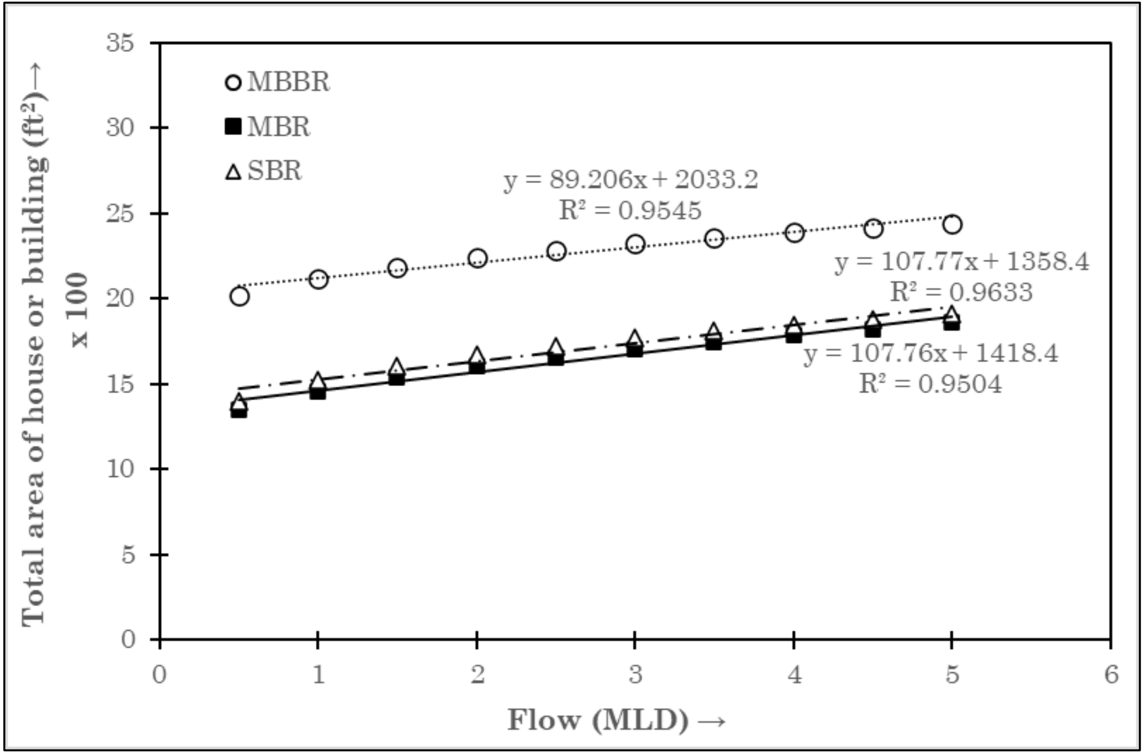


Figure 22: House curve for small range WWTPs with MBR, MBBR and SBR

In Figure 22, it is clear that within this flow range, the total co-efficient required for housing or building (ft²) is significantly higher for MBBR technology compared to MBR and SBR technology.

The total costs related to the housing or building (ft²) can be calculated by multiplying the total co-efficient by the unit rate price specific to the area. The total co-efficient data were analyzed using linear regression, with R² values exceeding 0.95 for all technologies, indicating a robust fit of the data to the regression line. Hence, this curve can be utilized to forecast the total cost of area requirements for WWTPs across a flow range from 0.5 MLD to 5 MLD, thereby obviating the necessity for elaborate cost estimation procedures.

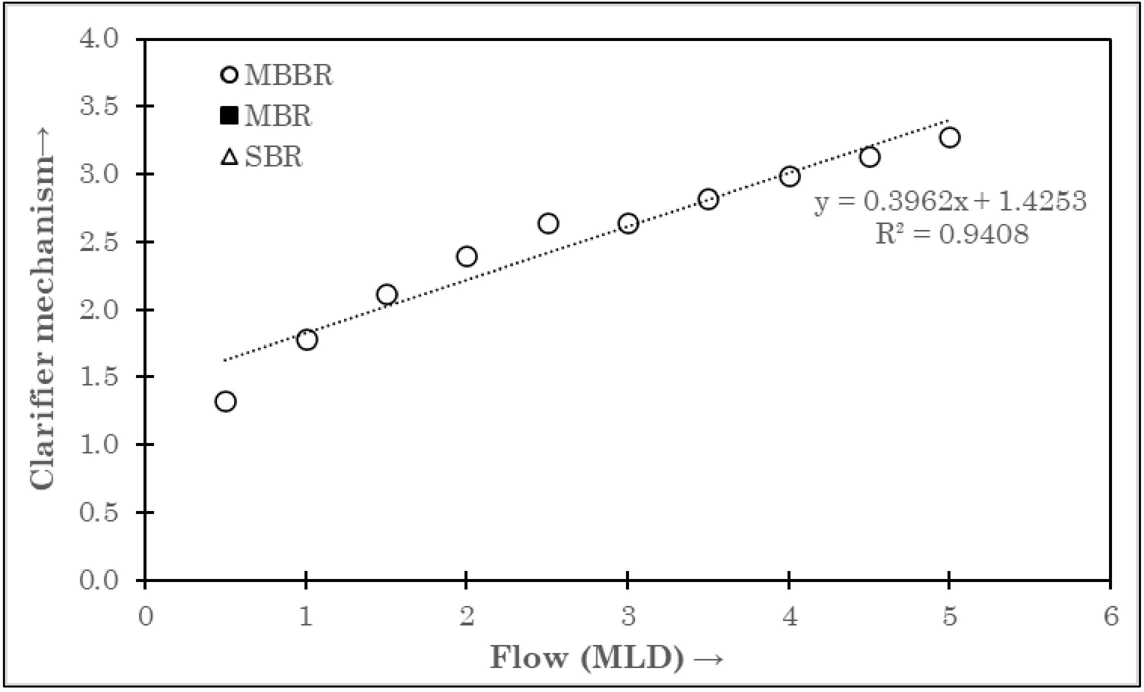


Figure 23: Clarifier mechanism for small range WWTPs with MBBR

Figure 23 illustrates the total co-efficient of clarifier mechanisms required for small-range WWTPs employing MBBR technology. For MBR and SBR technologies, clarifier mechanisms are not necessary and therefore curve is shown only for MBBR technology. It is apparent from the figure that as the flow increases, the co-efficient requirement for clarifier mechanisms also increases

The total costs associated with clarifier mechanisms can be computed by multiplying the total co-efficient of clarifier mechanisms by the unit rate price of mechanism for a standard size of clarifier. The data were analyzed using linear regression, achieving an R^2 value exceeding 0.94, indicating a strong fit of the data to the regression line. Thus, this curve can be employed to predict the total cost attributed to clarifier mechanisms for WWTPs utilizing MBBR technology across a flow range from 0.5 MLD to 5 MLD, eliminating the need for complex cost estimation procedures.

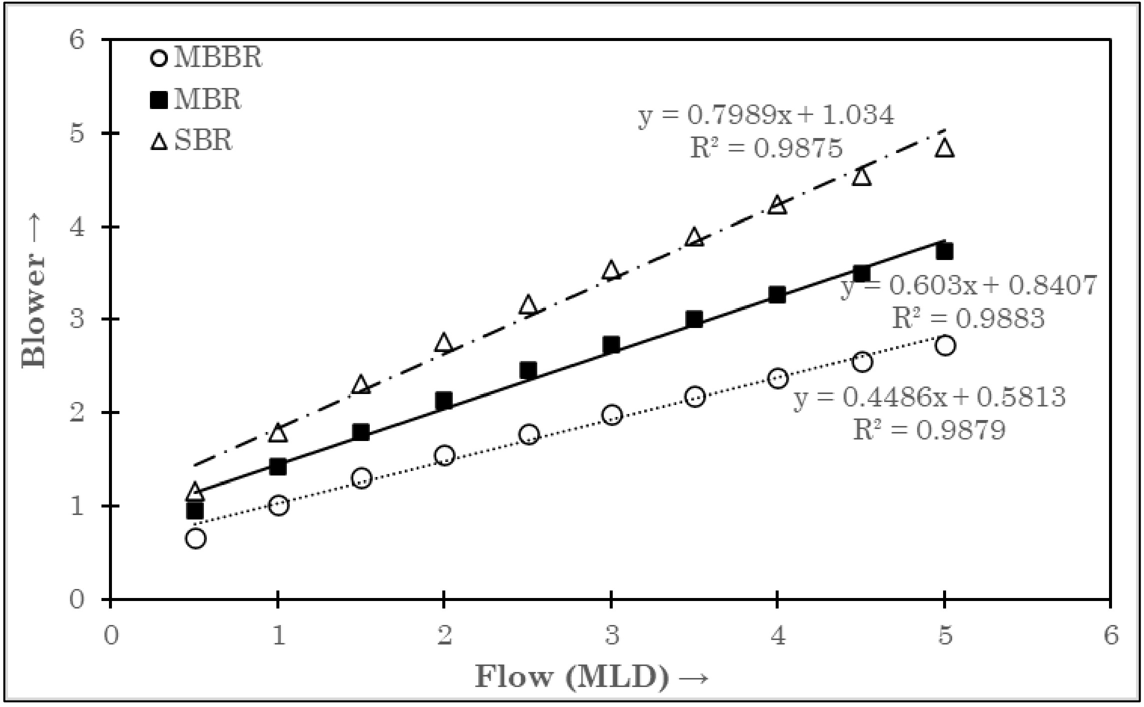


Figure 24: Blower curve for small range WWTPs with MBR, MBBR and SBR

Figure 24 depicts the total co-efficient of blowers required for small-range WWTPs employing MBR, MBBR, and SBR technologies. It is evident from the figure that as the flow increases, the total co-efficient for blowers also increases. Within this flow range, the total co-efficient of blowers tends to be higher for SBR technology, followed by MBR technology, and then MBBR technology.

The total costs associated with blowers can be calculated by multiplying the total co-efficient of blowers by the unit rate price of a standard size of blower. The data were analyzed using linear regression, achieving an R^2 value exceeding 0.98 in all cases, indicating a strong fit of the data to the regression line. Thus, this curve can be utilized to predict the total cost attributed to blowers for WWTPs utilizing MBR, MBBR, and SBR technologies across a flow range from 0.5 MLD to 5 MLD, eliminating the need for complex cost estimation procedures.

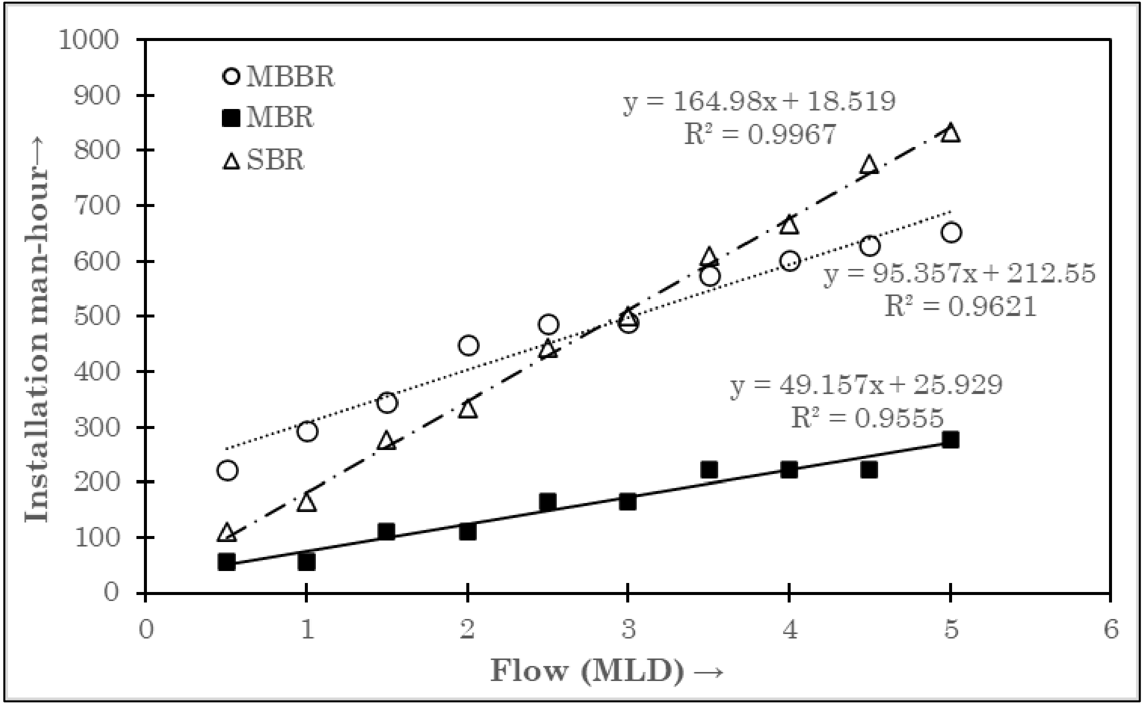


Figure 25: Installation man-hour curve for small-range WWTPs with MBR, MBBR and SBR

Figure 25 illustrates the co-efficient of installation man-hours required for small-range WWTPs utilizing MBR, MBBR, and SBR technologies. The figure clearly shows that as the flow increases, the total co-efficient of man-hours required also rise. For flows up to 3 MLD, MBBR technology demands more co-efficient of installation man-hours compared to SBR technology. However, beyond 3 MLD, SBR requires more co-efficient of man-hours than MBBR. Generally, MBR technology requires the least co-efficient of installation man-hours.

The total costs associated with man-hours can be calculated by multiplying the total co-efficient of man-hours by the unit rate price of man-hours. The data were analyzed using linear regression, with an R^2 value exceeding 0.95 in all cases, indicating a strong fit of the data to the regression line. Consequently, this curve can be used to predict the total cost attributed to man-hours for WWTPs using MBR, MBBR, and SBR technologies across a flow range from 0.5 MLD to 5 MLD, simplifying the cost estimation process.

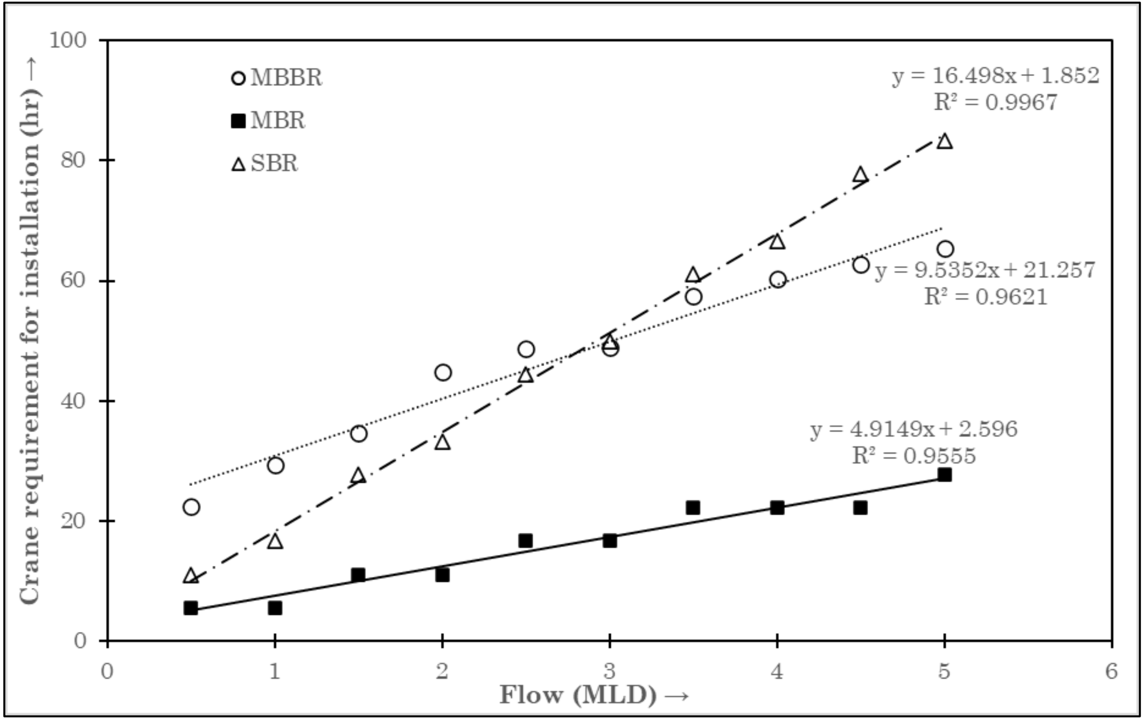


Figure 26: Crane curve for small-range WWTPs with MBR, MBBR and SBR

Figure 26 illustrates the crane co-efficient for the installation of small-range WWTPs utilizing MBR, MBBR, and SBR technologies. The figure shows that as the flow increases, the total crane co-efficient required also rise. For flows up to 3 MLD, MBBR technology demands more crane co-efficient compared to SBR technology. However, beyond 3 MLD, SBR requires more crane co-efficient than MBBR. Generally, MBR technology requires the least crane co-efficient for installation.

The total costs associated with crane usage can be calculated by multiplying the total crane co-efficient by the unit rate price of crane hours. The data were analyzed using linear regression, achieving an R^2 value exceeding 0.95 in all cases, indicating a strong fit of the data to the regression line. Consequently, this curve can be used to predict the total cost attributed to the crane for WWTPs using MBR, MBBR, and SBR technologies across a flow range from 0.5 MLD to 5 MLD, simplifying the cost estimation process.

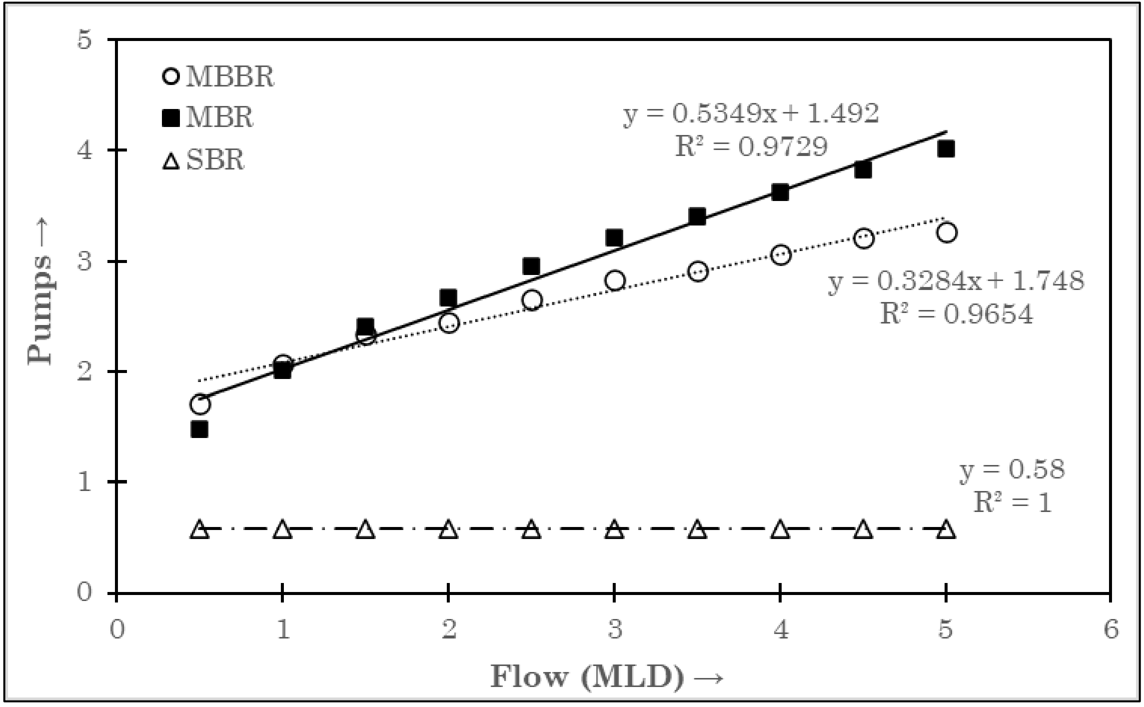


Figure 27: Pumps curve for small-range WWTPs with MBR, MBBR and SBR

Figure 27 illustrates the co-efficient of standard pumps (3000 gpm) required for the small-range WWTPs utilizing MBR, MBBR, and SBR technologies. The figure shows that as the flow increases, the co-efficient of standard pumps required rises for MBBR and MBR technologies, while for SBR, it remains constant. Within this flow range, MBR technology generally requires the highest co-efficient of standard pumps, followed by MBBR technology, and then SBR technology.

The total costs associated with pumps can be calculated by multiplying the total co-efficient of standard pumps (3000 gpm) by the unit rate price of standard pumps. The data were analyzed using linear regression, achieving an R^2 value exceeding 0.96 in all cases, indicating a strong fit to the regression line. Therefore, this curve can be used to predict the total cost of pumps for WWTPs using MBR, MBBR, and SBR technologies across a flow range from 0.5 MLD to 5 MLD, simplifying the cost estimation process.

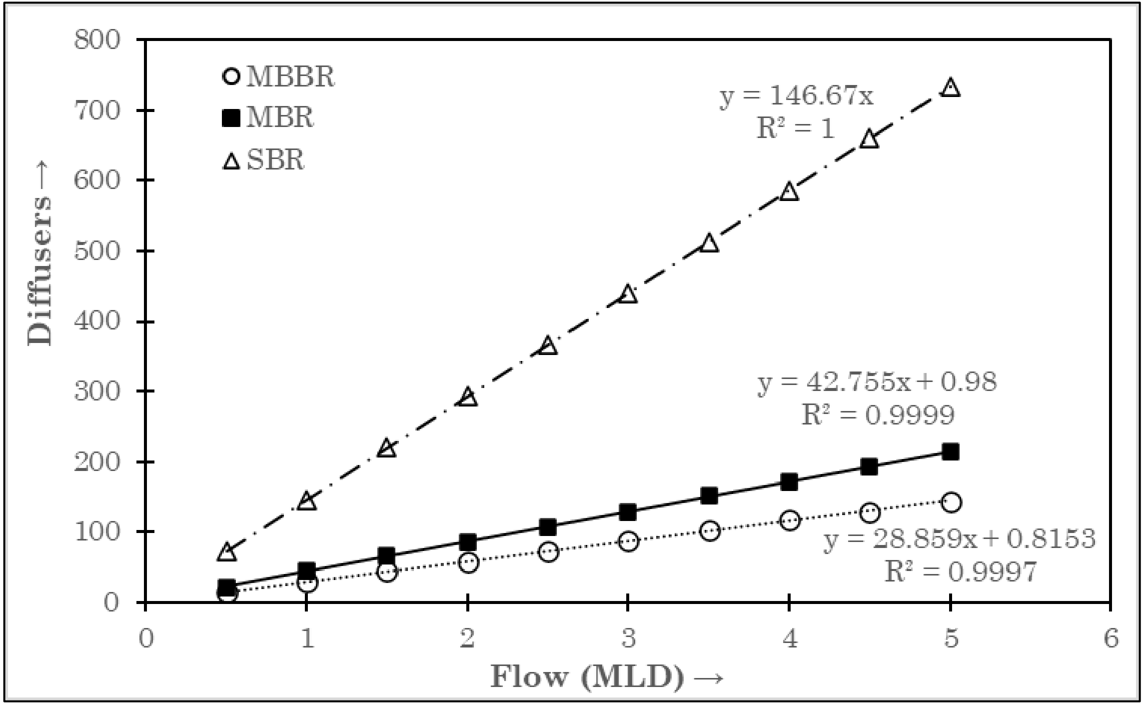


Figure 28: Diffusers curve for small range WWTPs with MBR, MBBR and SBR

Figure 28 illustrates the co-efficient of diffusers required for small-range WWTPs utilizing MBR, MBBR, and SBR technologies. The diffuser requirement is significantly higher in SBR technologies compared to the other two technologies. The figure clearly shows that as the flow increases, the total co-efficient for diffusers also rises. Within this flow range, SBR technology generally requires the highest co-efficient of diffusers, followed by MBR technology, and then MBBR technology.

The total costs associated with diffusers can be determined by multiplying the total co-efficient of diffusers by the unit rate price per diffuser. The data were analyzed using linear regression, achieving an R^2 value exceeding 0.999 in all cases, indicating an excellent fit to the regression line. As a result, this curve can be used to predict the total cost of diffusers for WWTPs utilizing MBR, MBBR, and SBR technologies across a flow range from 0.5 MLD to 5 MLD, thereby simplifying the cost estimation process.

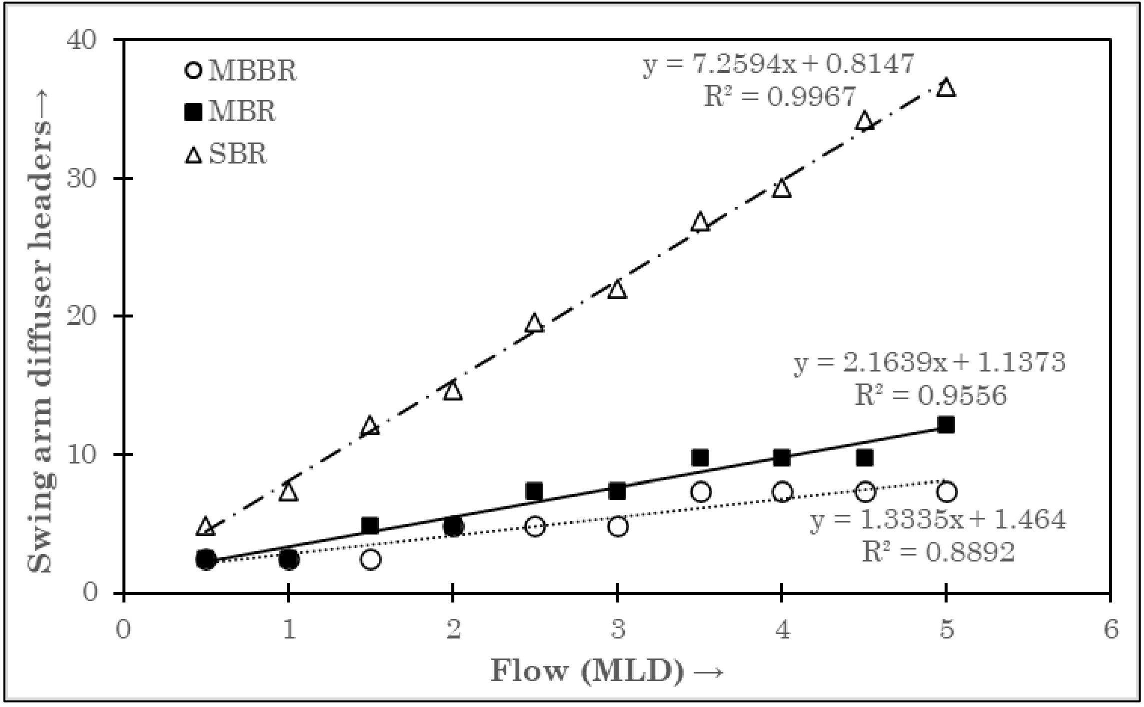


Figure 29: Swing arm diffuser header curve for small range WWTPs with MBR, MBBR and SBR

Figure 29 depicts the co-efficient of swing arm diffuser headers required for small-range WWTPs utilizing MBR, MBBR, and SBR technologies. The need for swing arm diffuser headers is significantly higher in SBR technologies compared to the other two technologies. The figure clearly shows that as the flow increases, the total co-efficient for swing arm diffuser headers also rises. Within this flow range, SBR technology generally requires the highest co-efficient of diffuser headers, followed by MBR technology, and then MBBR technology.

The total costs associated with diffusers can be determined by multiplying the total co-efficient of diffusers by the unit rate price per diffuser headers. The data were analyzed using linear regression, achieving an R^2 value exceeding 0.95 for MBR and SBR technologies, indicating an excellent fit to the regression line. However, this is not the case for MBBR technology, as the R^2 value is nearly 0.889, suggesting a maximum possible error of 10% when predicting the total cost of swing arm diffuser headers for MBBR. Nevertheless, the R^2 value is generally good for all the curves. Therefore, these curves can be used to calculate the cost of swing arm diffuser headers for WWTPs utilizing MBR, MBBR, and SBR technologies across a flow range from 0.5 MLD to 5 MLD, simplifying the cost estimation process.

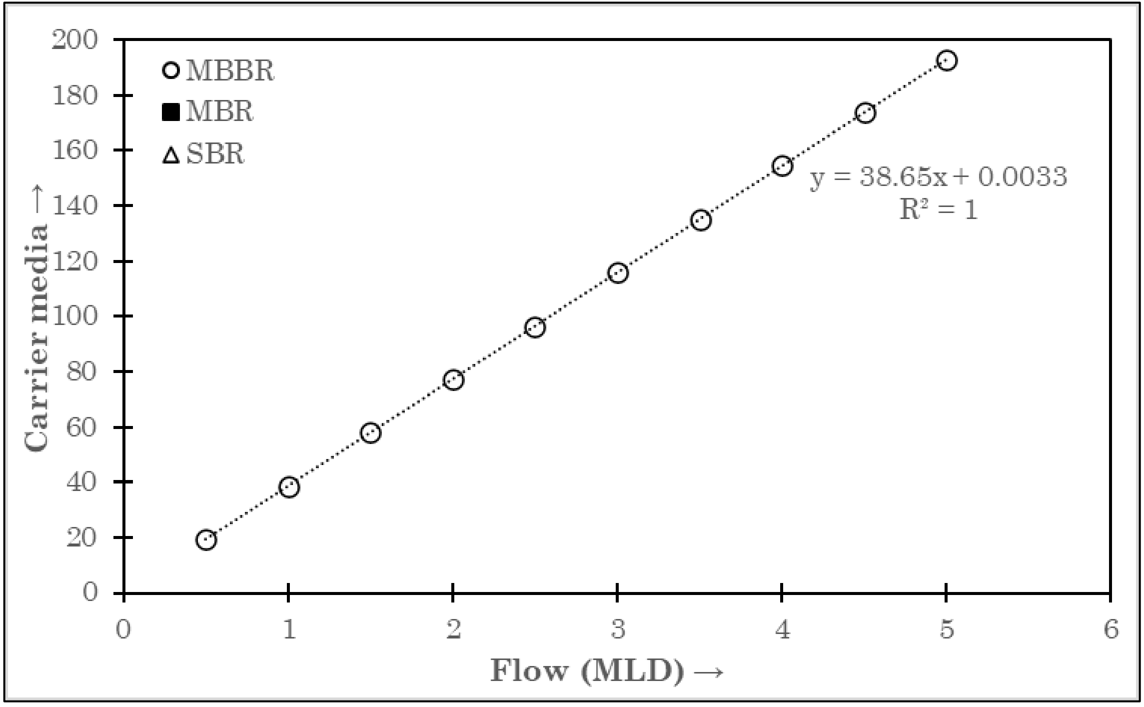


Figure 30: Carrier media curve for small range WWTPs with MBBR

Figure 30 illustrates the co-efficient of carrier media (m^3) needed for small-scale WWTPs using MBBR technology. In contrast, MBR and SBR technologies do not require carrier media and therefore curve is shown only for MBBR technology. The figure shows a clear trend: as the flow rate increases, the required co-efficient of carrier media also rises.

To calculate the total costs associated with carrier media, multiply the total co-efficient by the unit price of the carrier media. The data were analyzed using linear regression, resulting in an R^2 value of 1, which indicates an excellent fit to the regression line. Therefore, this curve can be used to predict the total cost of carrier media for WWTPs utilizing MBBR technology over a flow range of 0.5 MLD to 5 MLD, simplifying the cost estimation process.

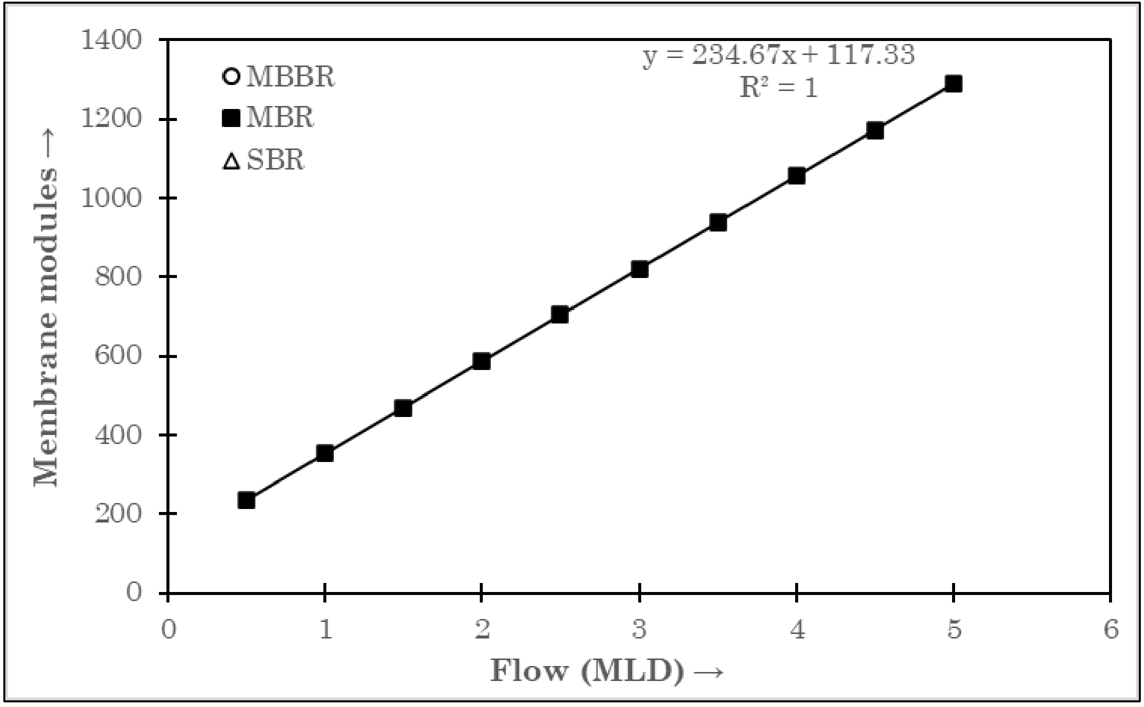


Figure 31: Membrane modules curve for small range WWTPs with MBR

Figure 31 illustrates the co-efficient of membrane modules needed for small-scale WWTPs using MBR technology. In contrast, MBBR and SBR technologies do not require membrane modules and therefore curve is shown only for MBR technology. The figure clearly shows that as the flow rate increases, the required co-efficient of membrane modules also rises.

To calculate the total costs associated with membrane modules, multiply the total co-efficient by the unit price of the membrane modules. The data were analyzed using linear regression, resulting in an R^2 value of 1, indicating an excellent fit to the regression line. Consequently, this curve can be used to predict the total cost of membrane modules for WWTPs using MBR technology over a flow range of 0.5 MLD to 5 MLD, simplifying the cost estimation process.

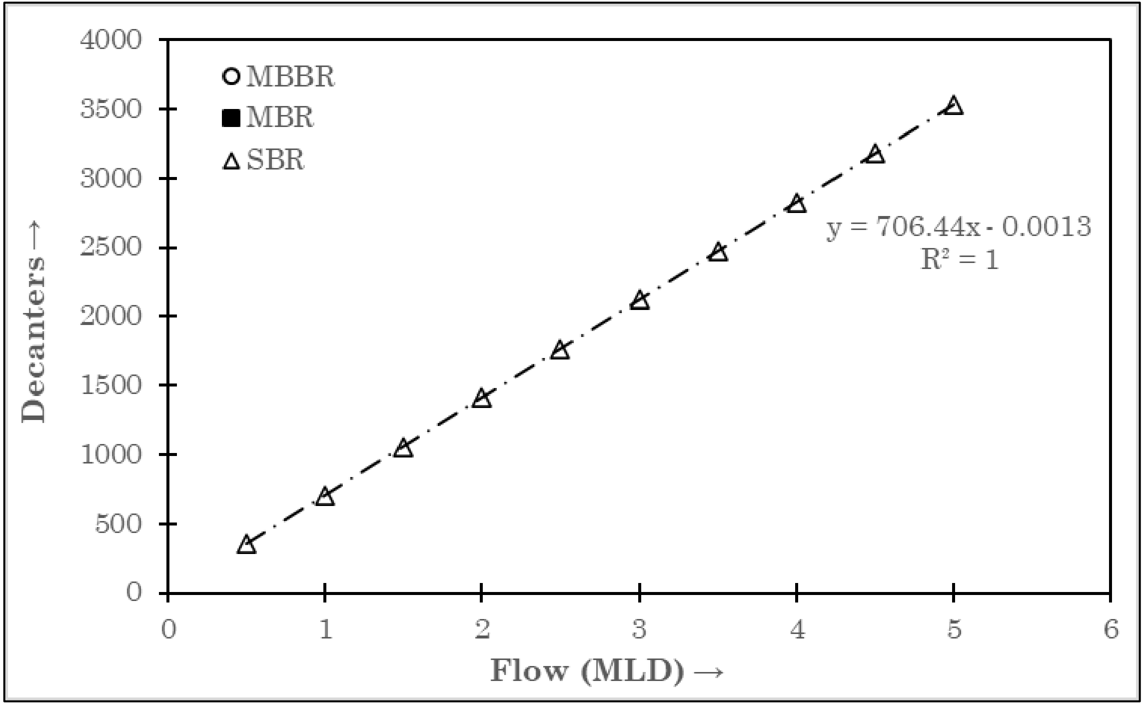


Figure 32: Decanters curve for small range WWTPs with SBR

Figure 32 illustrates the co-efficient of decanters (m^3/hr) needed for small-scale WWTPs using SBR technology. In contrast, MBR and MBBR technologies do not require decanters and therefore curve is shown only for SBR technology. The figure clearly indicates that as the flow rate increases, the required co-efficient of decanters also rises.

To calculate the total costs associated with decanters, multiply the total co-efficient by the unit price of the decanters. The data were analyzed using linear regression, resulting in an R^2 value of 1, which indicates an excellent fit to the regression line. Consequently, this curve can be used to predict the total cost of decanters for WWTPs using SBR technology over a flow range of 0.5 MLD to 5 MLD, simplifying the cost estimation process.

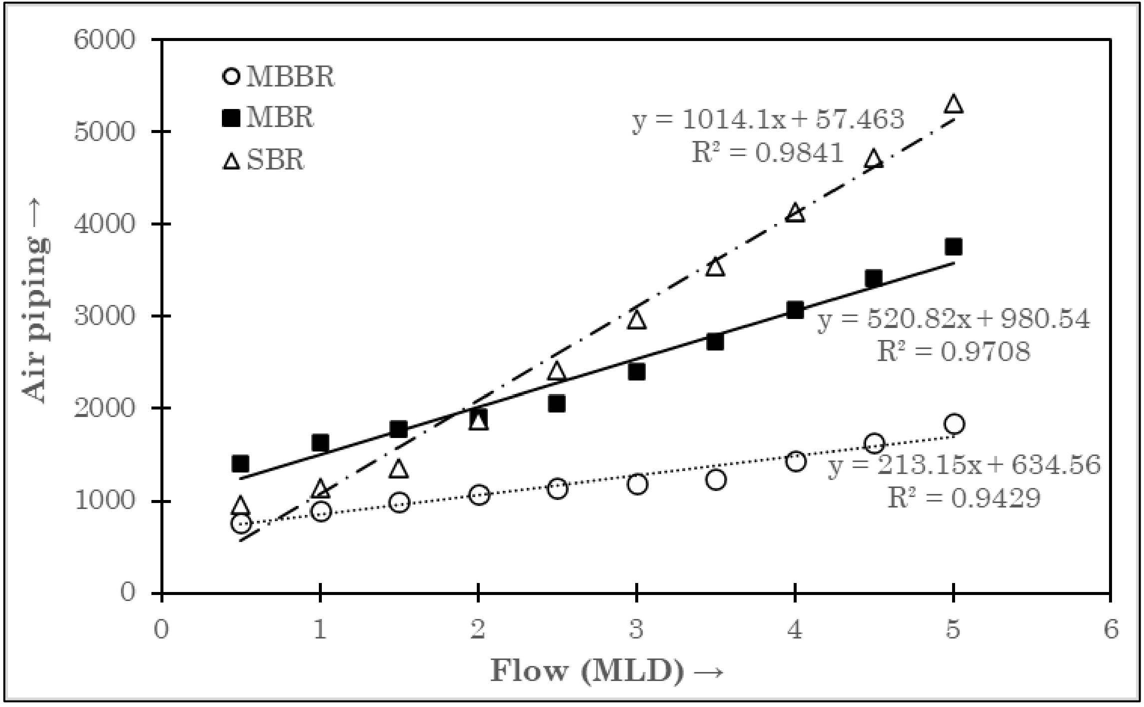


Figure 33: Air pipe curve for small range WWTPs with MBR, MBBR and SBR

Figure 33 shows the co-efficient of air piping needed for small-scale WWTPs using MBR, MBBR, and SBR technologies. The need for air piping is significantly lower in MBBR technologies compared to the other two technologies. The figure clearly indicates that as the flow increases, the total co-efficient for air piping also rises. Within this flow range, SBR technology generally requires the most air piping, followed by MBR technology, and then MBBR technology.

To calculate the total costs associated with air piping, multiply the total co-efficient of air piping by the unit price per air pipe. The data were analyzed using linear regression, resulting in an R^2 value exceeding 0.94 in all cases, indicating an excellent fit to the regression line. Consequently, this curve can be used to estimate the cost of air piping for WWTPs using MBR, MBBR, and SBR technologies over a flow range of 0.5 MLD to 5 MLD, simplifying the cost estimation process.

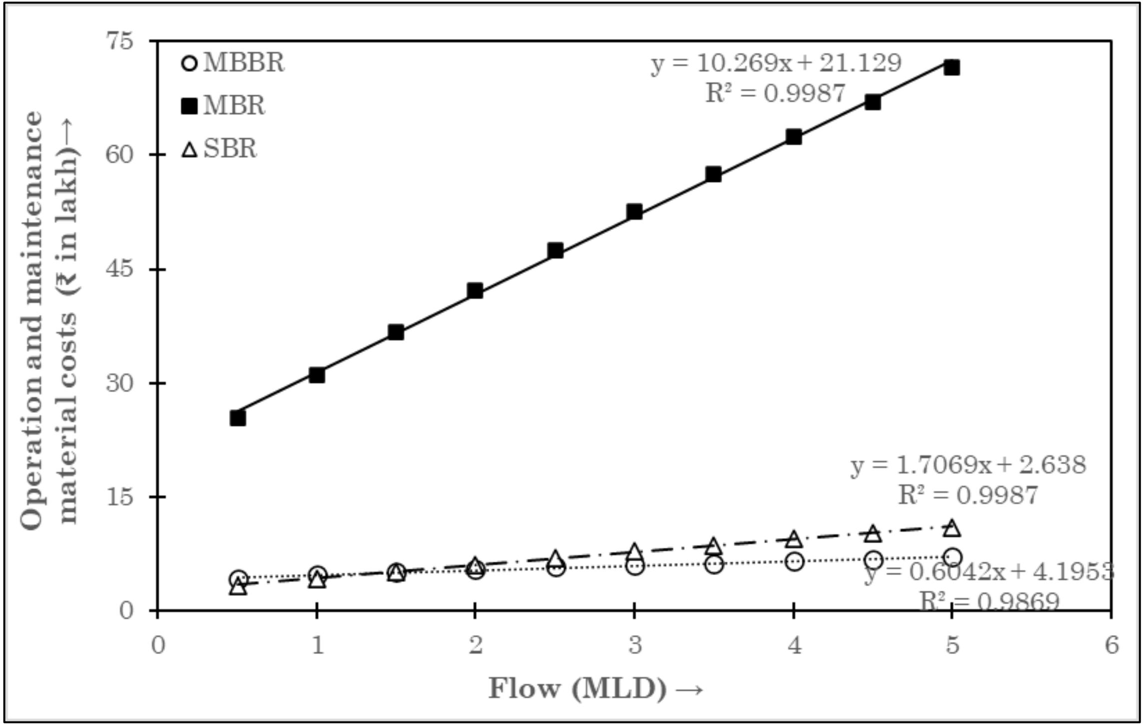


Figure 34: O&M material cost curve for small range WWTPs with MBR, MBBR and SBR

Figure 34 presents the co-efficient of O&M materials for small-scale WWTPs using MBR, MBBR, and SBR technologies. The co-efficient of O&M materials is significantly higher for MBR technology compared to the other two technologies. The figure clearly indicates that as the flow increases, the total co-efficient of O&M materials also rises. Within this flow range, MBR technology generally incurs the highest O&M material co-efficient, followed by SBR technology, and then MBBR technology.

The data were analyzed using linear regression, resulting in an R^2 value exceeding 0.98 in all cases, indicating an excellent fit to the regression line. Consequently, this curve can be used to estimate the cost of O&M materials for WWTPs using MBR, MBBR, and SBR technologies over a flow range of 0.5 MLD to 5 MLD, simplifying the cost estimation process.

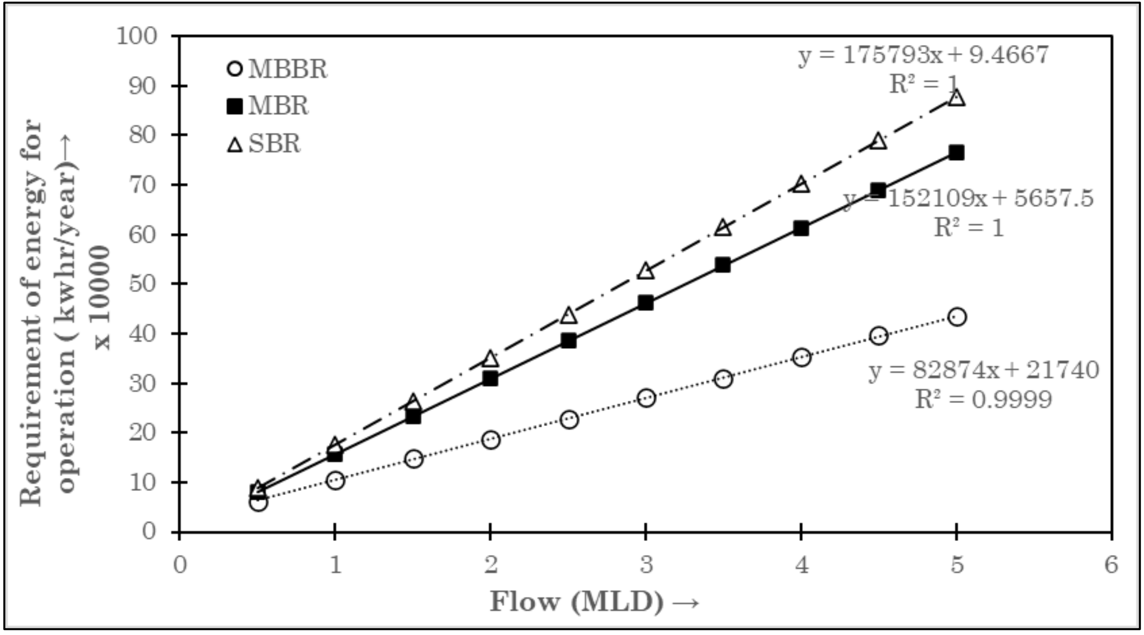


Figure 35: Energy curve for small range WWTPs with MBR, MBBR and SBR

Figure 35 illustrates the co-efficient of energy required for small-scale WWTPs using MBR, MBBR, and SBR technologies. The energy demand is significantly lower for MBBR technology compared to the other two technologies. The figure clearly shows that as the flow increases, the total energy requirement also rises. Within this flow range, SBR technology generally requires the most energy, followed by MBR technology, and then MBBR technology.

To calculate the total costs associated with energy, multiply the total co-efficient of energy by the unit price per unit of energy. The data were analyzed using linear regression, resulting in an R² value exceeding 0.999 in all cases, indicating an excellent fit to the regression line. Consequently, this curve can be used to estimate the energy costs for WWTPs using MBR, MBBR, and SBR technologies over a flow range of 0.5 MLD to 5 MLD, simplifying the cost estimation process.

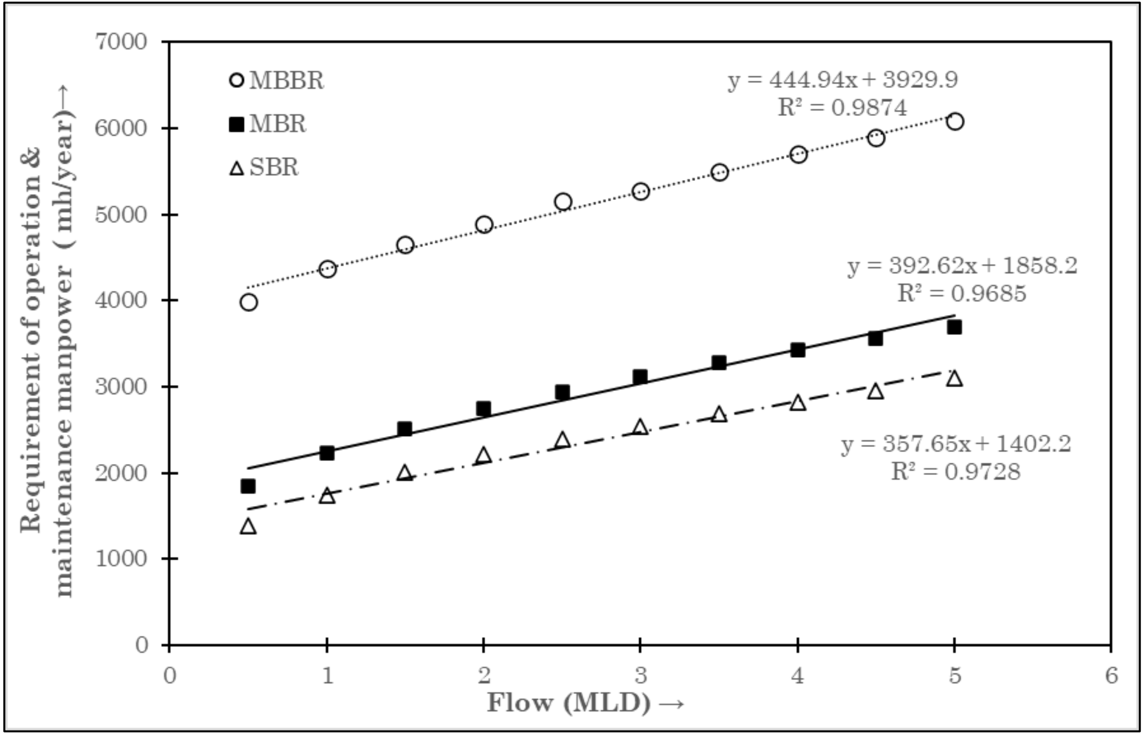


Figure 36: O&M man-hour curve for small range WWTPs with MBR, MBBR and SBR

Figure 36 shows the co-efficient of O&M manpower required for small-scale WWTPs using MBR, MBBR, and SBR technologies. The O&M manpower needed is significantly higher for MBBR technology compared to the other two technologies. The figure clearly indicates that as the flow increases, the O&M manpower co-efficient also rises. Within this flow range, MBBR technology generally requires the most O&M manpower, followed by MBR technology, and then SBR technology.

The data were analyzed using linear regression, resulting in an R^2 value exceeding 0.96 in all cases, indicating an excellent fit to the regression line. Consequently, this curve can be used to estimate the O&M manpower costs for WWTPs using MBR, MBBR, and SBR technologies over a flow range of 0.5 MLD to 5 MLD, simplifying the cost estimation process.

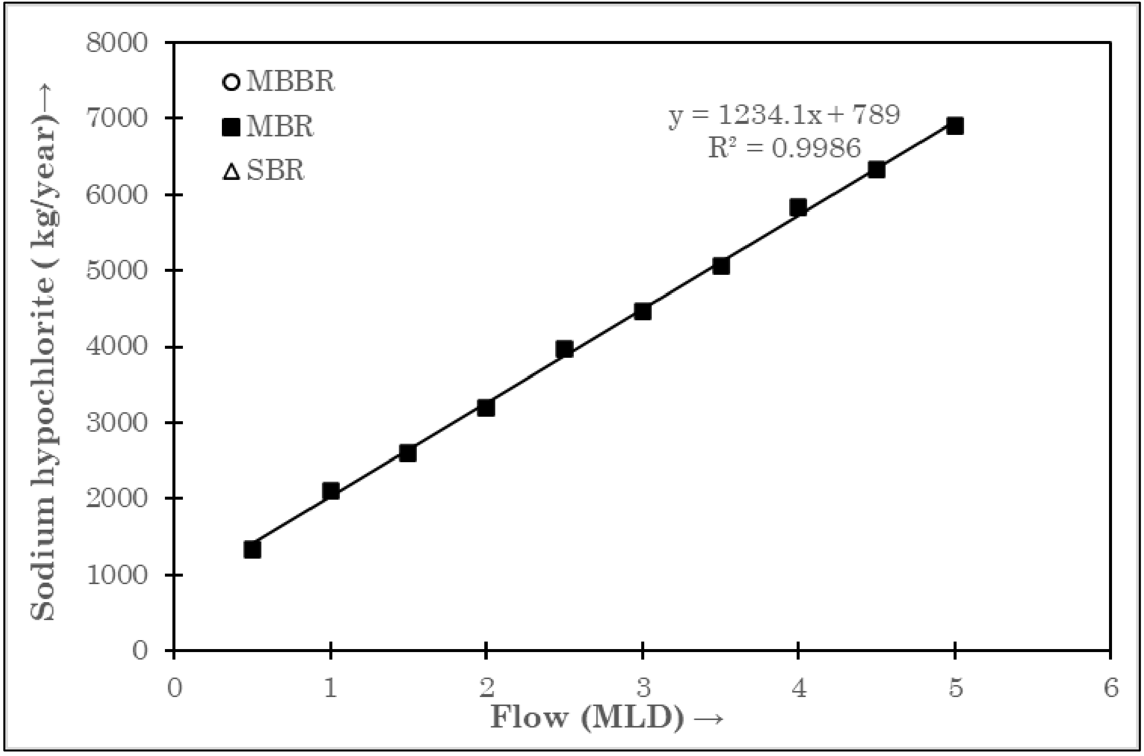


Figure 37: Sodium hypochlorite curve for small range WWTPs with MBR

Figure 37 illustrates the co-efficient of sodium hypochlorite needed for small-scale WWTPs using MBR technology. In contrast, SBR and MBBR technologies do not require sodium hypochlorite and therefore curve is shown only for MBR technology. The figure clearly indicates that as the flow rate increases, the required co-efficient of sodium hypochlorite also rises.

To calculate the total costs associated with sodium hypochlorite, multiply the total co-efficient by the unit price of sodium hypochlorite. The data were analyzed using linear regression, resulting in an R^2 value greater than 0.998, which indicates an excellent fit to the regression line. Consequently, this curve can be used to predict the total cost of sodium hypochlorite for WWTPs using MBR technology over a flow range of 0.5 MLD to 5 MLD, simplifying the cost estimation process.

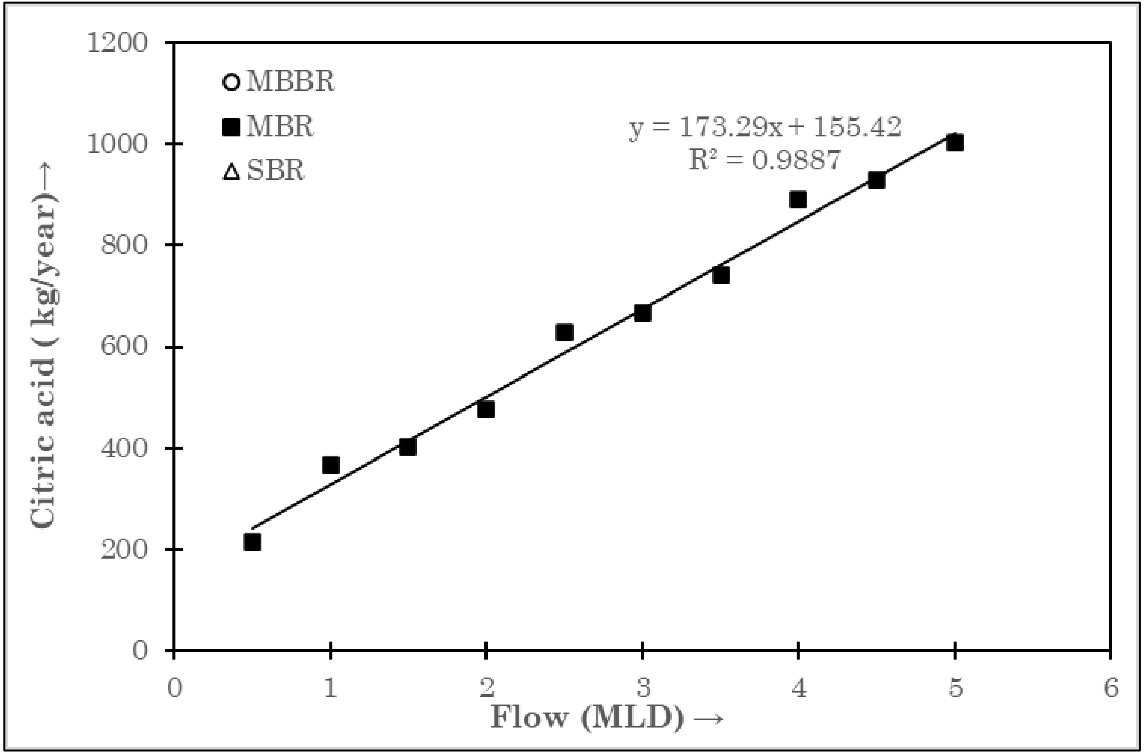


Figure 38: Acid curve for small range WWTPs with MBR

Figure 38 shows the co-efficient of citric acid needed for small-scale WWTPs using MBR technology. In contrast, SBR and MBBR technologies do not require citric acid and therefore curve is shown only for MBR technology. The figure clearly indicates that as the flow rate increases, the required co-efficient of citric acid also rises.

To calculate the total costs associated with citric acid, multiply the total co-efficient by the unit price of citric acid. The data were analyzed using linear regression, resulting in an R^2 value greater than 0.988, indicating an excellent fit to the regression line. Consequently, this curve can be used to predict the total cost of citric acid for WWTPs using MBR technology over a flow range of 0.5 MLD to 5 MLD, simplifying the cost estimation process.

The unit cost co-efficient functions for different items of small range WWTPs with MBR technology as displayed in the Figures 19 to 38 are tabulated in Table 15:

Table 15: Small range WWTPs with MBR - Functions for calculations of cost

Small range WWTPs with MBR - Functions for calculations of total bare construction cost							
Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient function for unit cost (y)**	**Cost for x mld capacity WWTP with MBR**	
			Value	***Unit***		***Value***	***Unit***
1	x	Cost of total earthwork	C_1	per ft^3	$y_1 = (6409.7*x) + 25172$	C_1*y_1	currency
2	x	Cost of total quantity of RCC	C_2	per ft^3	$y_2 = (2834.9*x) + 10202$	C_2*y_2	currency
3	x	Cost of total quantity of handrails	C_3	per ft	$y_3 = (90.989*x) + 304.76$	C_3*y_3	currency
4	x	Cost of houses or buildings	C_4	per ft^2	$y_4 = (107.76*x) + 1418.4$	C_4*y_4	currency
5	x	Cost of blowers	C_5	per blower	$y_5 = (0.6030*x) + 0.8407$	C_5*y_5	currency
6	x	Cost of installation man-hours	C_6	per hr	$y_6 = (49.157*x) + 25.929$	C_6*y_6	currency
7	x	Cost of crane requirements for installation	C_7	per hr	$y_7 = (4.9149*x) + 2.596$	C_7*y_7	currency
8	x	Cost of pumps	C_8	Purchase cost of standard pump (3000 gpm)	$y_8 = (0.5349*x) +1.492$	C_8*y_8	currency
9	x	Cost of diffusers	C_9	per diffuser	$y_9 = (42.755*x) + 0.98$	C_9*y_9	currency
10	x	Cost of swing arm diffuser headers	C_{10}	per header	$y_{10} = (2.1639*x) + 1.1373$	$C_{10}*y_{10}$	currency
11	x	Cost of membrane modules	C_{11}	per module	$y_{11} = (234.67*x) + 117.33$	$C_{11}*y_{11}$	currency
12	x	Cost of air piping	C_{12}	cost index	$y_{12} = (520.82*x) + 980.4$	$C_{12}*y_{12}$	currency

Table 15: Small range WWTPs with MBR - Functions for calculations of cost (continued)

Small range WWTPs with MBR - Functions for calculations of levelized cost for 25 years of operation							
Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient function for unit cost (y)**	**Cost for x mld capacity WWTP with MBR**	
			Value	***Unit***		***Value***	***Unit***
13	x	Cost of operation and maintenance material costs			$y_{13} = [(10.269*x) + 21.129]*10^5$	y_{13}	currency
14	x	Cost of energy requirement	C_{13}	per kwhr	$y_{14} = (152109*x) + 5657.5$	$C_{14}*y_{14}$	currency
15	x	Cost of operation and maintenance hours	C_{14}	per hr	$y_{15} = (392.62*x) + 1858.2$	$C_{15}*y_{15}$	currency
16	x	Cost of chemical for maintenance - sodium hypochlorite	C_{15}	per kg of solution	$y_{16} = (1234.1*x) + 789$	$C_{16}*y_{16}$	currency
17	x	Cost of chemical for maintenance - citric acid	C_{16}	per kg of solution	$y_{17} = (173.29*x) + 155.42$	$C_{17}*y_{17}$	currency
		Present worth factor considered				9.82	
		Levelized cost for 25 years of operation			$9.82 * [y_{13} + (C_{14}*y_{14}) + (C_{15}*y_{15}) + (C_{16}*y_{16}) + (C_{17}*y_{17})]$		currency

The co-efficients for respective unit costs have been calculated based on derived functions for a case of 3 mld capacity WWTP with MBR technology and costs with unit cost base in India at year 2021 are furnished in Table – 16.

Table 16: Small range WWTPs with MBR - Validation for calculated costs

Small range WWTPs with MBR - Validation for calculated total bare construction cost						
Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient function for unit cost (y)**	**Cost for 3 mld capacity WWTP with MBR**
			Value	***Unit***		***Value***
1	3.0	Cost of total earthwork	₹ 10.38	per ft^3	44401.1	₹ 460,988.59
2	3.0	Cost of total quantity of RCC	₹ 243.72	per ft^3	18706.7	₹ 4,559,280.05
3	3.0	Cost of total quantity of handrails	₹ 600.00	per ft	577.727	₹ 346,636.20
4	3.0	Cost of houses or buildings	₹ 7,500.00	per ft^2	1741.68	₹ 13,062,600.00
5	3.0	Cost of blowers	₹ 53,00,895.04	per blower	2.6497	₹ 14,045,781.58
6	3.0	Cost of installation man-hours	₹ 125.00	per hr	173.4	₹ 21,675.00
7	3.0	Cost of crane requirements for installation	₹ 1,000.00	per hr	17.3407	₹ 17,340.70
8	3.0	Cost of pumps	₹ 12,93,750.00	Purchase cost of standard pump (3000 gpm)	3.0967	₹ 4,006,355.63
9	3.0	Cost of diffusers	₹ 1,200.00	per diffuser	129.245	₹ 155,094.00
10	3.0	Cost of swing arm diffuser headers	₹ 35,000.00	per header	7.629	₹ 267,015.00
11	3.0	Cost of membrane modules	₹ 1,63,506.94	per module	821.34	₹ 134,294,793.75
12	3.0	Cost of air piping	₹ 750.00	cost index	2542.86	₹ 1,907,145.00
		Consolidated bare cost				₹ 173,144,705.50

Table 16: Small range WWTPs with MBR - Validation for calculated costs (continued)

Small range WWTPs with MBR - Validation for calculated levelized cost of 25 years operation						
Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient function for unit cost (y)**	**Cost for 3 mld capacity WWTP with MBR**
			Value	***Unit***		***Value***
13	3.0	Cost of operation and maintenance material costs			5193600	₹ 5,193,600.00
14	3.0	Cost of energy requirement	₹ 6.00	per kwhr	461984.5	₹ 2,771,907.00
15	3.0	Cost of operation and maintenance hours	₹ 250.00	per hr	3036.06	₹ 759,015.00
16	3.0	Cost of chemical for maintenance - sodium hypochlorite	₹ 30.00	per kg of solution	4491.3	₹ 134,739.00
17	3.0	Cost of chemical for maintenance - citric acid	₹ 90.00	per kg of solution	675.29	₹ 60,776.10
		Present worth factor considered				9.82
		Levelized cost for 25 years of operation			$9.82 * [y_{13} + (C_{14}*y_{14}) + (C_{15}*y_{15}) + (C_{16}*y_{16}) + (C_{17}*y_{17})]$	₹ 87,617,774.49

It has been scrutinized and noted that variation is within 1 % for each of estimated total bare construction cost and levelized cost of 25 years of operation.

The unit cost co-efficient functions for different items of small range WWTPs with MBBR technology as displayed in the Figures 19 to 38 are tabulated in Table 17:

Table 17: Small range WWTPs with MBBR - Functions for calculations of cost

Small range WWTPs with MBBR - Functions for calculations of total bare construction cost

Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient function for unit cost (y)**	**Cost for x mld capacity WWTP with MBBR**	
			Value	***Unit***		***Value***	***Unit***
1	x	Cost of total earthwork	C_1	per ft^3	$y_1 = (28016*x) + 17686$	C_1*y_1	currency
2	x	Cost of total quantity of RCC	C_2	per ft^3	$y_2 = (5540.7*x) + 19867$	C_2*y_2	currency
3	x	Cost of total quantity of handrails	C_3	per / ft	$y_3 = (34.307*x) + 349.86$	C_3*y_3	currency
4	x	Cost of houses or buildings	C_4	per ft^2	$y_4 = (89.206*x) + 2033.2$	C_4*y_4	currency
5	x	Cost of clarifier mechanisms	C_5	per mechanism	$y_5 = (0.3962*x) + 1.4253$	C_5*y_5	currency
6	x	Cost of blowers	C_6	per blower	$y_6 = (0.4486*x) + 0.5813$	C_6*y_6	currency
7	x	Cost of installation man-hours	C_7	per hr	$y_7 = (95.357*x) + 212.55$	C_7*y_7	currency
8	x	Cost of crane requirements for installation	C_8	per hr	$y_8 = (9.5352*x) + 21.257$	C_8*y_8	currency
9	x	Cost of pumps	C_9	Purchase cost of standard pump (3000 gpm)	$y_9 = (0.3284*x) + 1.748$	C_9*y_9	currency
10	x	Cost of diffusers	C_{10}	per diffuser	$y_{10} = (28.859*x) + 0.8153$	$C_{10}*y_{10}$	currency
11	x	Cost of swing arm diffuser headers	C_{11}	per header	$y_{11} = (1.3335*x) + 1.4640$	$C_{11}*y_{11}$	currency
12	x	Cost of carrier media	C_{12}	per m^3	$y_{12} = (38.65*x) + 0.0033$	$C_{12}*y_{12}$	currency
13	x	Cost of air piping	C_{13}	cost index	$y_{13} = (213.15*x) + 634.56$	$C_{13}*y_{13}$	currency

Table 17: Small range WWTPs with MBBR - Functions for calculations of cost (continued)

Sl. no.	Capacity in mld	Cost component	Unit cost		Co-efficient function for unit cost (y)	Cost for x mld capacity WWTP with MBBR	
		Small range WWTPs with MBBR - Functions for calculations of levelized cost for 25 years of operation					
			Value	***Unit***		***Value***	***Unit***
14	x	Cost of operation and maintenance material costs			$y_{14} = [(0.6042*x) + 4.1953]*10^5$	y_{14}	currency
15	x	Cost of energy requirement	C_{15}	per kwhr	$y_{15} = (82874*x) + 21740$	$C_{15}*y_{15}$	currency
16	x	Cost of operation and maintenance hours	C_{16}	per hr	$y_{16} = (444.94*x) + 3929.9$	$C_{16}*y_{16}$	currency
		Present worth factor considered				9.82	
		Levelized cost for 25 years of operation			$9.82 * [y_{14} + (C_{15}*y_{15}) + (C_{16}*y_{16})]$		currency

The co-efficients for respective unit costs have been calculated based on derived functions for a case of 3 mld capacity WWTP with MBBR technology and costs with unit cost base in India at year 2021 are furnished in Table – 18:

Table 18: Small range WWTPs with MBBR - Validation for calculated costs

Small range WWTPs with MBBR - Validation for calculated total bare construction cost						
Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient function for unit cost (y)**	**Cost for 3 mld capacity WWTP with MBBR**
			Value	***Unit***		***Value***
1	3.0	Cost of total earthwork	₹ 10.38	per ft^3	101734	₹ 1,056,239.91
2	3.0	Cost of total quantity of RCC	₹ 243.72	per ft^3	36489.1	₹ 8,893,285.59
3	3.0	Cost of total quantity of handrails	₹ 600.00	per / ft	452.781	₹ 271,668.60
4	3.0	Cost of houses or buildings	₹ 7,500.00	per ft^2	2300.818	₹ 17,256,135.00
5	3.0	Cost of clarifier mechanisms	₹ 75,00,000.00	per mechanism	2.6139	₹ 19,604,250.00
6	3.0	Cost of blowers	₹ 53,00,895.04	per blower	1.9271	₹ 10,215,354.83
7	3.0	Cost of installation man-hours	₹ 125.00	per hr	498.621	₹ 62,327.63
8	3.0	Cost of crane requirements for installation	₹ 1,000.00	per hr	49.8626	₹ 49,862.60
9	3.0	Cost of pumps	₹ 12,93,750.00	Purchase cost of standard pump (3000 gpm)	2.7332	₹ 3,536,077.50
10	3.0	Cost of diffusers	₹ 1,200.00	per diffuser	87.3923	₹ 104,870.76
11	3.0	Cost of swing arm diffuser headers	₹ 35,000.00	per header	5.4645	₹ 191,257.50
12	3.0	Cost of carrier media	₹ 11,000.00	per m^3	115.9533	₹ 1,275,486.30
13	3.0	Cost of air piping	₹ 750.00	cost index	1274.01	₹ 955,507.50
		Consolidated bare cost				₹ 63,472,323.71

Table 18: Small range WWTPs with MBBR - Validation for calculated costs (continued)

Small range WWTPs with MBBR - Validation for calculated levelized cost of 25 years operation						
Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient function for unit cost (y)**	**Cost for 3 mld capacity WWTP with MBBR**
			Value	***Unit***		***Value***
14	3.0	Cost of operation and maintenance material costs			600790	₹ 600,790.00
15	3.0	Cost of energy requirement	₹ 6.00	per kwhr	270362	₹ 1,622,172.00
16	3.0	Cost of operation and maintenance hours	₹ 250.00	per hr	5264.72	₹ 1,316,180.00
		Present worth factor considered				9.82
		Levelized cost for 25 years of operation			$9.82 * [y_{14} + (C_{15}*y_{15}) + (C_{16}*y_{16})]$	₹ 34,763,504.03

It has been reviewed that variation is around 1.5 % for estimated total bare construction cost and within 0.5 % for levelized cost of 25 years of operation.

The unit cost co-efficient functions for different items of small range WWTPs with SBR technology as displayed in the Figures 19 to 38 are tabulated in Table 19:

Table 19: Small range WWTPs with SBR - Functions for calculations of cost

Small range WWTPs with SBR - Functions for calculations of total bare construction cost							
Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient function for unit cost (y)**	**Cost for x mld capacity WWTP with MBBR**	
			Value	***Unit***		***Value***	***Unit***
1	x	Cost of total earthwork	C_1	per ft^3	y_1 =(23277*x) + 87946	C_1*y_1	currency
2	x	Cost of total quantity of RCC	C_2	per ft^3	y_2 = (9633.8*x) + 39843	C_2*y_2	currency
3	x	Cost of total quantity of handrails	C_3	per / ft	y_3 = (237.24*x) + 1791.2	C_3*y_3	currency
4	x	Cost of houses or buildings	C_4	per ft^2	y_4 = (6.0531*x) + 2441.3	C_4*y_4	currency
5	x	Cost of blowers	C_5	per blower	y_5 = (0.2151*x) + 8.47	C_5*y^5	currency
6	x	Cost of installation man-hours	C_6	per hr	y_6 = (6369.8*x)	C_6*y_6	currency
7	x	Cost of crane requirements for installation	C_7	per hr	y_7 = (289.58*x) - 12545	C_7*y_7	currency
8	x	Cost of pumps	C_8	Purchase cost of standard pump (3000 gpm)	y_8 = 0.58	C_8*y_8	currency
9	x	Cost of diffusers	C_9	per diffuser	y_9 = (2545.8*x) - 110361	C_9*y_9	currency
10	x	Cost of swing arm diffuser headers	C_{10}	per header	y_{10} = (127.41*x) - 5520	C_{10}*y_{10}	currency
11	x	Cost of decanters	C_{11}	per m^3	y_{11} = (706.44*x)	C_{11}*y_{11}	currency
12	x	Cost of air piping	C_{12}	cost index	y_{12} = (472.77*x) + 14348	C_{12}*y_{12}	currency

Table 19: Small range WWTPs with SBR - Functions for calculations of cost (continued)

Small range WWTPs with SBR - Functions for calculations of levelized cost for 25 years of operation

Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient function for unit cost (y)**	**Cost for x mld capacity WWTP with MBBR**	
			Value	***Unit***		***Value***	***Unit***
13	x	Cost of operation and maintenance material costs			$y_{13} = [(1.546*x) - 15.569]*10^5$	y_{13}	currency
14	x	Cost of energy requirement	C_{14}	per kwhr	$y_{14} = (113972*x) + 770413$	$C_{14}*y_{15}$	currency
15	x	Cost of operation and maintenance hours	C_{15}	per hr	$y_{15} = (54.661*x) + 5611.7$	$C_{15}*y_{15}$	currency
		Present worth factor considered				9.82	
		Levelized cost for 25 years of operation			$9.82 * [y_{13} + (C_{14}*y_{14}) + (C_{15}*y_{15})]$		currency

The co-efficients for respective unit costs have been calculated based on derived functions for a case of 3 mld capacity WWTP with SBR technology and costs with unit cost base in India at year 2021 are furnished in Table – 20.

Table 20: Small range WWTPs with SBR - Validation for calculated costs

Small range WWTPs with SBR - Validation for calculated total bare construction cost						
Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient for unit cost (y)**	**Cost for 3 mld capacity WWTP with SBR**
			Value	***Unit***		***Value***
1	3.0	Cost of total earthwork	₹ 10.38	per ft^3	125575	₹ 1,303,765.96
2	3.0	Cost of total quantity of RCC	₹ 243.72	per ft^3	40414.2	₹ 9,849,928.41
3	3.0	Cost of total quantity of handrails	₹ 600.00	per ft	1156.92	₹ 694,152.00
4	3.0	Cost of houses or buildings	₹ 7,500.00	per ft^2	1681.71	₹ 12,612,825.00
5	3.0	Cost of blowers	₹ 53,00,895.04	per blower	3.4307	₹ 18,185,780.60
6	3.0	Cost of installation man-hours	₹ 125.00	per hr	513.459	₹ 64,182.38
7	3.0	Cost of crane requirements for installation	₹ 1,000.00	per hr	51.346	₹ 51,346.00
8	3.0	Cost of pumps	₹ 12,93,750.00	Purchase cost of standard pump (3000 gpm)	0.58	₹ 750,375.00
9	3.0	Cost of diffusers	₹ 1,200.00	per diffuser	440.01	₹ 528,012.00
10	3.0	Cost of swing arm diffuser headers	₹ 35,000.00	per header	22.5929	₹ 790,751.50
11	3.0	Cost of decanters	₹ 2,400.00	per m^3/h	2119.3187	₹ 5,086,364.88
12	3.0	Cost of air piping	₹ 750.00	cost index	3099.763	₹ 2,324,822.25
		Consolidated bare cost				₹ 52,242,305.97

Table 20: Small range WWTPs with SBR - Validation for calculated costs (continued)

Small range WWTPs with SBR - Validation for calculated levelized cost for 25 years operation

Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient for unit cost (y)**	**Cost for 3 mld capacity WWTP with SBR**
			Value	***Unit***		***Value***
13	3.0	Cost of operation and maintenance material costs			775870	₹ 775,870.00
14	3.0	Cost of energy requirement	₹ 6.00	kwhr/year	527388.4647	₹ 3,164,330.79
15	3.0	Cost of operation and maintenance hours	₹ 250.00	per hr	2475.15	₹ 618,787.50
		Present worth factor considered				9.82
		Levelized cost for 25 years of operation			9.82 * [y_{13} + (C_{14}*y_{14}) + (C_{15}*y_{15})]	₹ 44,781,025.38

It has been scrutinized and noted that variation is within 2 % for estimated total bare construction cost and within 1 % for estimated levelized cost of 25 years of operation.

The unit cost co-efficient curves of different items for medium range WWTPs with MBR, MBBR & SBR technologies are shown in Figures 39 through 58 hereinafter.

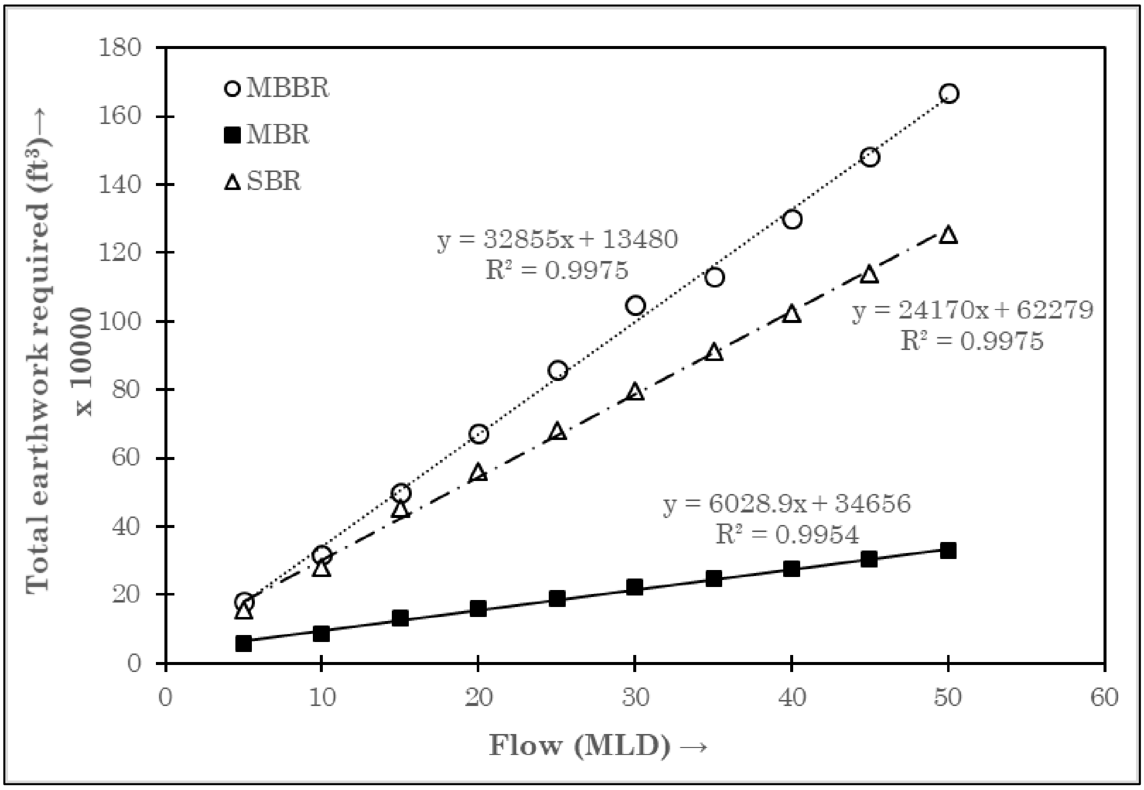


Figure 39: Excavation curve for medium range WWTPs with MBR, MBBR and SBR

Figure 39 illustrates the co-efficient of earthwork excavation (ft³) needed for medium-scale WWTPs using MBR, MBBR, and SBR technologies across varying flow rates. The observations closely resemble those in Figure 19. With a high R² value (>0.99), indicating a robust fit of the data to the regression line, this curve can accurately forecast the total cost of earthwork for WWTPs over a flow range from 5 MLD to 50 MLD, simplifying the cost estimation process.

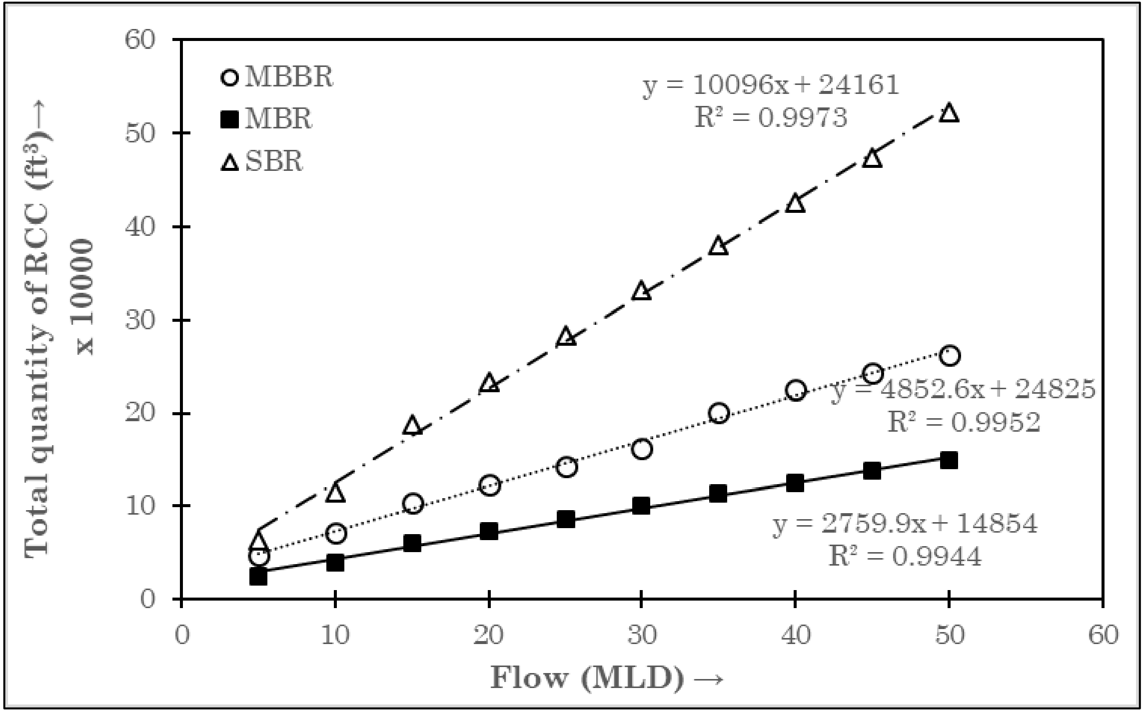


Figure 40: Concrete curve for medium range WWTPs with MBR, MBBR and SBR

In Figure 40, it is observed that as the flow increases, the total co-efficient of reinforced cement concrete (RCC) work (ft³) also increases, which aligns with expectations. Within this flow range, the total co-efficient of RCC work tends to be higher for SBR technology compared to MBBR technology. MBR technologies generally require less total co-efficient of RCC work due to their space-saving design.

The total costs related to RCC can be calculated by multiplying the total co-efficient of RCC by the unit rate price specific to the RCC. The total co-efficient of RCC data was analysed using linear regression. For all technologies, the R² values exceed 0.99, indicating a strong fit of the data to the regression line. Therefore, this curve can be used to predict the total cost of RCC for WWTPs across a flow range from 5 MLD to 50 MLD, eliminating the need for detailed cost estimation.

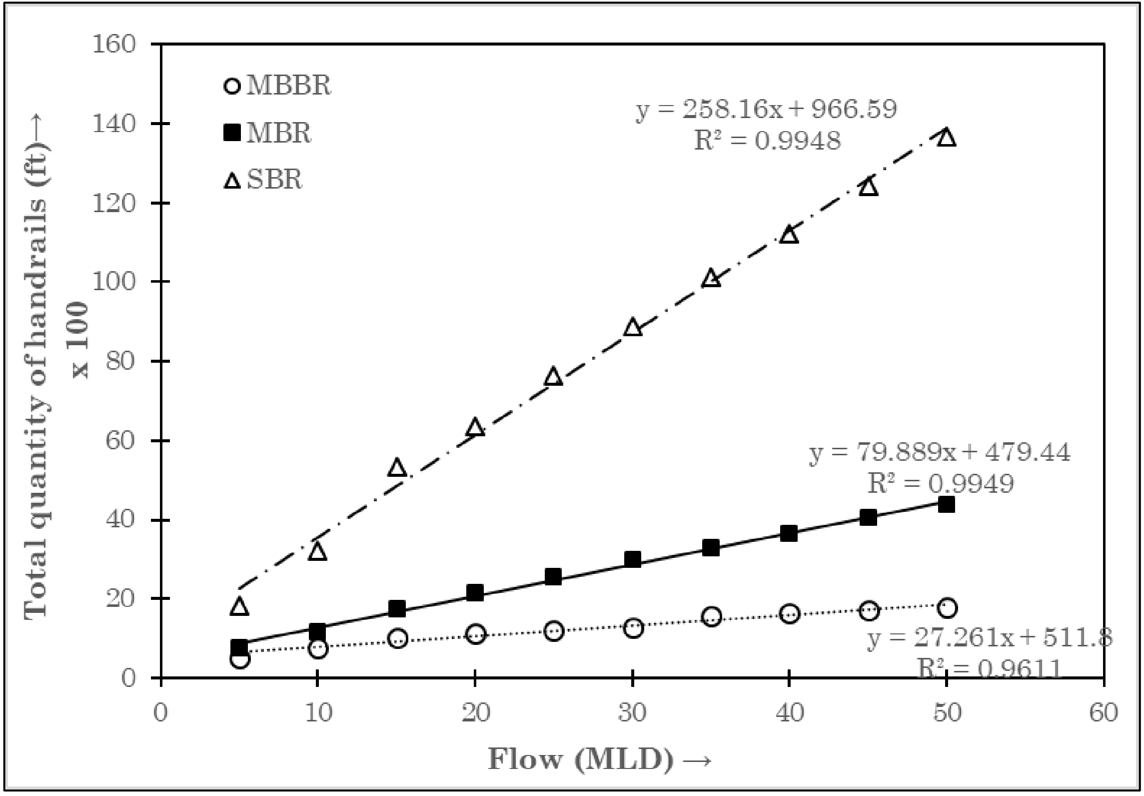


Figure 41: Hand-rail curve for medium range WWTPs with MBR, MBBR and SBR

Figure 41 depicts the total co-efficient of handrails (ft) required for medium-scale WWTPs using MBR, MBBR, and SBR technologies across different flow rates. The observations closely mirror those seen in Figure 21. With a high R^2 value (>0.96), indicating a strong fit of the data to the regression line, this curve can effectively predict the total cost of handrails for WWTPs over a flow range from 5 MLD to 50 MLD, streamlining the cost estimation process.

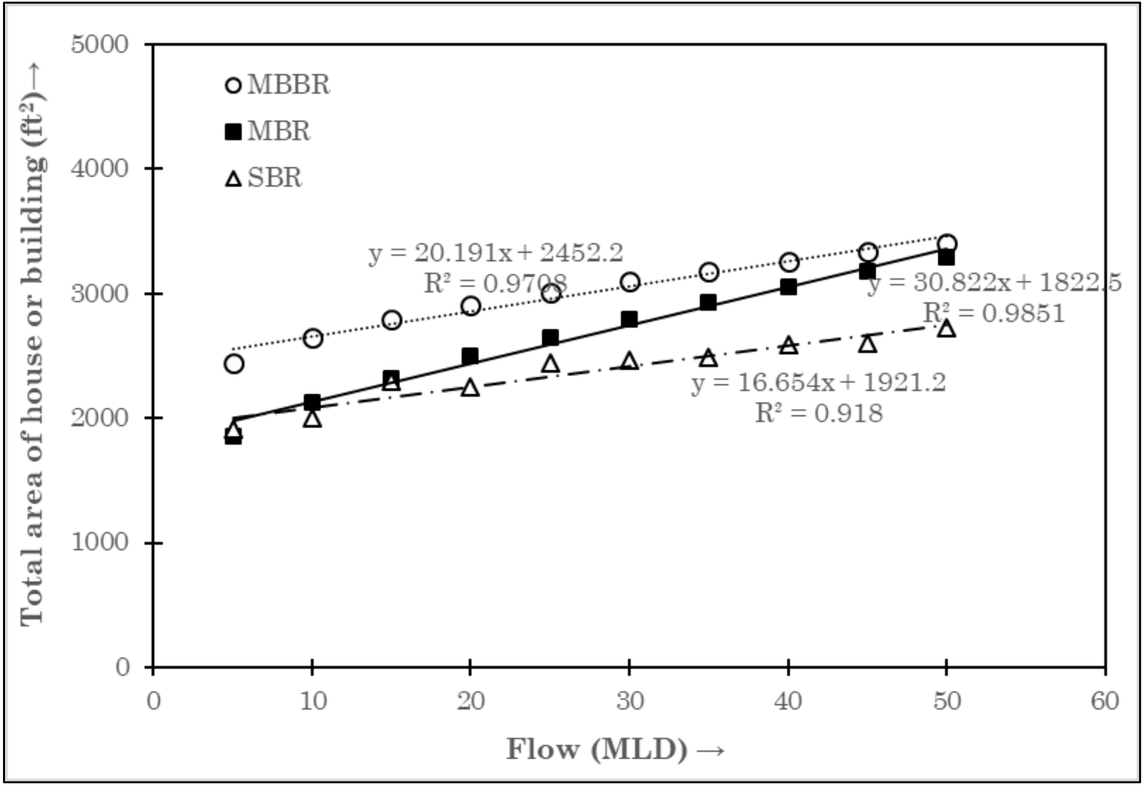


Figure 42: House curve for medium range WWTPs with MBR, MBBR and SBR

Figure 42 illustrates the total co-efficient required for housing or buildings (ft²) for medium-scale WWTPs using MBR, MBBR, and SBR technologies across various flow rates. The figure clearly shows that as the flow rate increases, the total co-efficient needed for housing or buildings (ft²) also increases. Within this flow range, MBBR technology generally necessitates a larger total co-efficient for housing or buildings (ft²), followed by MBR technology, and then SBR technology. The remaining observations closely resemble those seen in Figure 22. With a high R² value (>0.96), indicating a strong fit of the data to the regression line, this curve can reliably predict the total cost required for housing or buildings for WWTPs over a flow range from 5 MLD to 50 MLD, thereby simplifying the cost estimation process.

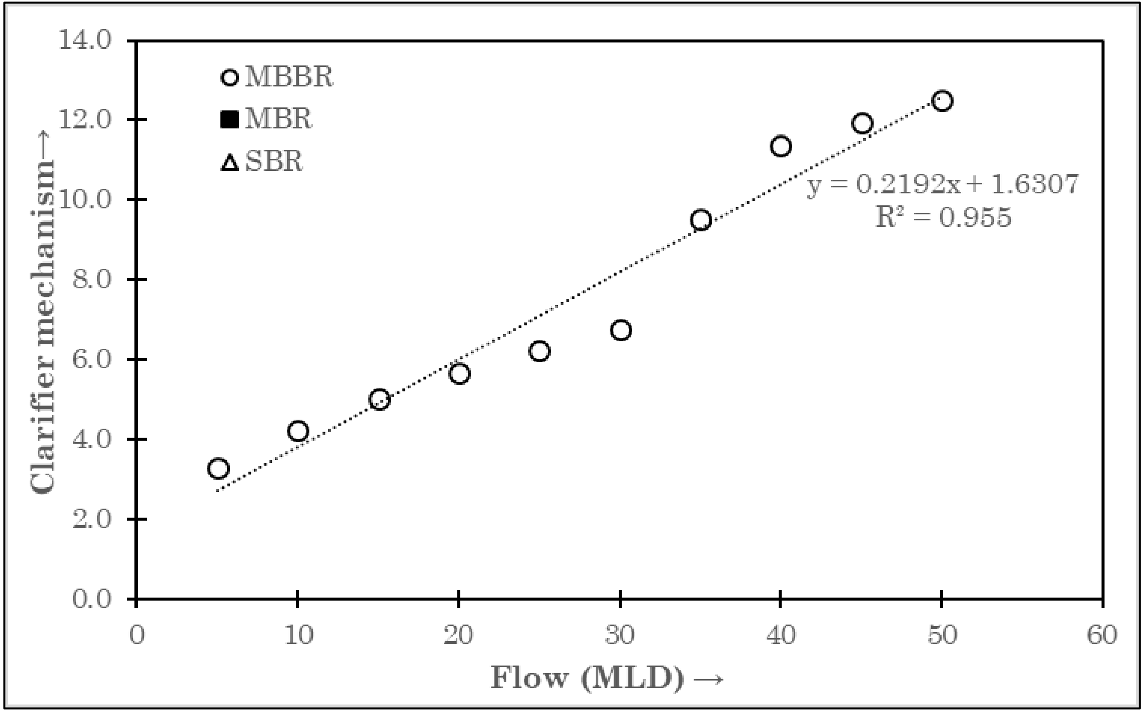


Figure 43: Clarifier mechanism for medium-range WWTPs with MBBR

Figure 43 shows the total co-efficient of clarifier mechanisms needed for medium-scale WWTPs using MBBR technology. For MBR and SBR technologies, clarifier mechanisms are not necessary and therefore curve is shown only for MBBR technology. The observations are very similar to those in Figure 23. With a high R² value (>0.95), indicating a strong fit of the data to the regression line, this curve can accurately predict the total cost of clarifier mechanisms for WWTPs with flow rates ranging from 5 MLD to 50 MLD, making cost estimation easier.

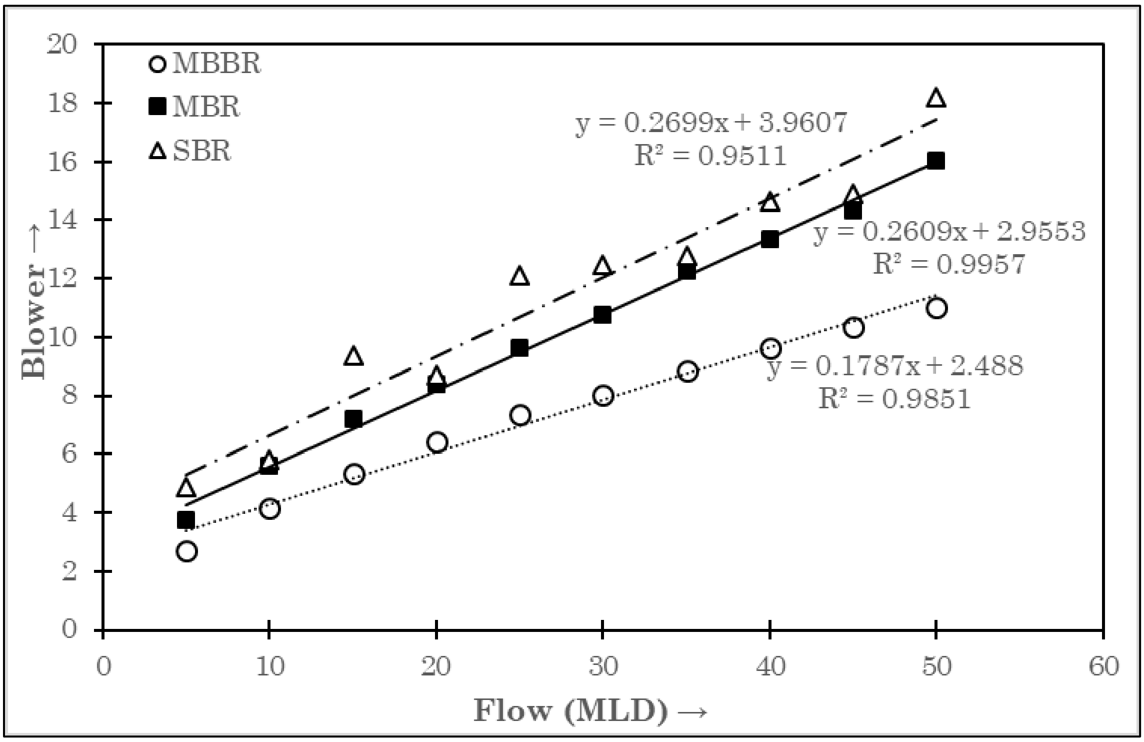


Figure 44: Blower curve for medium-range WWTPs with MBR, MBBR and SBR

Figure 44 displays the total co-efficient of blowers needed for medium-scale WWTPs utilizing MBR, MBBR, and SBR technologies across various flow rates. The observations are very similar to those in Figure 24. With a high R² value (>0.95), indicating a strong fit of the data to the regression line, this curve can accurately predict the total cost associated with blowers for WWTPs with flow rates ranging from 5 MLD to 50 MLD, making the cost estimation process simpler.

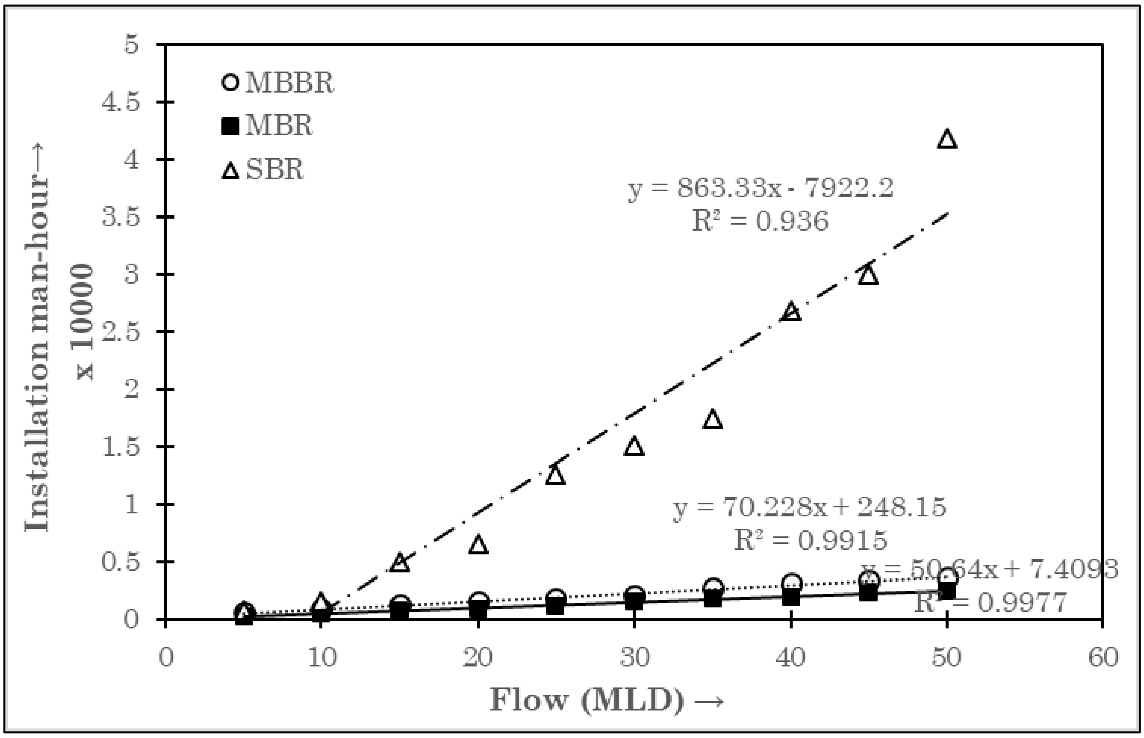


Figure 45: Installation man-hour curve for medium -range WWTPs with MBR, MBBR and SBR

Figure 45 shows the installation man-hours co-efficient required for medium-scale WWTPs using MBR, MBBR, and SBR technologies at different flow rates. The figure clearly indicates that as the flow rate increases, the total man-hours required also rise. Within this flow range, SBR technology generally requires more man-hours than the other two technologies. The remaining observations closely resemble those in Figure 25. With a high R² value (>0.93), indicating a strong fit of the data to the regression line, this curve can reliably predict the cost of man-hours required for WWTPs with flow rates from 5 MLD to 50 MLD, thus simplifying the cost estimation process.

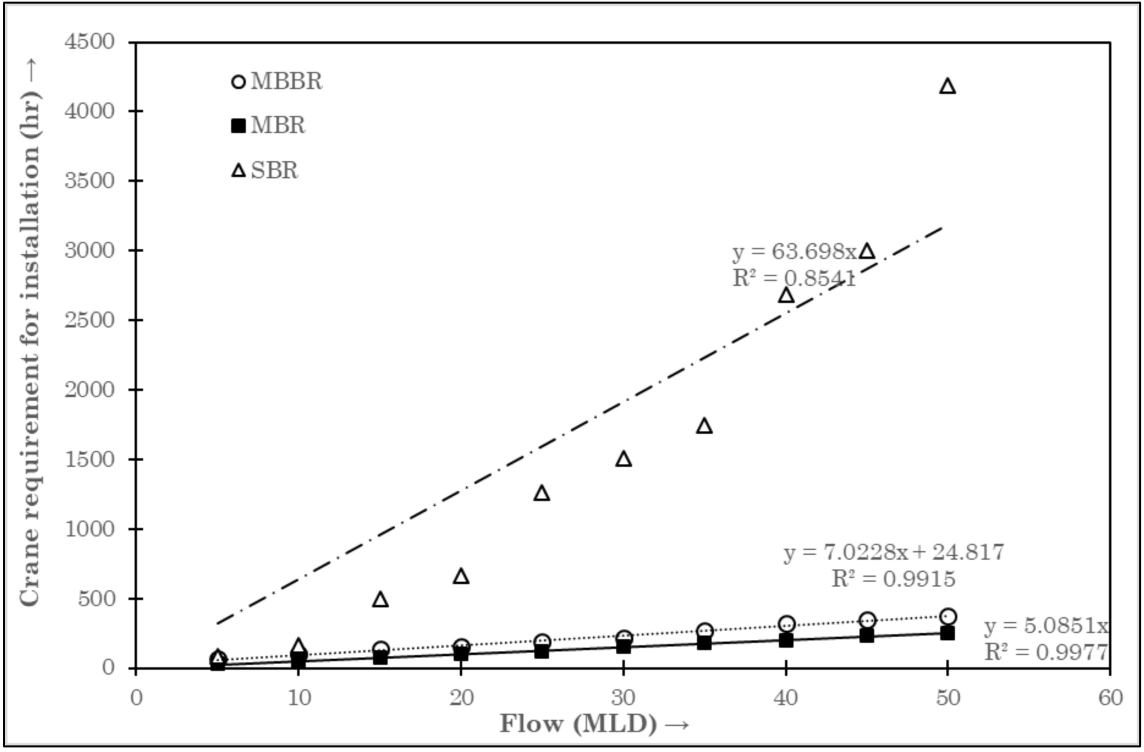


Figure 46: Crane curve for medium-range WWTPs with MBR, MBBR and SBR

Figure 46 illustrates the crane co-efficient for medium-scale WWTPs using MBR, MBBR, and SBR technologies across various flow rates. The figure clearly shows that as the flow rate increases, the total crane co-efficient also rise. Within this flow range, SBR technology generally requires more crane co-efficient than the other two technologies. The remaining observations closely resemble those in Figure 26. The data were analyzed using linear regression, achieving an R^2 value exceeding 0.99 for MBR and MBBR technologies, indicating an excellent fit to the regression line. However, for SBR technology, the R^2 value is nearly 0.85, suggesting a maximum possible error of 10-15% when predicting the total cost of crane requirements. Nonetheless, the R^2 values are generally good for all curves. Therefore, these curves can be used to estimate the cost of crane requirements for WWTPs using MBR, MBBR, and SBR technologies across a flow range from 5 MLD to 50 MLD, simplifying the cost estimation process.

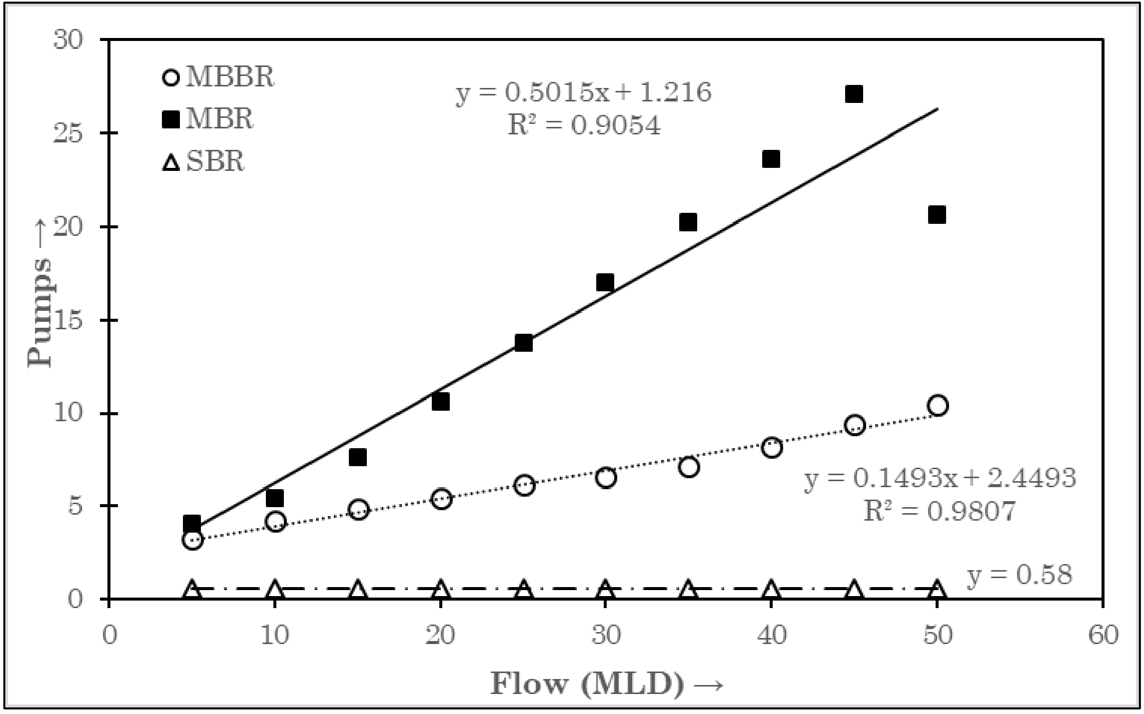


Figure 47: Pumps curve for medium-range WWTPs with MBR, MBBR and SBR

Figure 47 shows the co-efficient of standard pumps (3000 gpm) required for medium-scale WWTPs using MBR, MBBR, and SBR technologies across various flow rates. The observations closely resemble those in Figure 27. With a high R² value (>0.9), indicating a strong fit of the data to the regression line, this curve can accurately predict the total cost associated with pumps for WWTPs with flow rates ranging from 5 MLD to 50 MLD, simplifying the cost estimation process.

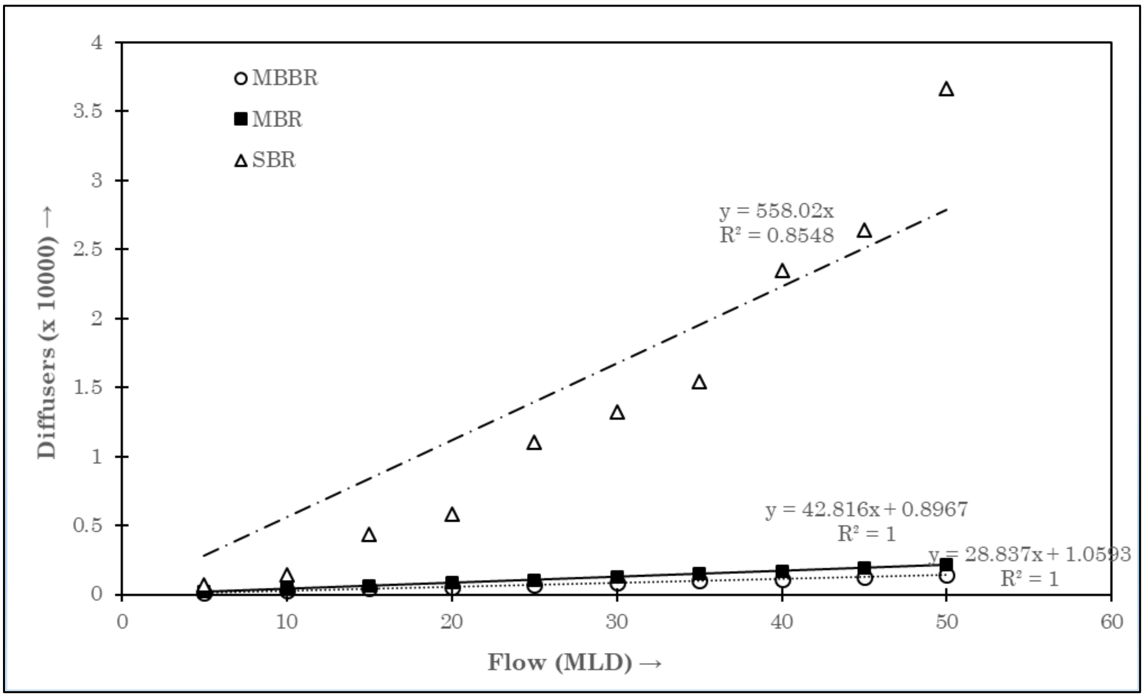


Figure 48: Diffusers curve for medium range WWTPs with MBR, MBBR and SBR

Figure 48 illustrates the co-efficient of diffusers required for medium-scale WWTPs using MBR, MBBR, and SBR technologies across various flow rates. The figure clearly shows that as the flow rate increases, the co-efficient of diffusers required also rises. Within this flow range, SBR technology generally requires more diffusers than the other two technologies. The remaining observations closely resemble those in Figure 28. The data were analyzed using linear regression, achieving an R² value exceeding 0.99 for MBR and MBBR technologies, indicating an excellent fit to the regression line. However, for SBR technology, the R² value is nearly 0.85, suggesting a maximum possible error of 10-15% when predicting the total cost for diffusers. Nonetheless, the R² values are generally good for all curves. Therefore, these curves can be used to estimate the cost of diffuser requirements for WWTPs using MBR, MBBR, and SBR technologies across a flow range from 5 MLD to 50 MLD, simplifying the cost estimation process.

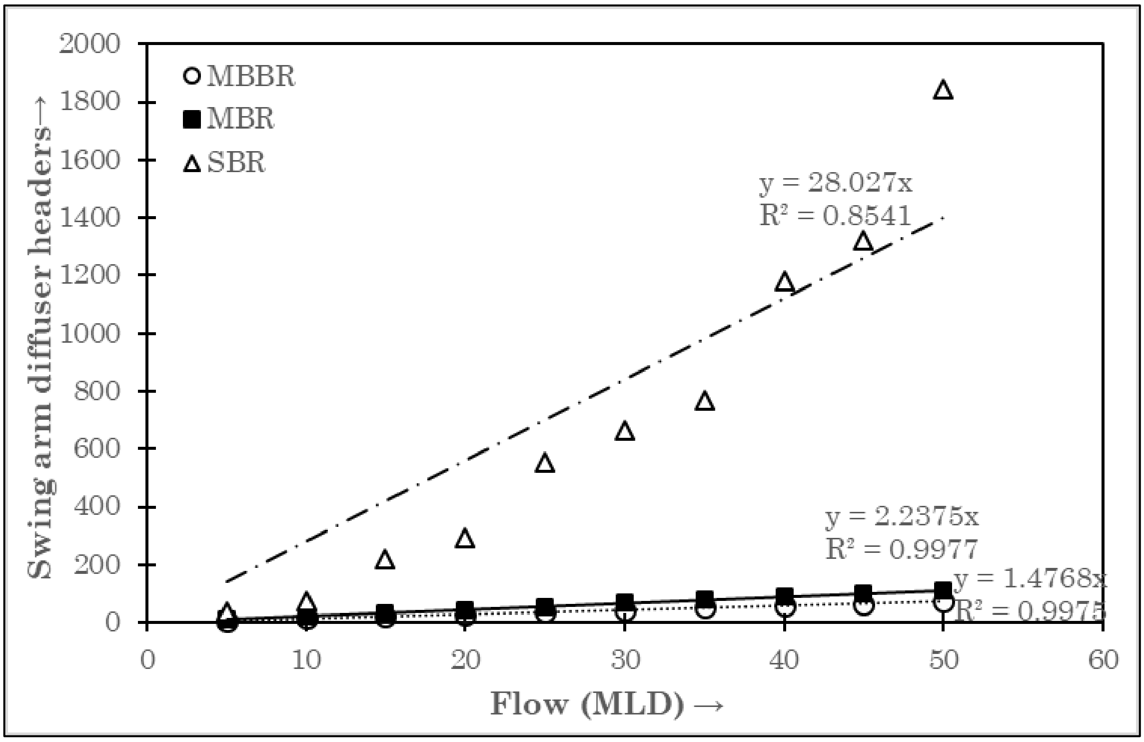


Figure 49: Swing arm diffuser header curve for medium range WWTPs with MBR, MBBR and SBR

Figure 49 illustrates the co-efficient of swing arm diffuser headers required for medium-scale WWTPs using MBR, MBBR, and SBR technologies across various flow rates. The figure clearly shows that as the flow rate increases, the co-efficient of swing arm diffuser headers also rises. Within this flow range, SBR technology generally requires more swing arm diffuser headers than the other two technologies. The remaining observations closely resemble those in Figure 29. The data were analyzed using linear regression, achieving an R^2 value exceeding 0.997 for MBR and MBBR technologies, indicating an excellent fit to the regression line. However, for SBR technology, the R^2 value is nearly 0.85, suggesting a maximum possible error of 10-15% when predicting the total cost of swing arm diffuser headers. Nonetheless, the R^2 values are generally good for all curves. Therefore, these curves can be used to estimate the cost of swing arm diffuser header requirements for WWTPs using MBR, MBBR, and SBR technologies across a flow range from 5 MLD to 50 MLD, simplifying the cost estimation process.

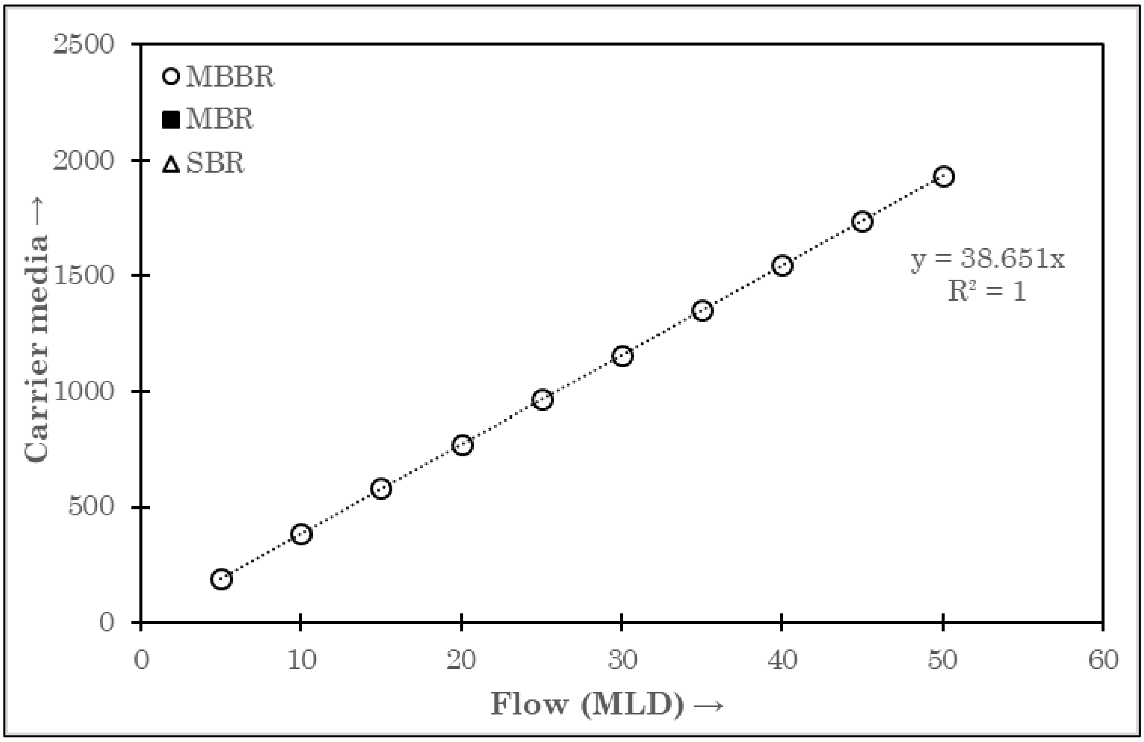


Figure 50: Carrier media curve for medium range WWTPs with MBBR

Figure 50 shows the co-efficient of carrier media (m^3) needed for medium-scale WWTPs using MBBR technology. MBR and SBR technologies do not require carrier media and therefore curve is shown only for MBBR technology. The observations are very similar to those in Figure 30. With an R^2 value of nearly 1, indicating a strong fit of the data to the regression line, this curve can accurately predict the total cost of carrier media for WWTPs with flow rates ranging from 5 MLD to 50 MLD, simplifying cost estimation.

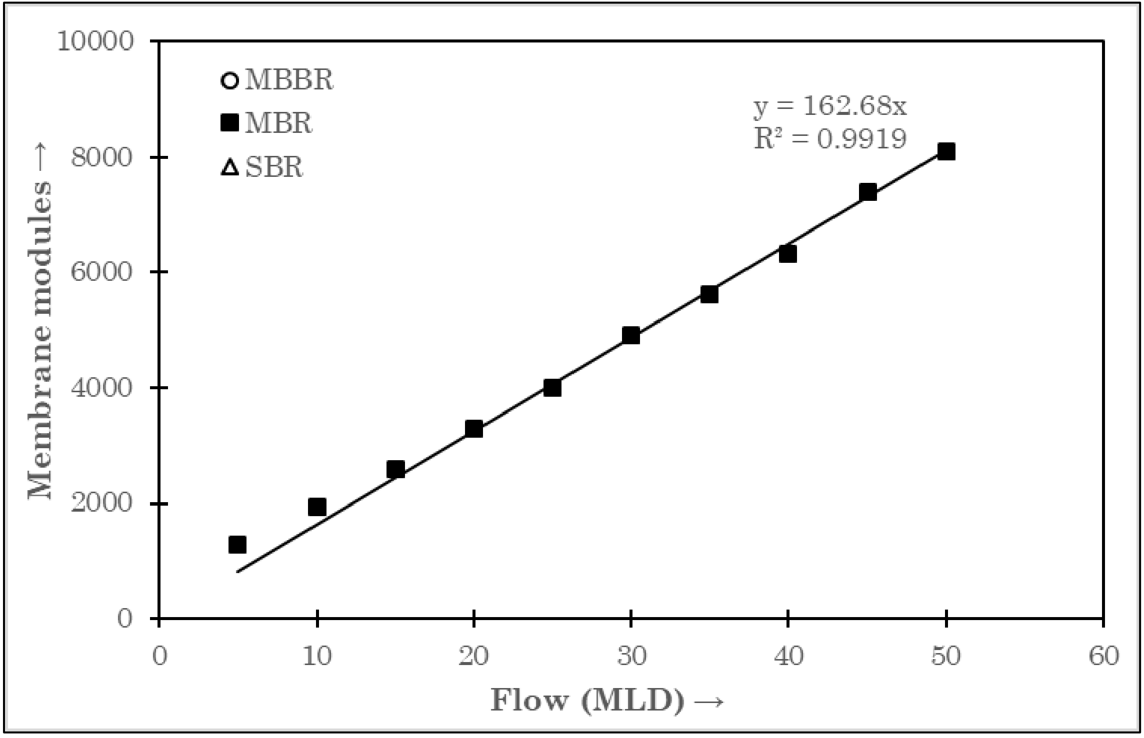


Figure 51: Membrane modules curve for medium range WWTPs with MBR

Figure 51 illustrates the co-efficient of membrane modules required for medium-scale WWTPs using MBR technology. The observations closely resemble those in Figure 31. MBBR and SBR technologies do not require membrane modules and therefore curve is shown only for MBR technology. With an R² value greater than 0.99, indicating a strong fit of the data to the regression line, this curve can accurately forecast the total cost of membrane modules for WWTPs with flow rates ranging from 5 MLD to 50 MLD, simplifying the cost estimation process.

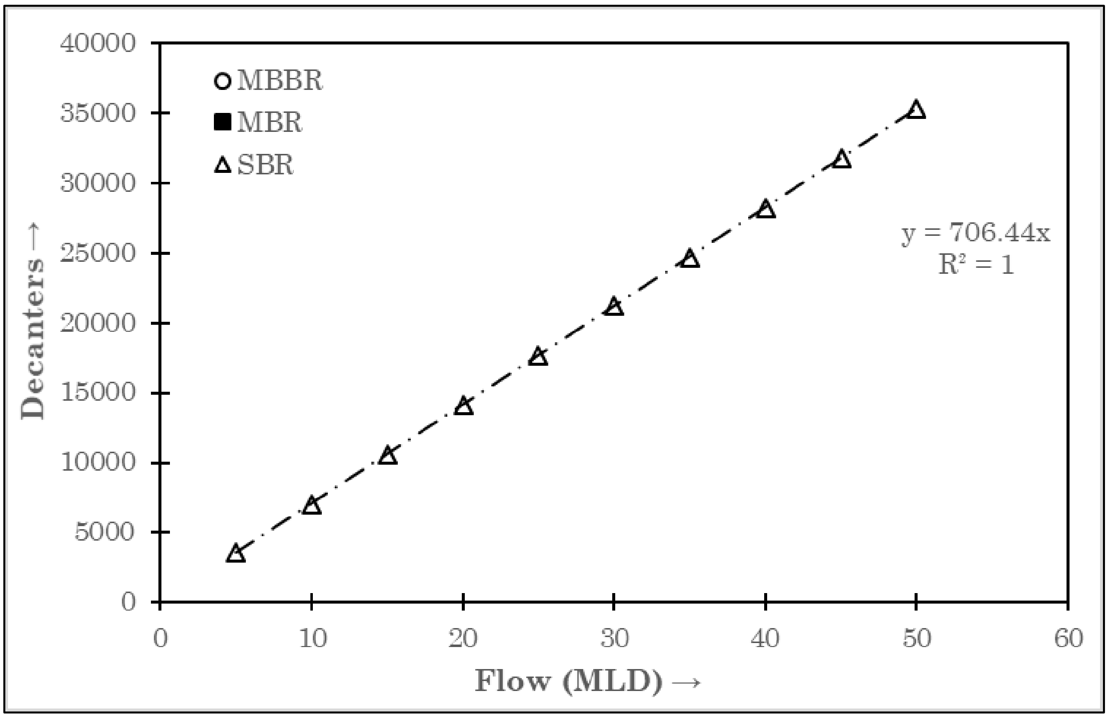


Figure 52: Decanters curve for medium range WWTPs with SBR

Figure 52 depicts the co-efficient of decanters (m^3/hr) required for medium-scale WWTPs using SBR technology. The observations closely mirror those in Figure 32. MBR and MBBR technologies do not require decanters and therefore curve is shown only for SBR technology. With an R² value of 1, indicating a perfect fit of the data to the regression line, this curve can accurately predict the total cost of decanters for WWTPs with flow rates ranging from 5 MLD to 50 MLD, simplifying the cost estimation process.

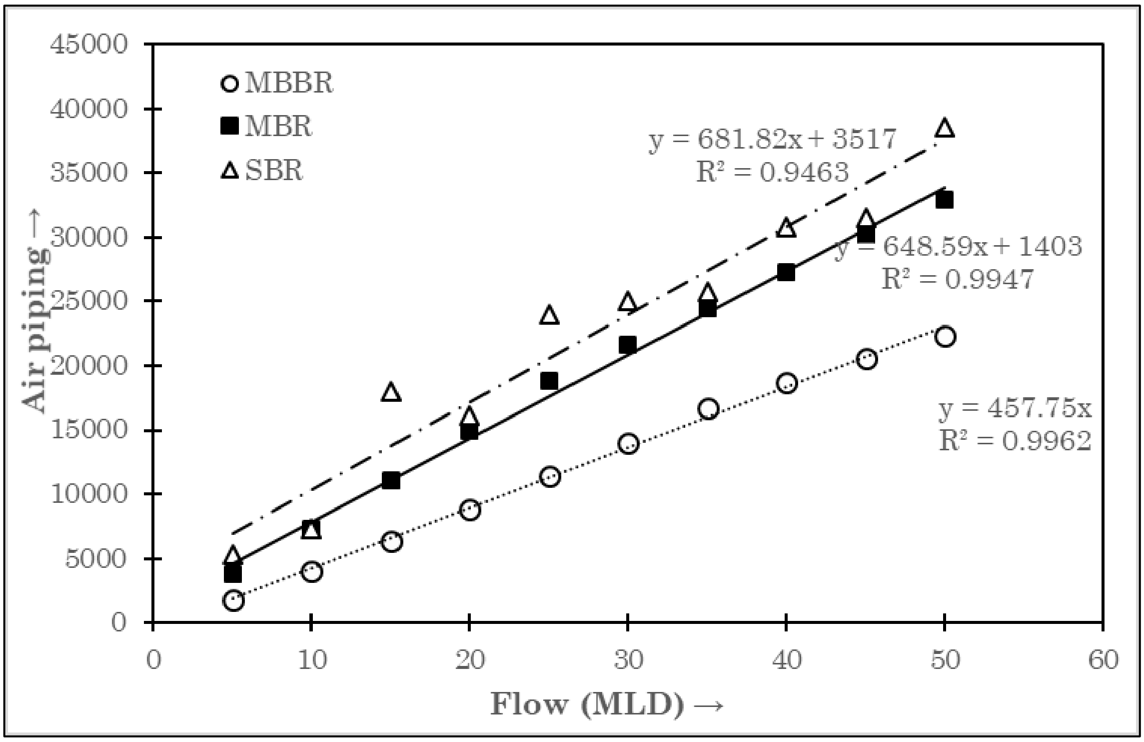


Figure 53: Air pipe curve for medium range WWTPs with MBR, MBBR and SBR

Figure 53 illustrates the co-efficient of air piping required for medium-scale WWTPs using MBR, MBBR, and SBR technologies across various flow rates. The observations closely resemble those in Figure 33. With a high R² value (>0.94), indicating a strong fit of the data to the regression line, this curve can reliably estimate the total cost associated with air piping for WWTPs with flow rates ranging from 5 MLD to 50 MLD, thereby simplifying the cost estimation process.

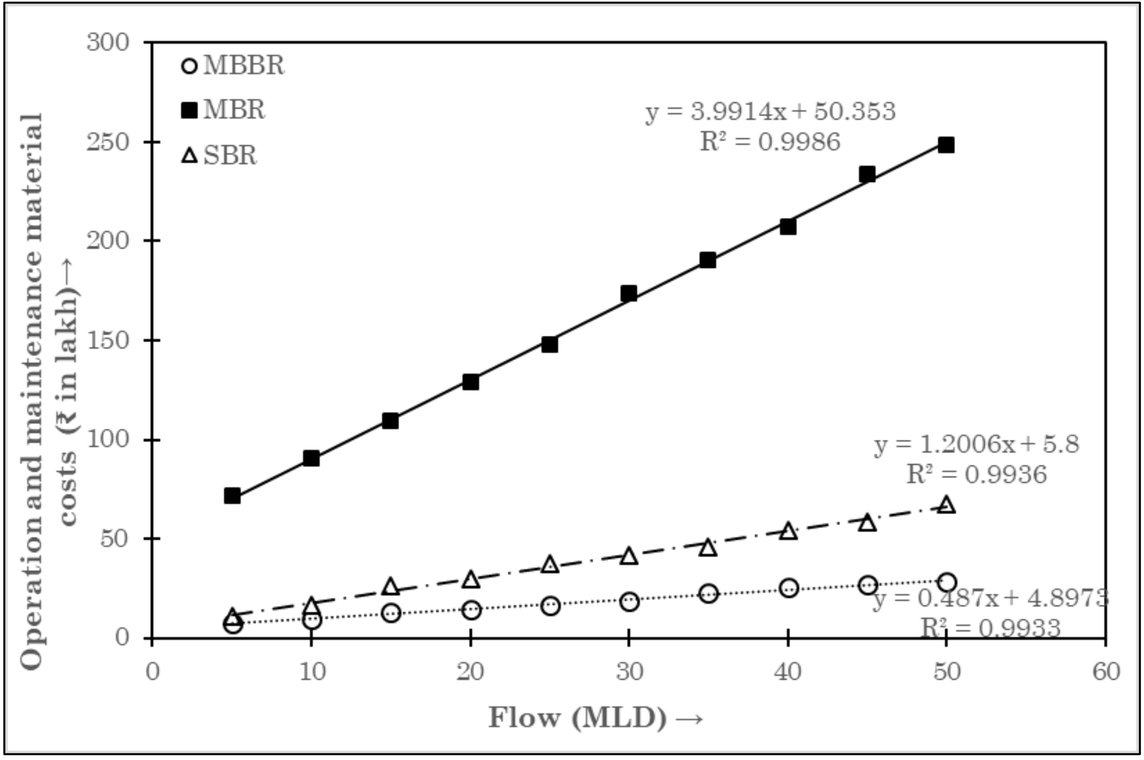


Figure 54: O&M material cost curve for medium range WWTPs with MBR, MBBR and SBR

Figure 54 depicts the co-efficient of O & M materials for medium-scale WWTPs using MBR, MBBR, and SBR technologies across various flow rates. The observations closely mirror those in Figure 34. With a high R² value (>0.99), indicating a strong fit of the data to the regression line, this curve can accurately estimate the total cost associated with O & M materials for WWTPs with flow rates ranging from 5 MLD to 50 MLD, simplifying the cost estimation process.

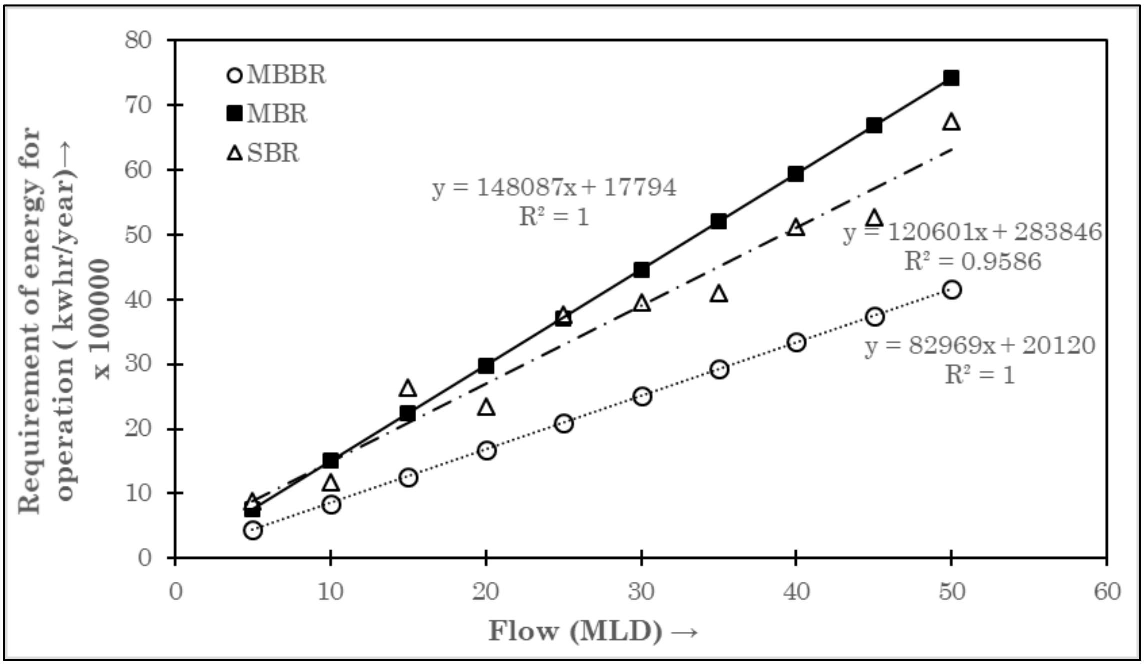


Figure 55: Energy curve for medium range WWTPs with MBR, MBBR and SBR

Figure 55 illustrates the energy co-efficient for medium-scale WWTPs using MBR, MBBR, and SBR technologies. A notable difference from Figure 35 is that within this flow range, MBR technology generally requires the highest energy, followed by SBR technology, and then MBBR technology. The remaining observations closely resemble those in Figure 35. The data underwent linear regression analysis, resulting in an R² value exceeding 0.95 for all cases, indicating an excellent fit to the regression line. Consequently, this curve can reliably estimate the energy costs for WWTPs utilizing MBR, MBBR, and SBR technologies over a flow range of 5 MLD to 50 MLD, simplifying the cost estimation process.

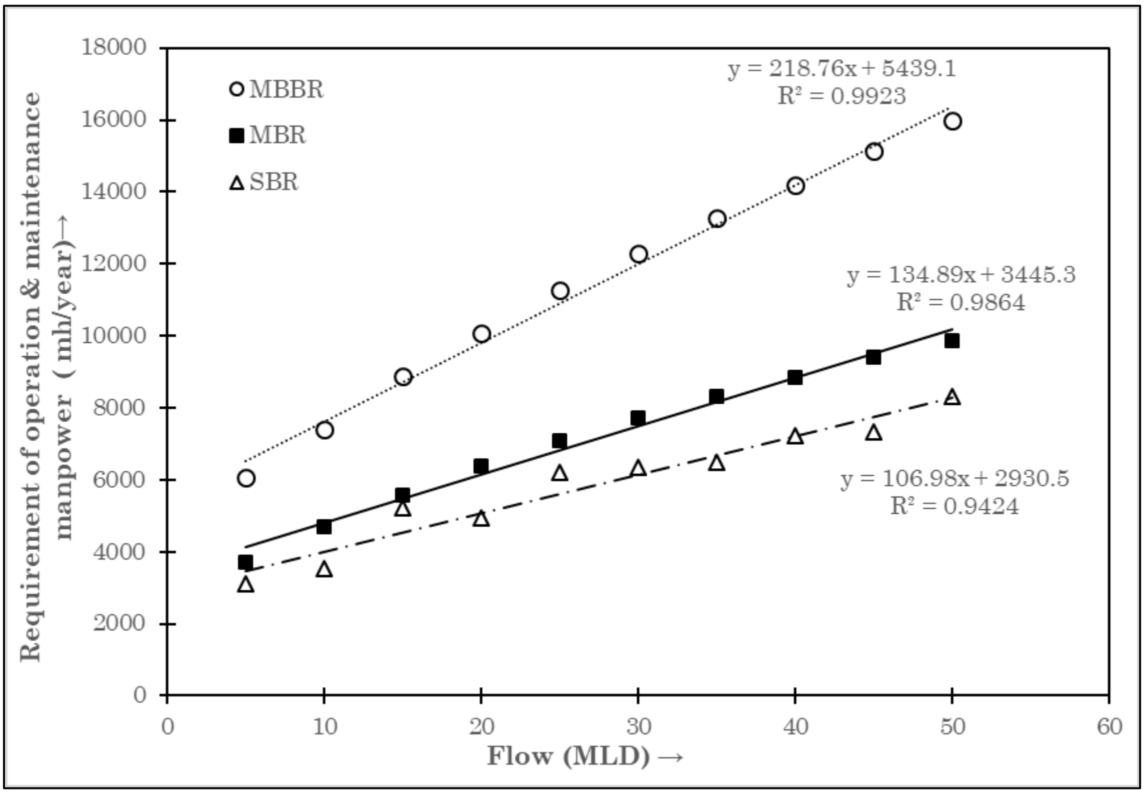


Figure 56: O&M man-hour curve for medium range WWTPs with MBR, MBBR and SBR

Figure 56 depicts the co-efficient of O & M man-hours required for medium-scale WWTPs using MBR, MBBR, and SBR technologies across various flow rates. The observations closely mirror those in Figure 36. With a high R² value (>0.94), indicating a strong fit of the data to the regression line, this curve can accurately estimate the total cost associated with O & M man-hours for WWTPs with flow rates ranging from 5 MLD to 50 MLD, simplifying the cost estimation process.

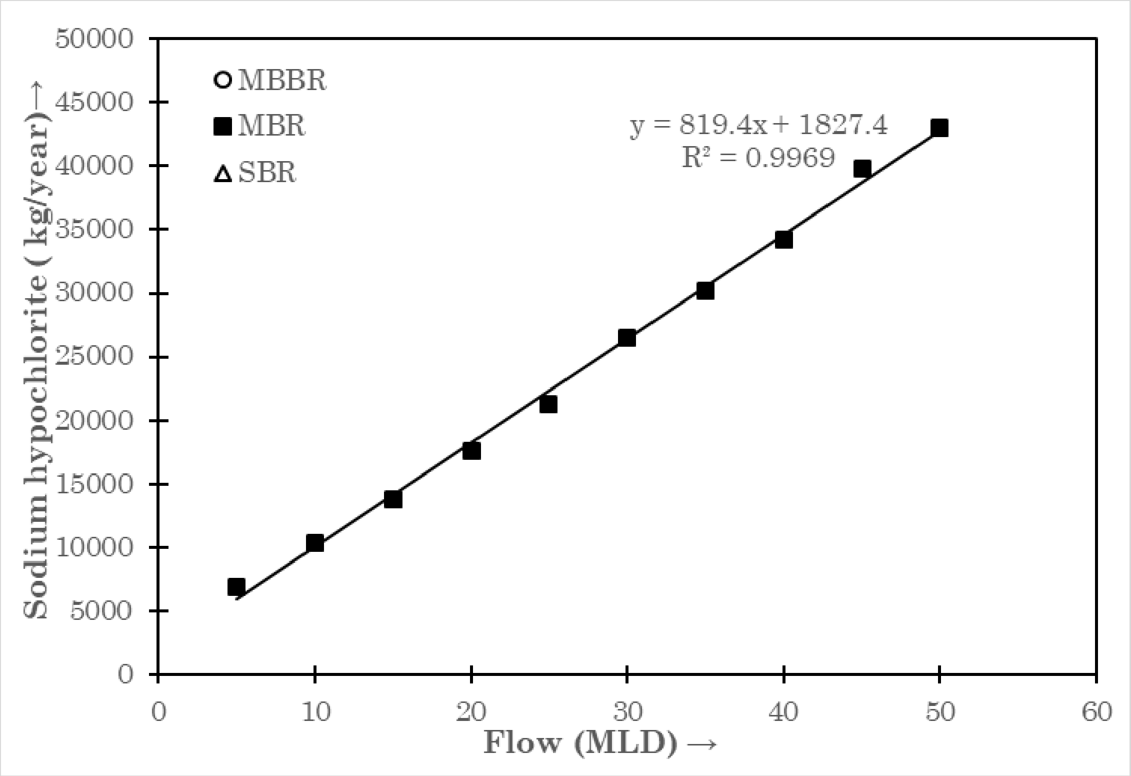


Figure 57: Sodium hypochlorite curve for medium range WWTPs with MBR

Figure 57 illustrates the co-efficient of sodium hypochlorite required for medium-scale WWTPs using MBR technology. SBR and MBBR technologies do not require sodium hypochlorite and therefore curve is shown only for MBR technology. The observations closely resemble those in Figure 37. With an R^2 value of 0.9969, indicating an excellent fit of the data to the regression line, this curve can accurately estimate the total cost of sodium hypochlorite for WWTPs with flow rates ranging from 5 MLD to 50 MLD, simplifying the cost estimation process.

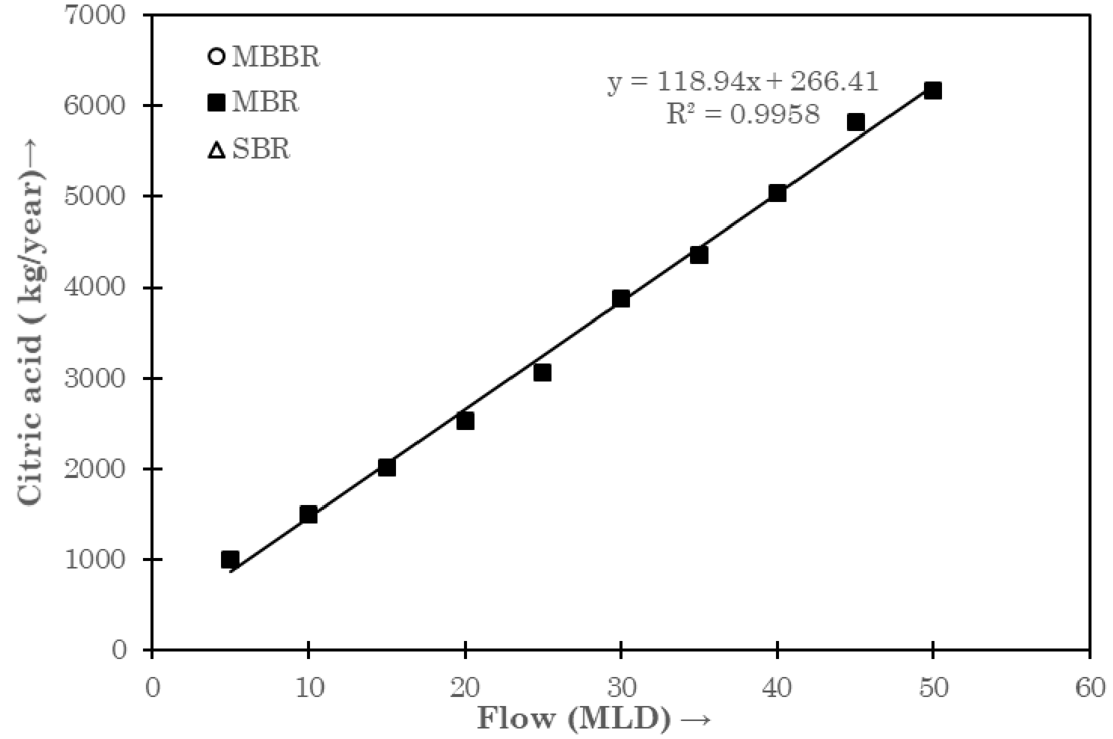


Figure 58: Acid curve for medium range WWTPs with MBR

Figure 58 shows the co-efficient of citric acid needed for medium-scale WWTPs using MBR technology. SBR and MBBR technologies do not require citric acid and therefore curve is shown only for MBR technology. The observations closely align with those in Figure 38. With an R^2 value greater than 0.99, indicating a strong fit of the data to the regression line, this curve can accurately predict the total cost of citric acid for WWTPs with flow rates ranging from 5 MLD to 50 MLD, simplifying the cost estimation process.

The unit cost co-efficient functions for different items of medium range WWTPs with MBR technology as displayed in the Figures 39 to 58 are tabulated in Table 21:

Table 21: Medium range WWTPs with MBR - Functions for calculations of cost

Medium range WWTPs with MBR - Functions for calculations of total bare construction cost

Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient function for unit cost (y)**	**Cost for x mld capacity WWTP with MBR**	
			Value	***Unit***		***Value***	***Unit***
1	x	Cost of total earthwork	C_1	per f^{t3}	$y_1 = (6028.9*x) + 34656$	C_1*y_1	currency
2	x	Cost of total quantity of RCC	C_2	per ft^3	$y_2 = (2759.9*x) + 14854$	C_2*y_2	currency
3	x	Cost of total quantity of handrails	C_3	per ft	$y_3 = (79.889*x) + 479.44$	C_3*y_3	currency
4	x	Cost of houses or buildings	C_4	per ft^2	$y_4 = (30.822*x) + 1822.5$	C_4*y_4	currency
5	x	Cost of blowers	C_5	per blower	$y_5 = (0.2609*x) + 2.9553$	C_6*y_6	currency
6	x	Cost of installation man-hours	C_6	per hr	$y_6 = (50.64*x) + 7.4093$	C_7*y_7	currency
7	x	Cost of crane requirements for installation	C_7	per hr	$y_7 = (5.0851*x)$	C_8*y_8	currency
8	x	Cost of pumps	C_8	Purchase cost of standard pump (3000 gpm)	$y_8 = (0.5015*x) + 1.216$	C_9*y_9	currency
9	x	Cost of diffusers	C_9	per diffuser	$y_9 = (42.816*x) + 0.8967$	$C_{10}*y_{10}$	currency
10	x	Cost of swing arm diffuser headers	C_{10}	per header	$y_{10} = (2.2375*x)$	$C_{11}*y_{11}$	currency
11	x	Cost of membrane modules	C_{11}	per module	$y_{11} = (162.68*x)$	$C_{12}*y_{12}$	currency
12	x	Cost of air piping	C_{12}	cost index	$y_{12} = (648.59*x) + 1403$	$C_{13}*y_{13}$	currency

Table 21: Medium range WWTPs with MBR - Functions for calculations of cost (continued)

Medium range WWTPs with MBR - Functions for calculations of levelized cost for 25 years of operation of small range WWTP with MBR							
Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient function for unit cost (y)**	**Cost for x mld capacity WWTP with MBR**	
			Value	***Unit***		***Value***	***Unit***
13	x	Cost of operation and maintenance material costs			$y_{13} = [(3.9914*x) + 50.353]*10^5$	y_{13}	currency
14	x	Cost of energy requirement	C_{15}	per kwhr	$y_{14} = (148087*x) + 17794$	$C_{14}*y_{14}$	currency
15	x	Cost of operation and maintenance hours	C_{16}	per hr	$y_{15} = (134.89*x) + 3445.3$	$C_{15}*y_{15}$	currency
16	x	Cost of chemical for maintenance - sodium hypochlorite	C_{15}	per kg of solution	$y_{16} = (819.4*x) + 1827.4$	$C_{16}*y_{16}$	currency
17	x	Cost of chemical for maintenance - citric acid	C_{16}	per kg of solution	$y_{17} = (118.94*x) + 266.41$	$C_{17}*y_{17}$	currency
		Present worth factor considered				9.82	
		Levelized cost for 25 years of operation			$9.82 * [y_{13} + (C_{14}*y_{14}) + (C_{15}*y_{15}) + (C_{16}*y_{16}) + (C_{17}*y_{17})]$		currency

The co-efficients for respective unit costs have been calculated based on derived functions for a case of 30 mld capacity WWTP with MBR technology and costs with unit cost base in India at year 2021 are furnished in Table – 22:

Table 22: Medium range WWTPs with MBR - Validation for calculated costs

Medium range WWTPs with MBR - Validation for calculated total bare construction cost						
Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient function for unit cost (y)**	**Cost for 30.0 mld capacity WWTP with MBR**
			Value	***Unit***		***Value***
1	30.0	Cost of total earthwork	₹ 10.38	per ft^3	215523	₹ 2,237,639.27
2	30.0	Cost of total quantity of RCC	₹ 243.72	per ft^3	97651	₹ 23,799,935.63
3	30.0	Cost of total quantity of handrails	₹ 600.00	per ft	2876.11	₹ 1,725,666.00
4	30.0	Cost of houses or buildings	₹ 7,500.00	per ft^2	2747.16	₹ 20,603,700.00
5	30.0	Cost of blowers	₹ 53,00,895.04	per blower	10.7823	₹ 57,155,840.55
6	30.0	Cost of installation man-hours	₹ 125.00	per hr	1526.6093	₹ 190,826.16
7	30.0	Cost of crane requirements for installation	₹ 1,000.00	per hr	152.553	₹ 152,553.00
8	30.0	Cost of pumps	₹ 12,93,750.00	Purchase cost of standard pump (3000 gpm)	16.261	₹ 21,037,668.75
9	30.0	Cost of diffusers	₹ 1,200.00	per diffuser	1285.3767	₹ 1,542,452.04
10	30.0	Cost of swing arm diffuser headers	₹ 35,000.00	per header	67.125	₹ 2,349,375.00
11	30.0	Cost of membrane modules	₹ 1,63,506.94	per module	4880.4	₹ 797,979,291.67
12	30.0	Cost of air piping	₹ 750.00	cost index	20860.7	₹ 15,645,525.00
		Consolidated bare cost				₹ 944,420,473.07

Table 22: Medium range WWTPs with MBR - Validation for calculated costs (continued)

Medium range WWTPs with MBR - Validation for calculated levelized cost of 25 years operation						
Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient function for unit cost (y)**	**Cost for 30.0 mld capacity WWTP with MBR**
			Value	***Unit***		***Value***
13	30.0	Cost of operation and maintenance material costs			17009500	₹ 17,009,500.00
14	30.0	Cost of energy requirement	₹ 6.00	per kwhr	4460404	₹ 26,762,424.00
15	30.0	Cost of operation and maintenance hours	₹ 250.00	per hr	7492	₹ 1,873,000.00
16	30.0	Cost of chemical for maintenance - sodium hypochlorite	₹ 30.00	per kg of solution	26409.4	₹ 792,282.00
17	30.0	Cost of chemical for maintenance - citric acid	₹ 90.00	per kg of solution	3834.61	₹ 345,114.90
						₹ 46,782,320.90
		Present worth factor considered				9.82
		Levelized cost for 25 years of operation			$9.82 * [y_{13} + (C_{14}*y_{14}) + (C_{15}*y_{15}) + (C_{16}*y_{16}) + (C_{17}*y_{17})]$	₹ 459,523,071.14

It has been reviewed that variation is around 1 % for each of estimated total bare construction cost and levelized cost of 25 years of operation.

The unit cost co-efficient functions for different items of medium range WWTPs with MBBR technology as displayed in the Figures 39 to 58 are tabulated in Table 23

Table 23: Medium range WWTPs with MBBR - Functions for calculations of cost

Medium range WWTPs with MBBR - Functions for calculations of total bare construction cost							
Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient function for unit cost (y)**	**Cost for x mld capacity WWTP with MBBR**	
			Value	***Unit***		***Value***	***Unit***
1	x	Cost of total earthwork	C_1	per ft^3	$y_1 = (32855*x) + 13480$	C_1*y_1	currency
2	x	Cost of total quantity of RCC	C_2	per ft^3	$y_2 = (4852.6*x) + 24825$	C_2*y_2	currency
3	x	Cost of total quantity of handrails	C_3	per / ft	$y_3 = (27.261*x) + 511.8$	C_3*y_3	currency
4	x	Cost of houses or buildings	C_4	per ft^2	$y_4 = (20.191*x) + 2452.2$	C_4*y_4	currency
5	x	Cost of clarifier mechanisms	C_5	per mechanism	$y_5 = (0.2192*x) + 1.6307$	C_5*y_5	currency
6	x	Cost of blowers	C_6	per blower	$y_6 = (0.1787*x) + 2.488$	C_6*y_6	currency
7	x	Cost of installation man-hours	C_7	per hr	$y_7 = (70.228*x) + 248.15$	C_7*y_7	currency
8	x	Cost of crane requirements for installation	C_8	per hr	$y_8 = (7.0228*x) + 24.817$	C_8*y_8	currency
9	x	Cost of pumps	C_9	Purchase cost of standard pump (3000 gpm)	$y_9 = (0.1493*x) + 2.4493$	C_9*y_9	currency
10	x	Cost of diffusers	C_{10}	per diffuser	$y_{10} = (28.837*x) + 1.0593$	$C_{10}*y_{10}$	currency
11	x	Cost of swing arm diffuser headers	C_{11}	per header	$y_{11} = (1.4768*x)$	$C_{11}*y_{11}$	currency
12	x	Cost of carrier media	C_{12}	per m^3	$y_{12} = (38.651*x)$	$C_{12}*y_{12}$	currency
13	x	Cost of air piping	C_{13}	cost index	$y_{13} = (457.75*x)$	$C_{13}*y_{13}$	currency

Table 23: Medium range WWTPs with MBBR - Functions for calculations of cost

Medium range WWTPs with MBBR - Functions for calculations of levelized cost for 25 years of operation of small range WWTP with MBBR							
Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient function for unit cost (y)**	**Cost for x mld capacity WWTP with MBBR**	
			Value	***Unit***		***Value***	***Unit***
14	x	Cost of operation and maintenance material costs			$y_{14} = [(0.487*x) + 4.8973]*10^5$	y_{14}	currency
15	x	Cost of energy requirement	C_{15}	per kwhr	$y_{15} = (82969*x) + 20120$	$C_{15}*y_{15}$	currency
16	x	Cost of operation and maintenance hours	C_{16}	per hr	$y_{16} = (218.76*x) + 5439.1$	$C_{16}*y_{16}$	currency
		Present worth factor considered				9.82	
		Levelized cost for 25 years of operation			$9.82 * [y_{14} + (C_{15}*y_{15}) + (C_{16}*y_{16})]$		currency

The co-efficients for respective unit costs have been calculated based on derived functions for a case of 30 mld capacity WWTP with MBBR technology and costs with unit cost base in India at year 2021 are furnished in Table – 24:

Table 24: Medium range WWTPs with MBBR - Validation for calculated costs

Medium range WWTPs with MBBR - Validation for calculated total bare construction cost						
Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient function for unit cost (y)**	**Cost for 30.0 mld capacity WWTP with MBBR**
			Value	***Unit***		***Value***
1	30.0	Cost of total earthwork	₹ 10.38	per ft^3	999130	₹ 10,373,336.12
2	30.0	Cost of total quantity of RCC	₹ 243.72	per ft^3	170403	₹ 41,531,376.35
3	30.0	Cost of total quantity of handrails	₹ 600.00	per / ft	1329.63	₹ 797,778.00
4	30.0	Cost of houses or buildings	₹ 7,500.00	per ft^2	3057.93	₹ 22,934,475.00
5	30.0	Cost of clarifier mechanisms	₹ 75,00,000.00	per mechanism	8.2067	₹ 61,550,250.00
6	30.0	Cost of blowers	₹ 53,00,895.04	per blower	7.849	₹ 41,606,725.14
7	30.0	Cost of installation man-hours	₹ 125.00	per hr	2354.99	₹ 294,373.75
8	30.0	Cost of crane requirements for installation	₹ 1,000.00	per hr	235.501	₹ 235,501.00
9	30.0	Cost of pumps	₹ 12,93,750.00	Purchase cost of standard pump (3000 gpm)	6.9283	₹ 8,963,488.13
10	30.0	Cost of diffusers	₹ 1,200.00	per diffuser	866.1693	₹ 1,039,403.16
11	30.0	Cost of swing arm diffuser headers	₹ 35,000.00	per header	44.304	₹ 1,550,640.00
12	30.0	Cost of carrier media	₹ 11,000.00	per m^3	1159.53	₹ 12,754,830.00
13	30.0	Cost of air piping	₹ 750.00	cost index	13732.5	₹ 10,299,375.00
		Consolidated bare cost				₹ 213,931,551.65

Table 24: Medium range WWTPs with MBBR - Validation for calculated costs (continued)

Medium range WWTPs with MBBR - Validation for calculated levelized cost of 25 years operation						
Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient function for unit cost (y)**	**Cost for 30.0 mld capacity WWTP with MBBR**
			Value	***Unit***		***Value***
14	30.0	Cost of operation and maintenance material costs			1950730	₹ 1,950,730.00
15	30.0	Cost of energy requirement	₹ 6.00	per kwhr	2509190	₹ 15,055,140.00
16	30.0	Cost of operation and maintenance hours	₹ 250.00	per hr	12001.9	₹ 3,000,475.00
		Present worth factor considered				9.82
		Levelized cost for 25 years of operation			9.82 * [y_{14} + (C_{15}*y_{15}) + (C_{16}*y_{16})]	₹ 196,513,916.37

It has been scrutinized and noted that variation is within 6 % for estimated total bare construction cost and 0.5 % for levelized cost of 25 years of operation.

The unit cost co-efficient functions for different items of medium range WWTPs with SBR technology as displayed in the Figures 39 to 58 are tabulated in Table 25:

Table 25: Medium range WWTPs with SBR - Functions for calculations of cost

Medium range WWTPs with SBR - Functions for calculations of total bare construction cost								
Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient function for unit cost (y)**	**Cost for x mld capacity WWTP with SBR**	
			Value	***Unit***		***Value***	***Unit***
1	x	Cost of total earthwork	C_1	per ft^3	$y_1 = (24170*x) + 62279$	C_1*y_1	currency
2	x	Cost of total quantity of RCC	C_2	per ft^3	$y_2 = (10096*x) + 24161$	C_2*y_2	currency
3	x	Cost of total quantity of handrails	C_3	per / ft	$y_3 = (258.16*x) + 966.59$	C_3*y_3	currency
4	x	Cost of houses or buildings	C_4	per ft^2	$y_4 = (16.654*x) + 1921.2$	C_4*y_4	currency
5	x	Cost of blowers	C_5	per blower	$y_5 = (0.2699*x) + 3.9607$	C_5*y_5	currency
6	x	Cost of installation man-hours	C_6	per hr	$y_6 = (863.33*x) - 7922.2$	C_6*y_6	currency
7	x	Cost of crane requirements for installation	C_7	per hr	$y_7 = (63.698*x)$	C_7*y_7	currency
8	x	Cost of pumps	C_8	Purchase cost of standard pump (3000 gpm)	$y_8 = 0.58$	C_8*y_8	currency
9	x	Cost of diffusers	C_9	per diffuser	$y_9 = (558.02*x)$	C_9*y_9	currency
10	x	Cost of swing arm diffuser headers	C_{10}	per header	$y_{10} = (28.027*x)$	$C_{10}*y_{10}$	currency
11	x	Cost of decanters	C_{11}	per m^3	$y_{11} = (706.44*x)$	$C_{11}*y_{11}$	currency
12	x	Cost of air piping	C_{12}	cost index	$y_{12} = (681.82*x) + 3517$	$C_{12}*y_{12}$	currency

Table 25: Medium range WWTPs with SBR - Functions for calculations of cost (continued)

Functions for calculations of levelized cost for 25 years of operation of medium range WWTP with SBR							
Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient function for unit cost (y)**	**Cost for x mld capacity WWTP with SBR**	
			Value	***Unit***		***Value***	***Unit***
13	x	Cost of operation and maintenance material costs			$y_{13} = [(1.2006*x) + 5.8]*10^5$	y_{13}	currency
14	x	Cost of energy requirement	C_{14}	per kwhr	$y_{14} = (120601*x) + 283846$	$C_{14}*y_{15}$	currency
15	x	Cost of operation and maintenance hours	C_{15}	per hr	$y_{15} = (106.98*x) + 2930.5$	$C_{15}*y_{15}$	currency
		Present worth factor considered				9.82	
		Levelized cost for 25 years of operation			$9.82 * [y_{13} + (C_{14}*y_{14}) + (C_{15}*y_{15})]$		currency

The co-efficients for respective unit costs have been calculated based on derived functions for a case of 30 mld capacity WWTP with SBR technology and costs with unit cost base in India at year 2021 are furnished in Table – 26.

Table 26: Medium range WWTPs with SBR - Validation for calculated costs

Medium range WWTPs with SBR - Functions for calculations of total bare construction cost

Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient for unit cost (y)**	**Cost for 30.0 mld capacity WWTP with SBR**
			Value	***Unit***		***Value***
1	30.0	Cost of total earthwork	₹ 10.38	per ft^3	787379	₹ 8,174,859.15
2	30.0	Cost of total quantity of RCC	₹ 243.72	per ft^3	327041	₹ 79,707,885.73
3	30.0	Cost of total quantity of handrails	₹ 600.00	per ft	8711.39	₹ 5,226,834.00
4	30.0	Cost of houses or buildings	₹ 7,500.00	per ft^2	2420.82	₹ 18,156,150.00
5	30.0	Cost of blowers	₹ 53,00,895.04	per blower	12.0577	₹ 63,916,602.08
6	30.0	Cost of installation man-hours	₹ 125.00	per hr	17977.7	₹ 2,247,212.50
7	30.0	Cost of crane requirements for installation	₹ 1,000.00	per hr	1910.94	₹ 1,910,940.00
8	30.0	Cost of pumps	₹ 12,93,750.00	Purchase cost of standard pump (3000 gpm)	0.58	₹ 750,375.00
9	30.0	Cost of diffusers	₹ 1,200.00	per diffuser	16740.6	₹ 20,088,720.00
10	30.0	Cost of swing arm diffuser headers	₹ 35,000.00	per header	840.81	₹ 29,428,350.00
11	30.0	Cost of decanters	₹ 2,400.00	per m^3/h	21193.2	₹ 50,863,680.00
12	30.0	Cost of air piping	₹ 750.00	cost index	23971.6	₹ 17,978,700.00
		Consolidated bare cost				₹ 298,450,308.47

Table 26: Medium range WWTPs with SBR - Validation for calculated costs (continued)

Medium range WWTPs with SBR - Functions for calculations of levelized cost for 25 years of operation						
Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient for unit cost (y)**	**Cost for 30.0 mld capacity WWTP with SBR**
			Value	***Unit***		***Value***
13	30.0	Cost of operation and maintenance material costs			4181800	₹ 4,181,800.00
14	30.0	Cost of energy requirement	₹ 6.00	kwhr/year	3901876	₹ 23,411,256.00
15	30.0	Cost of operation and maintenance hours	₹ 250.00	per hr	6139.9	₹ 1,534,975.00
		Present worth factor considered				9.82
		Levelized cost for 25 years of operation			9.82 * [y_{13} + (C_{14}*y_{14}) + (C_{15}*y_{15})]	₹ 286,112,403.23

It has been scrutinized and noted that variation is within 2.5 % for estimated total bare construction cost and within 1.5 % for estimated levelized cost of 25 years of operation.

The unit cost co-efficient curves of different items for large range WWTPs with MBR, MBBR & SBR technologies are shown in Figures 59 through 78 hereinafter.

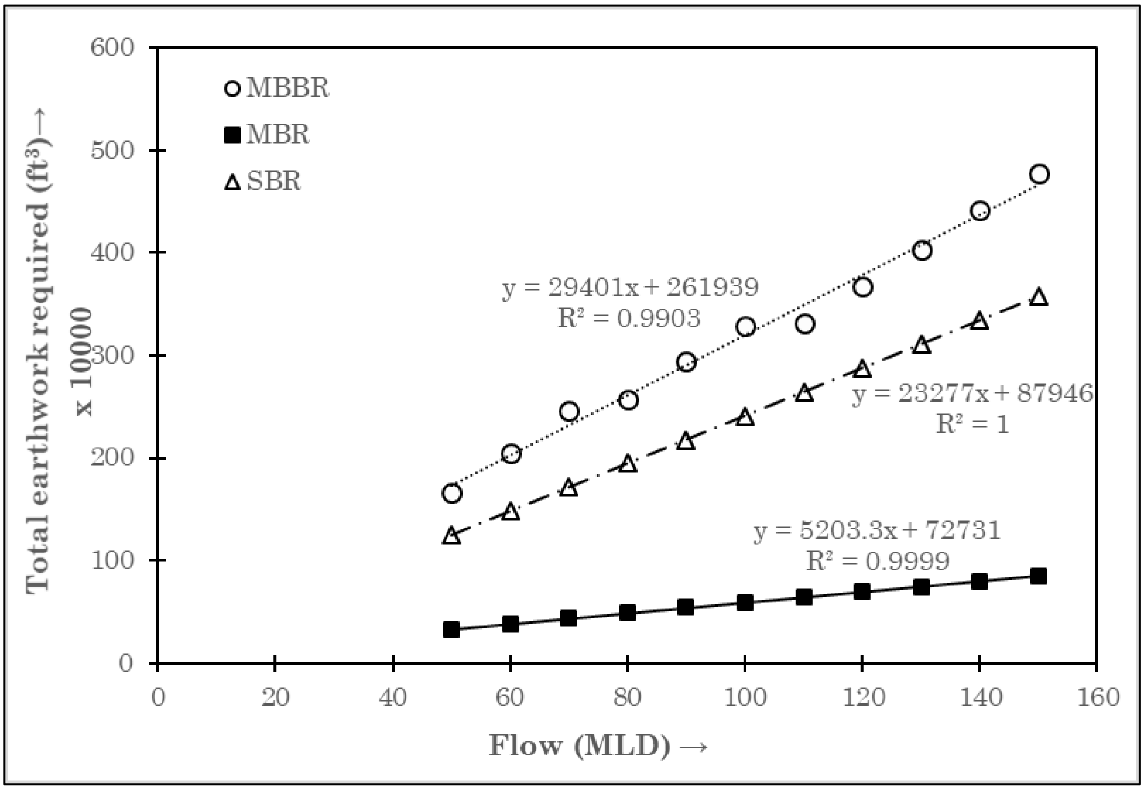


Figure 59: Excavation curve for large range WWTPs with MBR, MBBR and SBR

Figure 59 depicts the co-efficient of earthwork excavation (in cubic feet) required for large-scale wastewater treatment plants (WWTPs) utilizing MBR, MBBR, and SBR technologies at different flow rates. The trends observed are similar to those in Figures 19 and 39. The high R² value (> 0.99) signifies a strong correlation between the data and the regression line, making this curve a reliable predictor for estimating the total earthwork cost for WWTPs with flow rates ranging from 50 MLD to 150 MLD, thereby streamlining the cost estimation process.

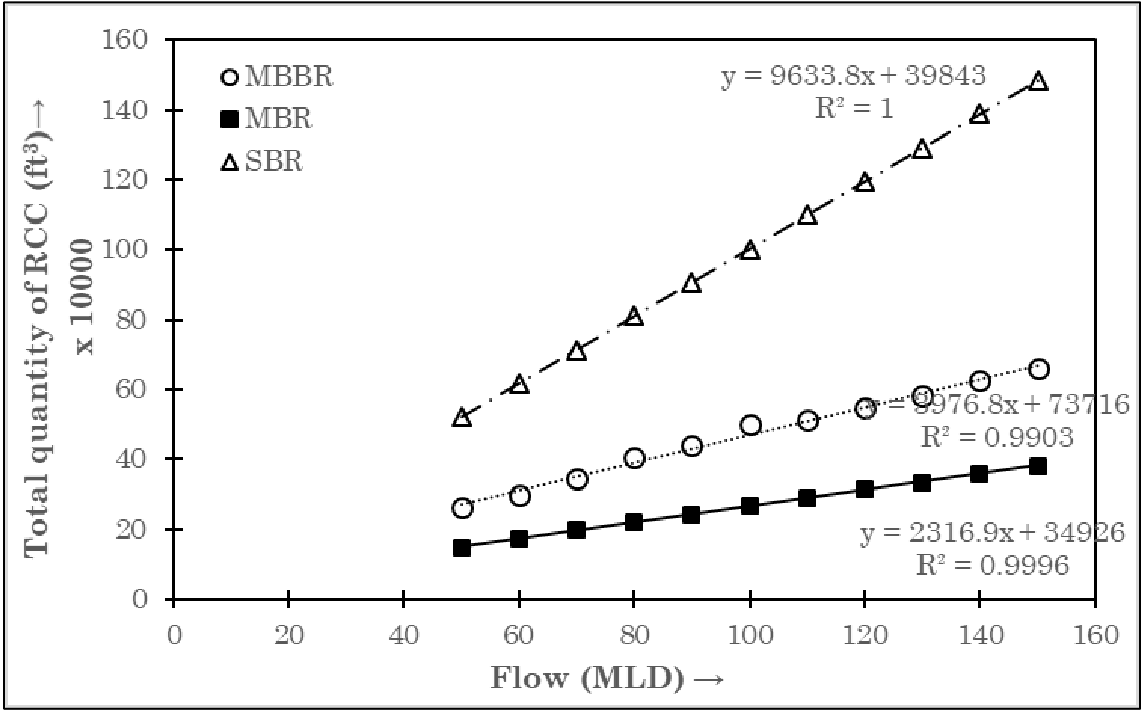


Figure 60: Concrete curve for large range WWTPs with MBR, MBBR and SBR

Figure 60 shows the total co-efficient of reinforced cement concrete (RCC) work (in cubic feet) needed for large-scale wastewater treatment plants (WWTPs) using MBR, MBBR, and SBR technologies at various flow rates. The trends are similar to those in Figure 40. The high R² value (> 0.99) indicates a strong correlation between the data and the regression line, making this curve a reliable predictor for estimating the total RCC cost for WWTPs with flow rates ranging from 50 MLD to 150 MLD, thus simplifying the cost estimation process.

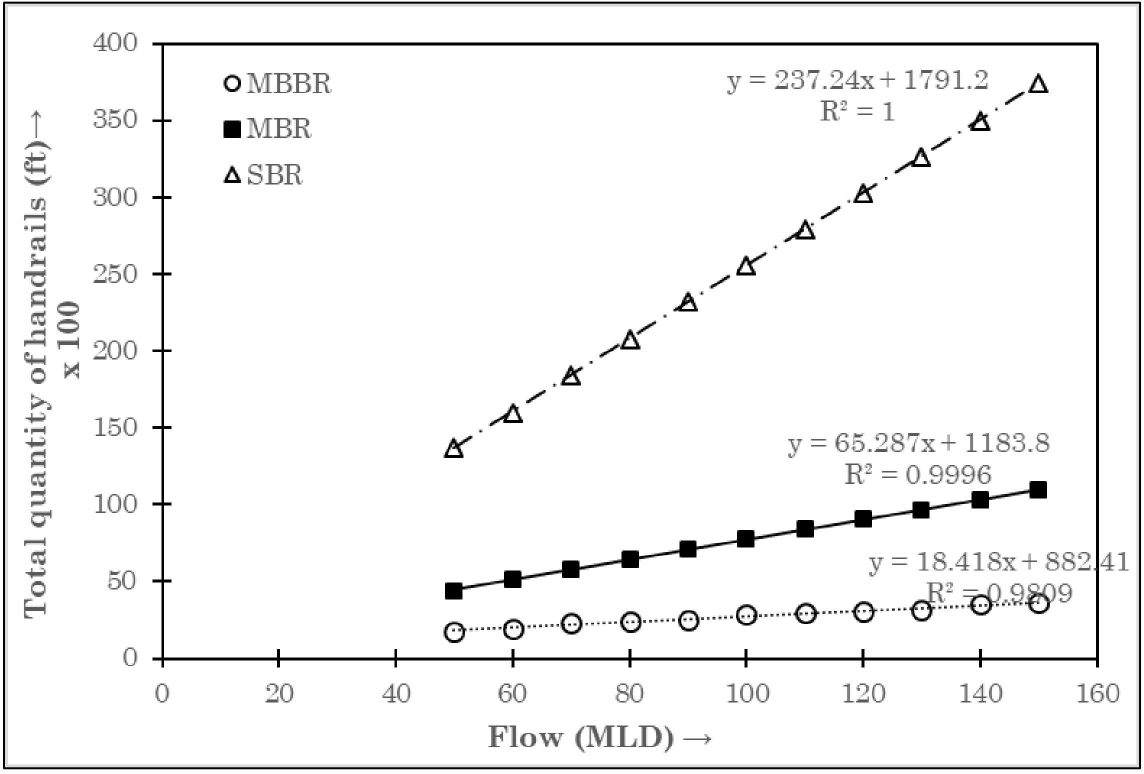


Figure 61: Hand-rail curve for large range WWTPs with MBR, MBBR and SBR

Figure 61 illustrates the total co-efficient of handrails (in feet) needed for large-scale wastewater treatment plants (WWTPs) using MBR, MBBR, and SBR technologies at various flow rates. The trends are similar to those in Figures 21 and 41. With a high R^2 value (> 0.98), indicating a strong correlation between the data and the regression line, this curve serves as a reliable predictor for estimating the cost of handrails for WWTPs with flow rates ranging from 50 MLD to 150 MLD, thereby simplifying the cost estimation process.

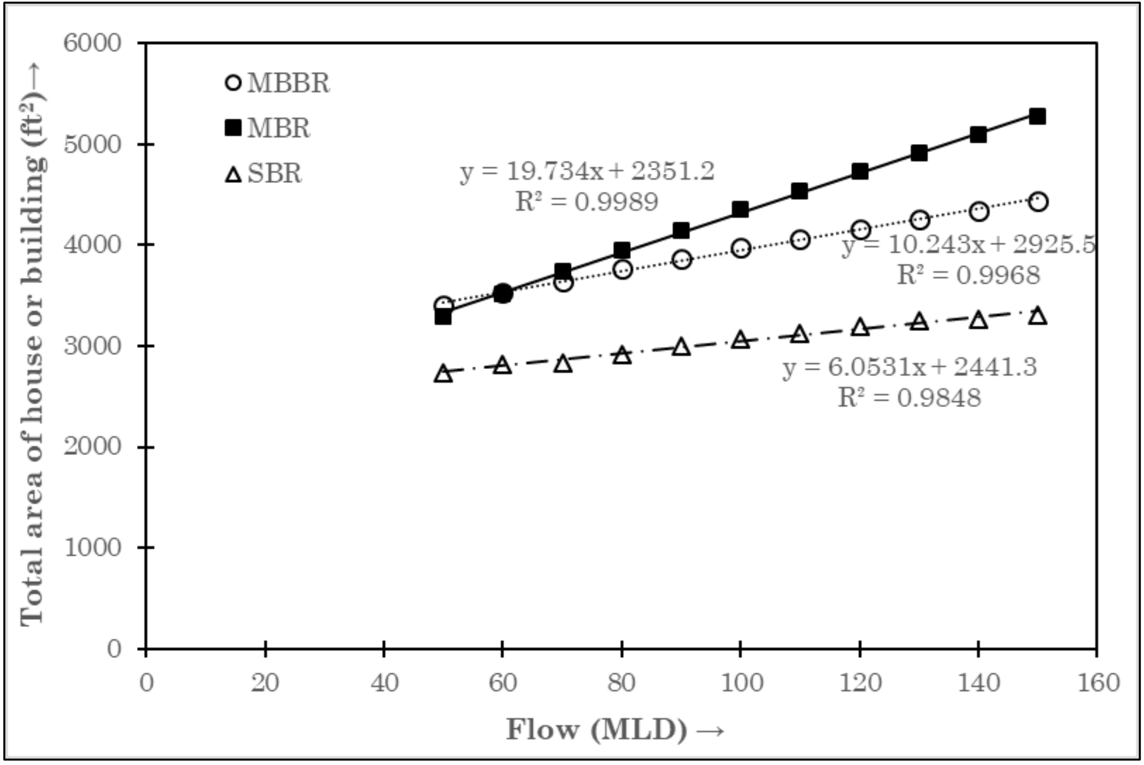


Figure 62: House curve for large range WWTPs with MBR, MBBR and SBR

Figure 62 depicts the total co-efficient needed for housing or buildings (in square feet) for large-scale WWTPs using MBR, MBBR, and SBR technologies at different flow rates. The figure clearly shows that as the flow rate increases, the required co-efficient also increases. Within this range, MBR technology generally requires the largest co-efficient, followed by MBBR and then SBR technology. This observation contrasts with those in Figure 42 (MBBR > MBR > SBR) and Figure 22 (MBBR > MBR > SBR). With a high R² value (> 0.98), indicating a strong correlation between the data and the regression line, this curve can reliably predict the total co-efficient required for housing or buildings for WWTPs with flow rates ranging from 5 MLD to 50 MLD, thereby simplifying the cost estimation process.

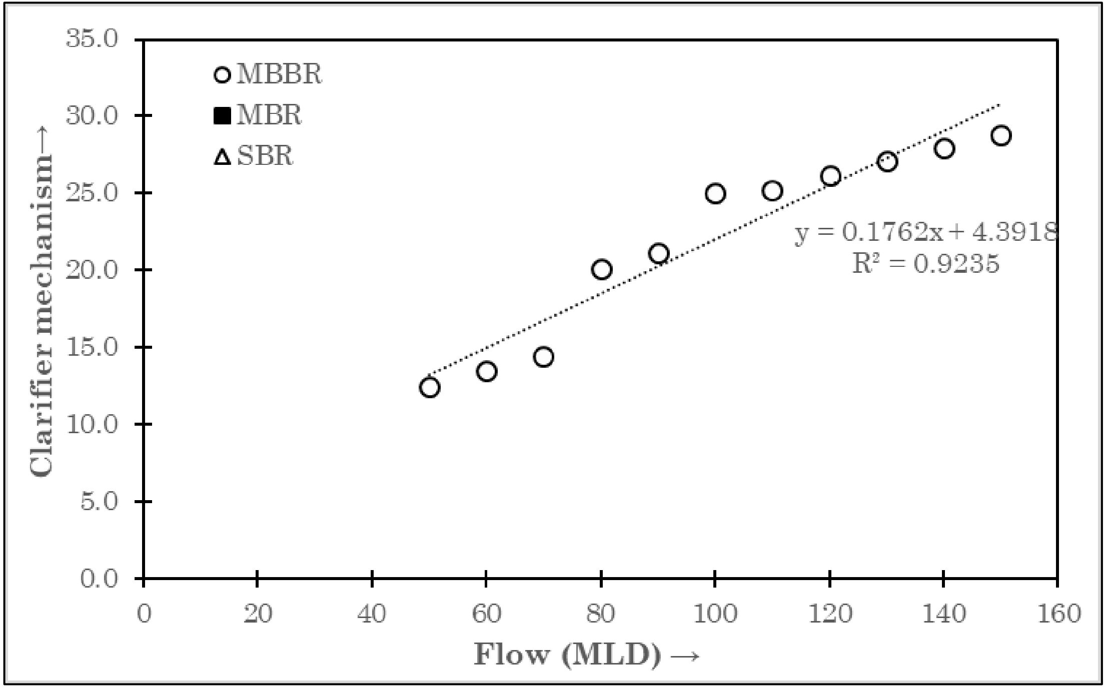


Figure 63: Clarifier mechanism for large range WWTPs with MBBR

Figure 63 displays the total co-efficient of clarifier mechanisms required for large-scale WWTPs using MBBR technology. For MBR and SBR technologies, clarifier mechanisms are not necessary and therefore curve is shown only for MBBR technology. The observations closely resemble those in Figures 43 and 23. With a high R² value of 0.92, indicating a strong correlation between the data and the regression line, this curve can accurately predict the total cost of clarifier mechanisms for WWTPs with flow rates ranging from 50 MLD to 150 MLD, thereby simplifying the cost estimation process.

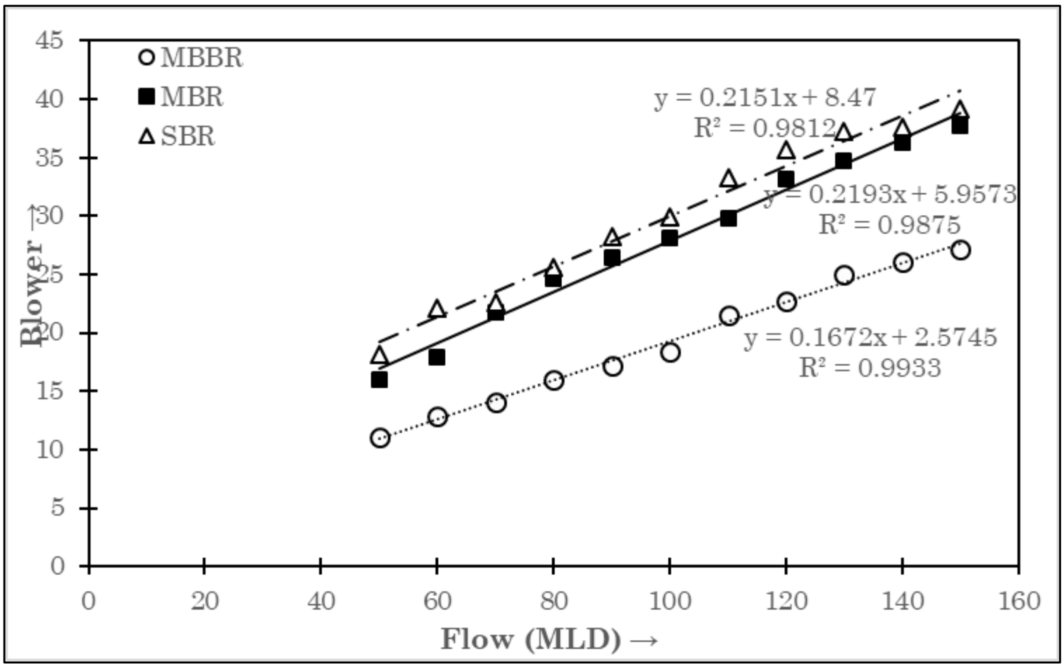


Figure 64: Blower curve for large range WWTPs with MBR, MBBR and SBR

Figure 64 shows the total co-efficient of blowers needed for large-scale wastewater treatment plants (WWTPs) using MBR, MBBR, and SBR technologies at various flow rates. The trends are similar to those in Figure 44 and Figure 24. The high R² value (> 0.99) indicates a strong correlation between the data and the regression line, making this curve a reliable predictor for estimating the total cost associated with blowers for WWTPs with flow rates ranging from 50 MLD to 150 MLD, thus simplifying the cost estimation process.

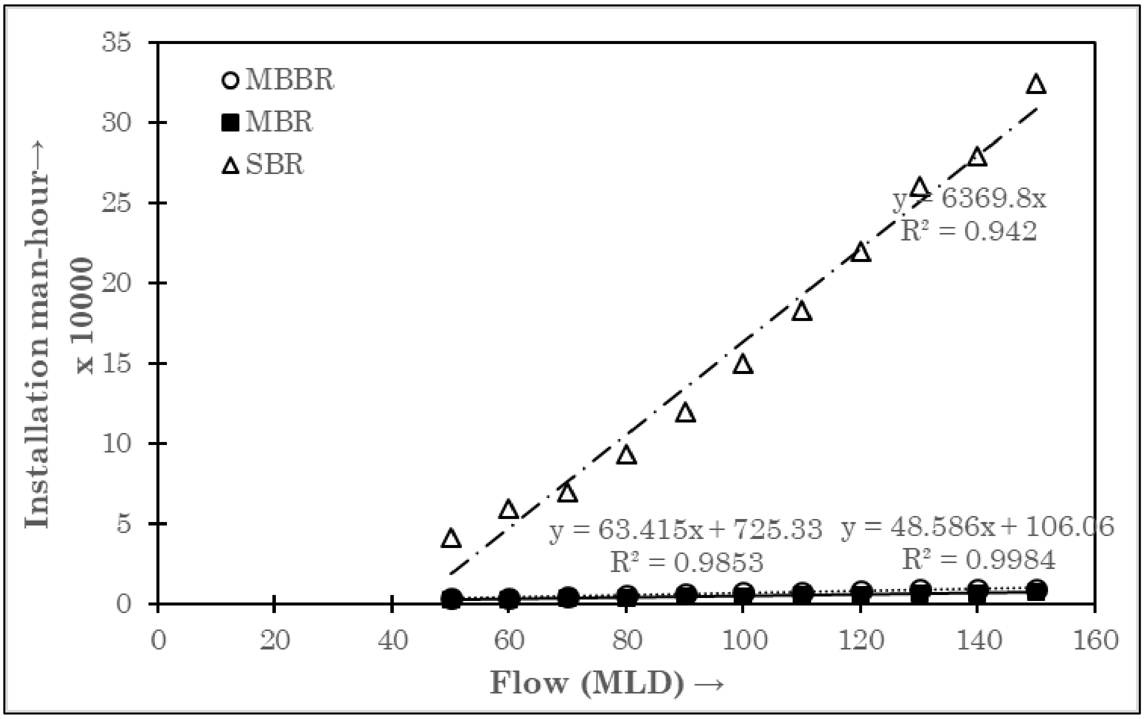


Figure 65: Installation man-hour curve for large-range WWTPs with MBR, MBBR and SBR

Figure 65 illustrates the installation man-hours co-efficient required for large-scale wastewater treatment plants (WWTPs) using MBR, MBBR, and SBR technologies at various flow rates. SBR technology generally requires significantly more man-hours co-efficient than the other two technologies. This observation, along with others, is similar to those in Figure 45. The high R² value (> 0.94) indicates a strong correlation between the data and the regression line, making this curve a reliable predictor for estimating the total cost associated with installation man-hours for WWTPs with flow rates ranging from 50 MLD to 150 MLD, thereby simplifying the cost estimation process.

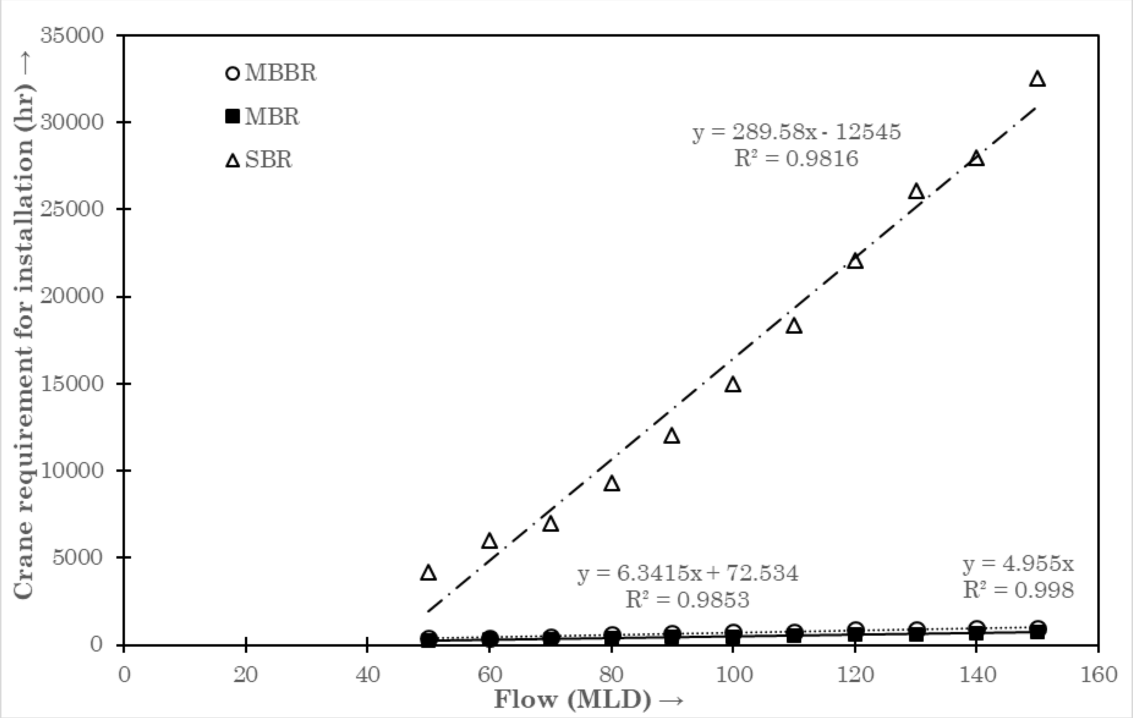


Figure 66: Crane curve for large-range WWTPs with MBR, MBBR and SBR

Figure 66 depicts the crane co-efficient for the installation of large-scale wastewater treatment plants (WWTPs) using MBR, MBBR, and SBR technologies at various flow rates. SBR technology generally requires significantly more crane usage than the other two technologies. This observation, along with others, is similar to those in Figure 46. The high R^2 value (> 0.98) indicates a strong correlation between the data and the regression line, making this curve a reliable predictor for estimating the total cost associated with crane requirements for WWTPs with flow rates ranging from 50 MLD to 150 MLD, thereby simplifying the cost estimation process.

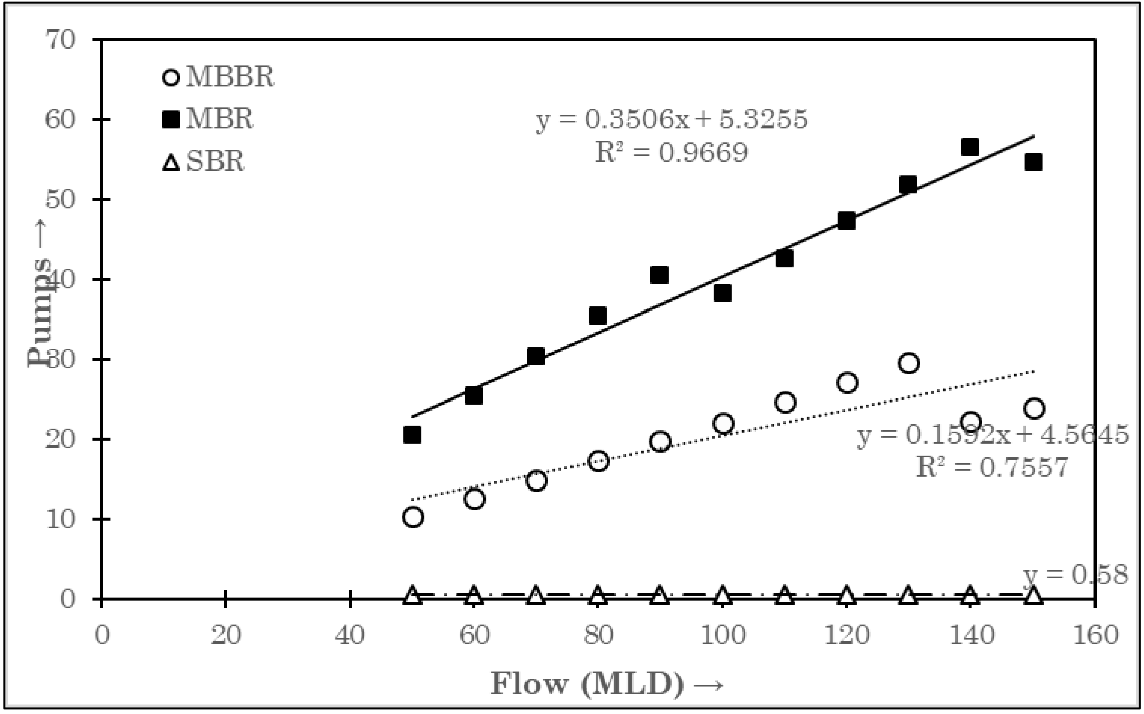


Figure 67: Pumps curve for large-range WWTPs with MBR, MBBR and SBR

Figure 67 illustrates the co-efficient of standard pumps (3000 gpm) required for large-scale wastewater treatment plants (WWTPs) using MBR, MBBR, and SBR technologies at various flow rates. The trends are similar to those in Figures 27 and 47. The co-efficient of standard pumps (3000 gpm) required for SBR remains constant. The data were analyzed using linear regression, achieving an R² value exceeding 0.96 for MBR and SBR technologies, indicating an excellent fit to the regression line. For MBBR technology, the R² value is nearly 0.79, indicating a moderate fit. Overall, the R² values are generally good for estimating the cost of pumps for WWTPs with flow rates ranging from 50 MLD to 150 MLD, thereby simplifying the cost estimation process.

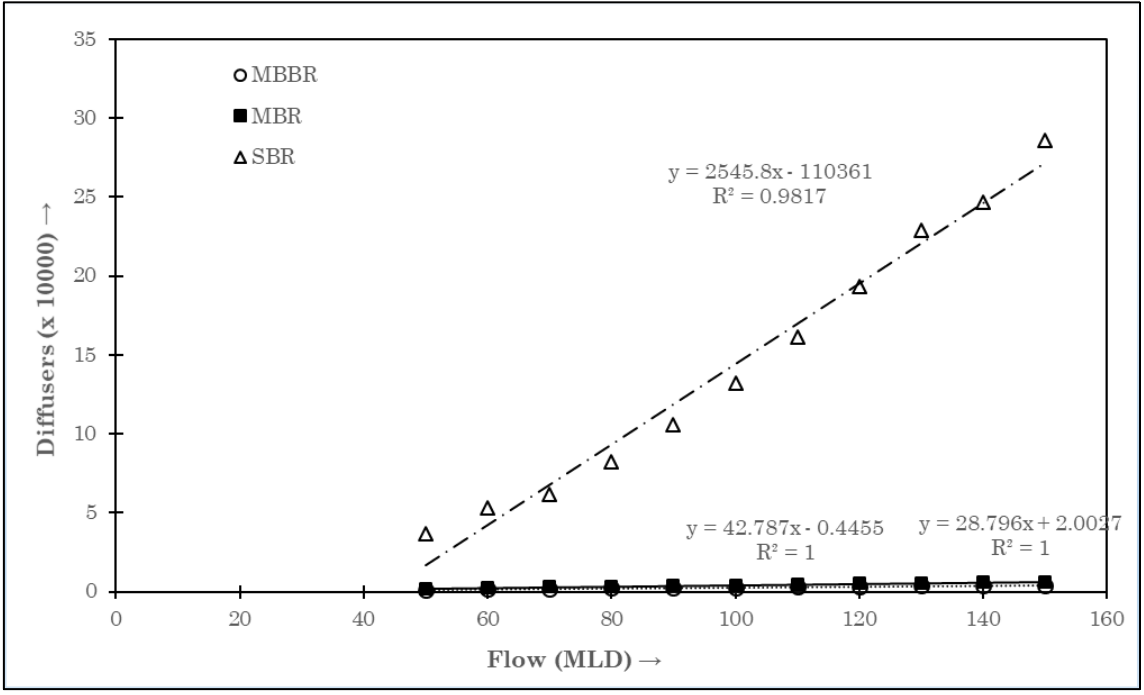


Figure 68: Diffusers curve for large range WWTPs with MBR, MBBR and SBR

Figure 68 shows the co-efficient of diffusers needed for large-scale wastewater treatment plants (WWTPs) using MBR, MBBR, and SBR technologies at various flow rates. SBR technology generally requires significantly more diffusers than the other two technologies. This observation is similar to those in Figures 48 and 28. The high R^2 value (> 0.98) indicates a strong correlation between the data and the regression line, making this curve a reliable predictor for estimating the total cost of diffusers for WWTPs with flow rates ranging from 50 MLD to 150 MLD, thereby simplifying the cost estimation process.

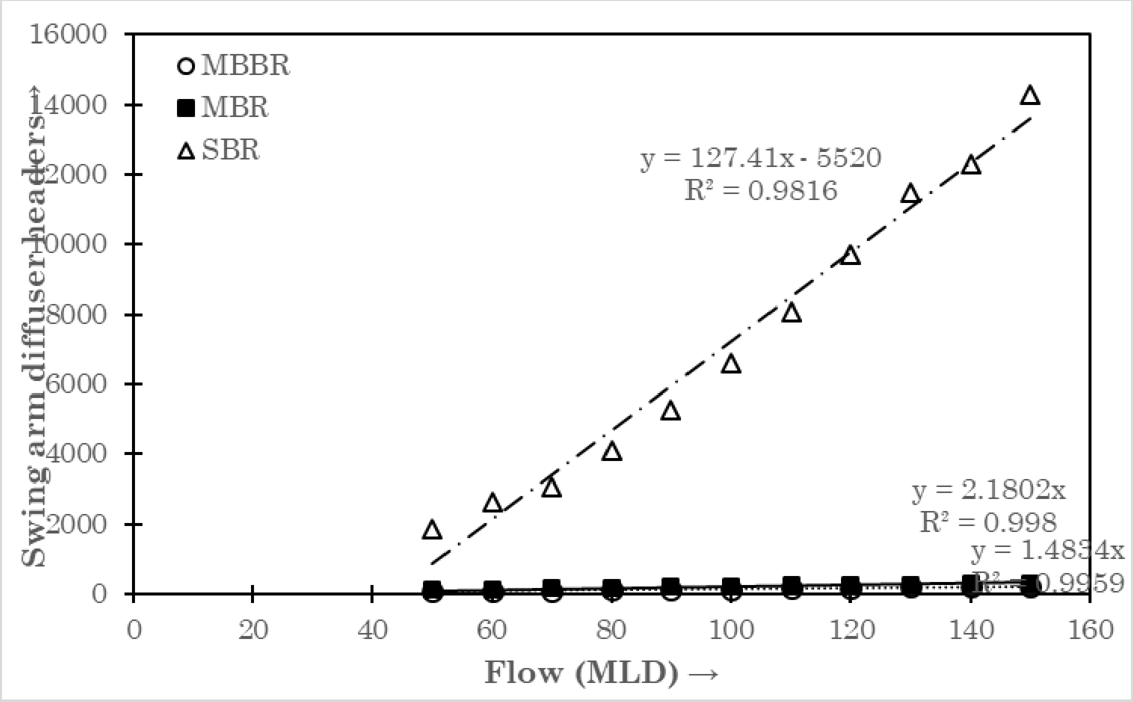


Figure 69: Swing arm diffuser header curve for large range WWTPs with MBR, MBBR and SBR

Figure 69 illustrates the co-efficient of swing arm diffuser headers required for large-scale wastewater treatment plants (WWTPs) using MBR, MBBR, and SBR technologies at various flow rates. SBR technology generally requires a significantly higher co-efficient of swing arm diffuser headers compared to the other two technologies. This observation aligns with those in Figures 49 and 29. The high R² value (> 0.98) indicates a strong correlation between the data and the regression line, making this curve a reliable predictor for estimating the total cost associated with swing arm diffuser headers for WWTPs with flow rates ranging from 50 MLD to 150 MLD, thereby simplifying the cost estimation process.

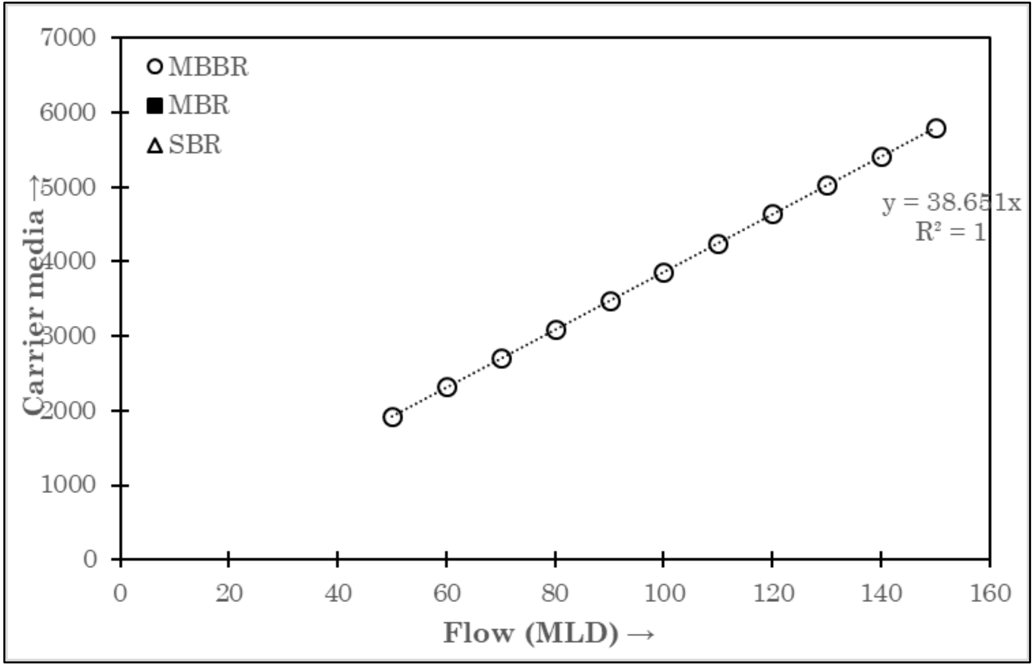


Figure 70: Carrier media curve for large range WWTPs with MBBR

Figure 70 depicts the total co-efficient of carrier media (m³) needed for large-scale WWTPs utilizing SBR technology. MBR and SBR technologies do not require carrier media and therefore curve is shown only for MBBR technology. The trends observed closely mirror those in Figures 50 and 30. The high R² value of 1 indicates a perfect correlation between the data and the regression line, enabling accurate prediction of the total cost of carrier media for WWTPs with flow rates ranging from 50 MLD to 150 MLD, thereby simplifying the cost estimation process.

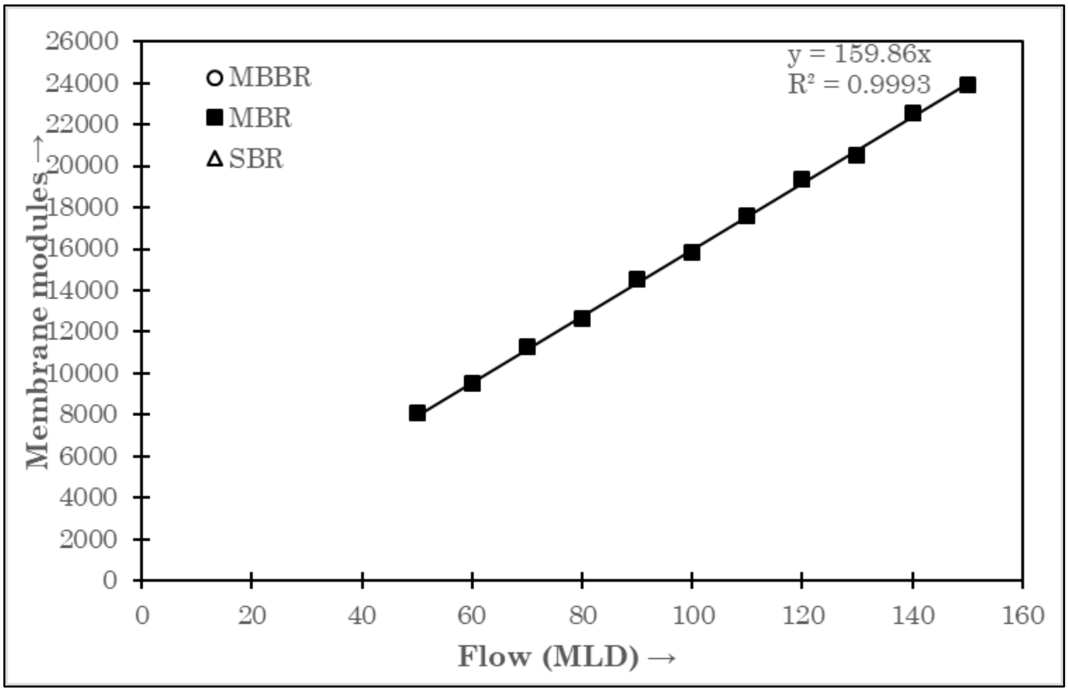


Figure 71: Membrane modules curve for large range WWTPs with MBR

Figure 71 illustrates the co-efficient of membrane modules required for large-scale WWTPs using MBR technology. MBBR and SBR technologies do not require membrane modules and therefore curve is shown only for MBR technology. The trends observed closely resemble those in Figures 51 and 31. The high R² value of 1 indicates a perfect correlation between the data and the regression line, allowing for precise prediction of the total cost associated with membrane modules for WWTPs with flow rates ranging from 50 MLD to 150 MLD, thus simplifying the cost estimation process.

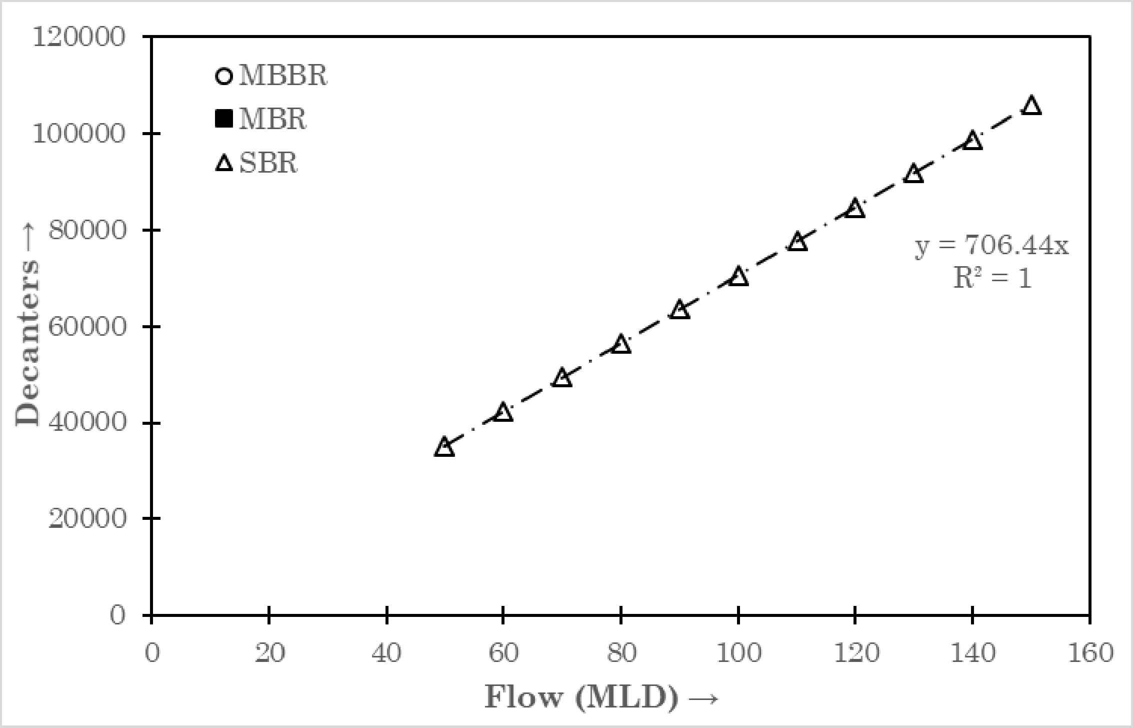


Figure 72: Decanters curve for large range WWTPs with SBR

Figure 72 depicts the co-efficient of decanters (m^3/hr) needed for large-scale WWTPs employing SBR technology. MBR and MBBR technologies do not require decanters and therefore curve is shown only for SBR technology. The observed trends closely parallel those in Figures 52 and 32. A high R² value of 1 indicates a perfect correlation between the data and the regression line, facilitating accurate prediction of the total cost related to decanters for WWTPs with flow rates ranging from 50 MLD to 150 MLD, thereby streamlining the cost estimation process.

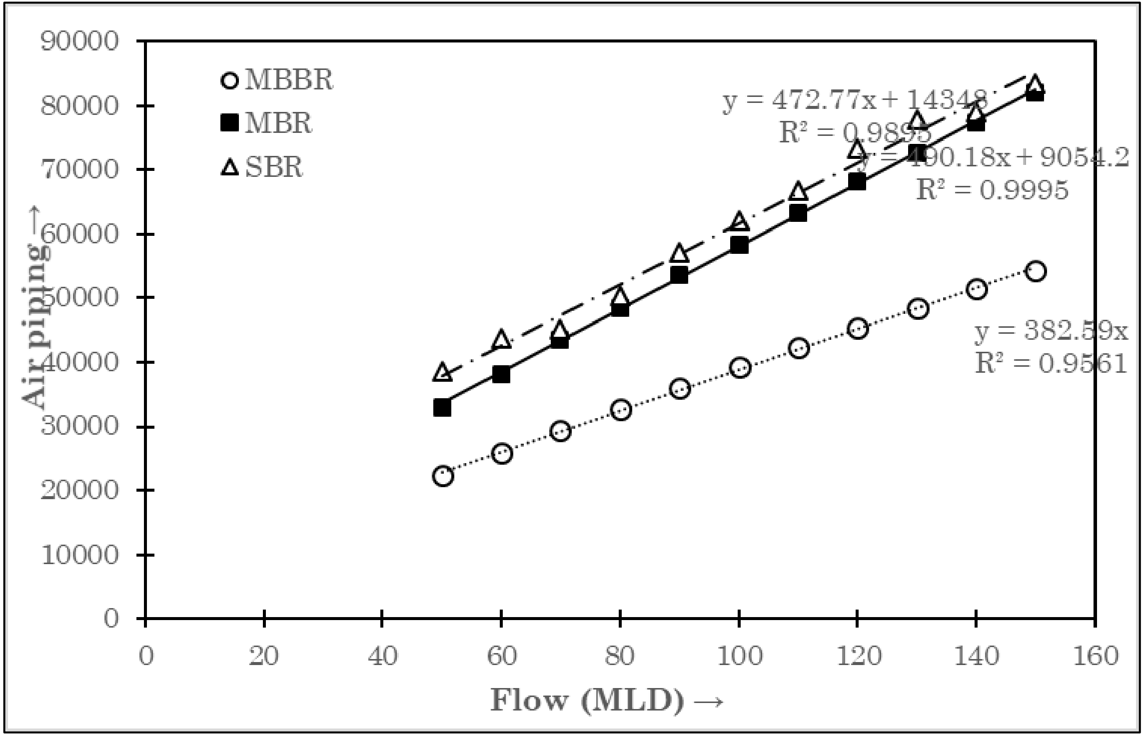


Figure 73: Air pipe curve for large range WWTPs with MBR, MBBR and SBR

Figure 73 illustrates the co-efficient of air piping needed for large-scale wastewater treatment plants (WWTPs) utilizing MBR, MBBR, and SBR technologies at varying flow rates. The trends closely resemble those in Figures 53 and 33. With a high R² value (> 0.95), indicating a robust correlation between the data and the regression line, this curve serves as a dependable predictor for estimating the total cost associated with air piping for WWTPs with flow rates ranging from 50 MLD to 150 MLD, thereby facilitating the cost estimation process.

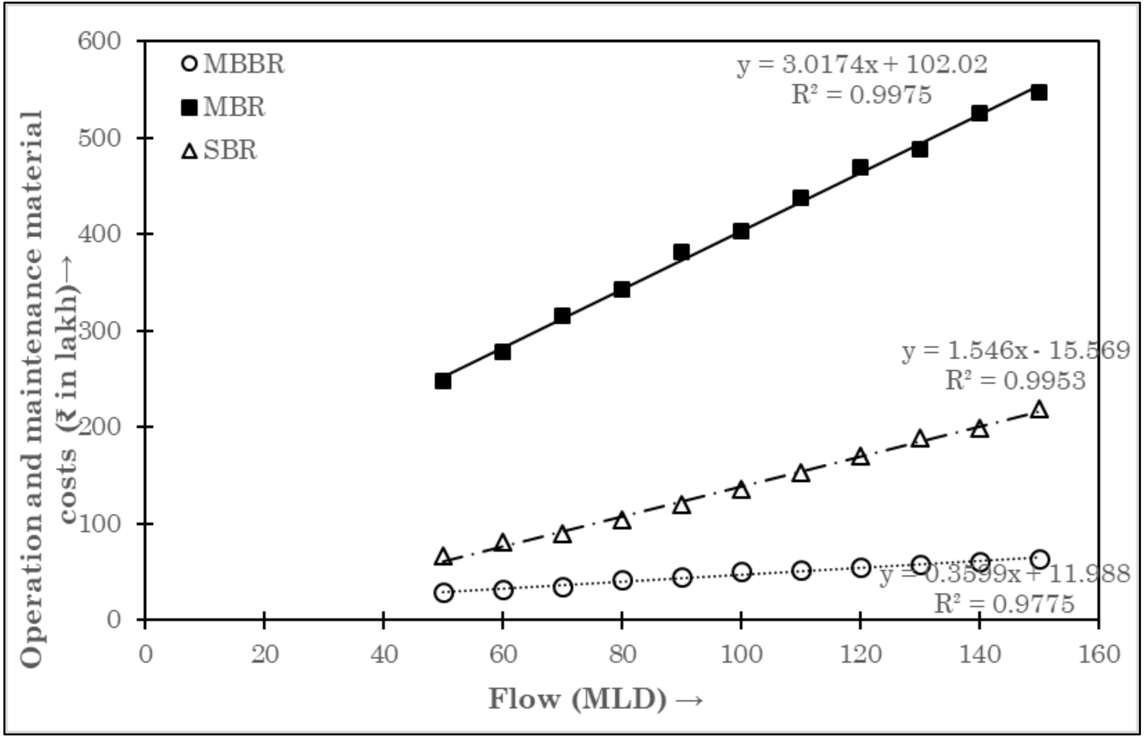


Figure 74: O&M material cost curve for large range WWTPs with MBR, MBBR and SBR

Figure 74 depicts the expenditure co-efficient on O & M materials for large-scale wastewater treatment plants (WWTPs) employing MBR, MBBR, and SBR technologies across different flow rates. The trends mirror those in Figures 54 and 34. A high R² value (> 0.97) indicates a strong correlation between the data and the regression line, making this curve a reliable tool for estimating the cost of O & M materials for WWTPs with flow rates ranging from 50 MLD to 150 MLD, thus simplifying the cost estimation process.

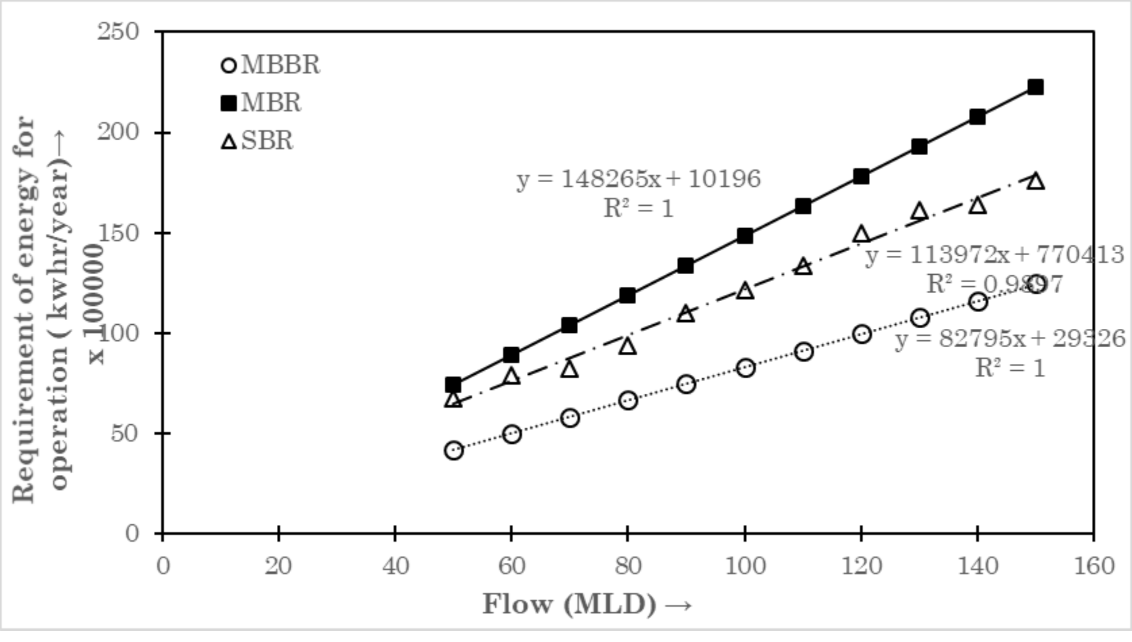


Figure 75: Energy curve for large range WWTPs with MBR, MBBR and SBR

Figure 75 illustrates the co-efficient for energy requirements for large-scale wastewater treatment plants (WWTPs) utilizing MBR, MBBR, and SBR technologies across various flow rates. There is a notable difference from Figure 35, yet consistent with the findings of Figure 55, indicating that MBR technology generally demands the highest energy, followed by SBR technology, and then MBBR technology. Other observations closely resemble those in Figures 55 and 35. A high R² value (> 0.98) confirms a strong correlation between the data and the regression line, establishing this curve as a reliable tool for estimating energy costs for WWTPs with flow rates ranging from 50 MLD to 150 MLD, thereby simplifying the cost estimation process.

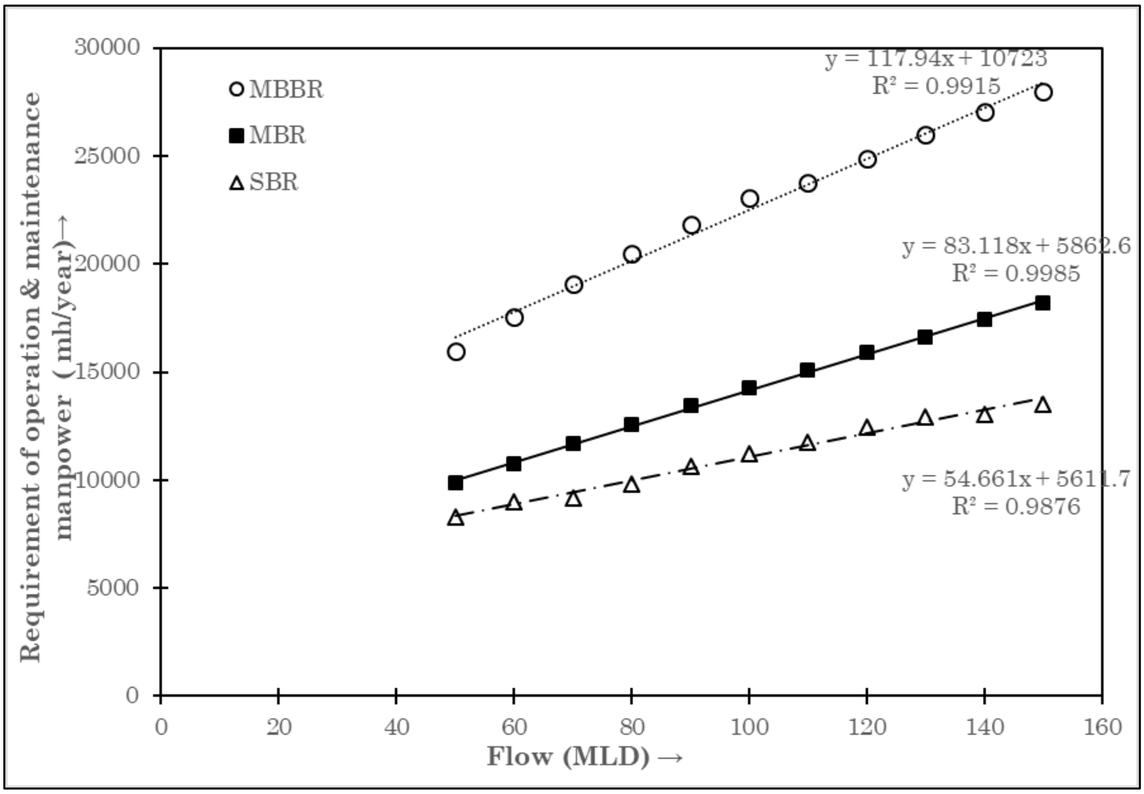


Figure 76: O&M man-hour curve for large range WWTPs with MBR, MBBR and SBR

Figure 76 shows the O & M man-hours co-efficient required for large-scale wastewater treatment plants (WWTPs) using MBR, MBBR, and SBR technologies at various flow rates. The trends closely resemble those in Figures 56 and 36. A high R² value (> 0.98) indicates a strong correlation between the data and the regression line, making this curve a reliable tool for estimating the cost of O & M man-hours for WWTPs with flow rates ranging from 50 MLD to 150 MLD, thereby simplifying the cost estimation process.

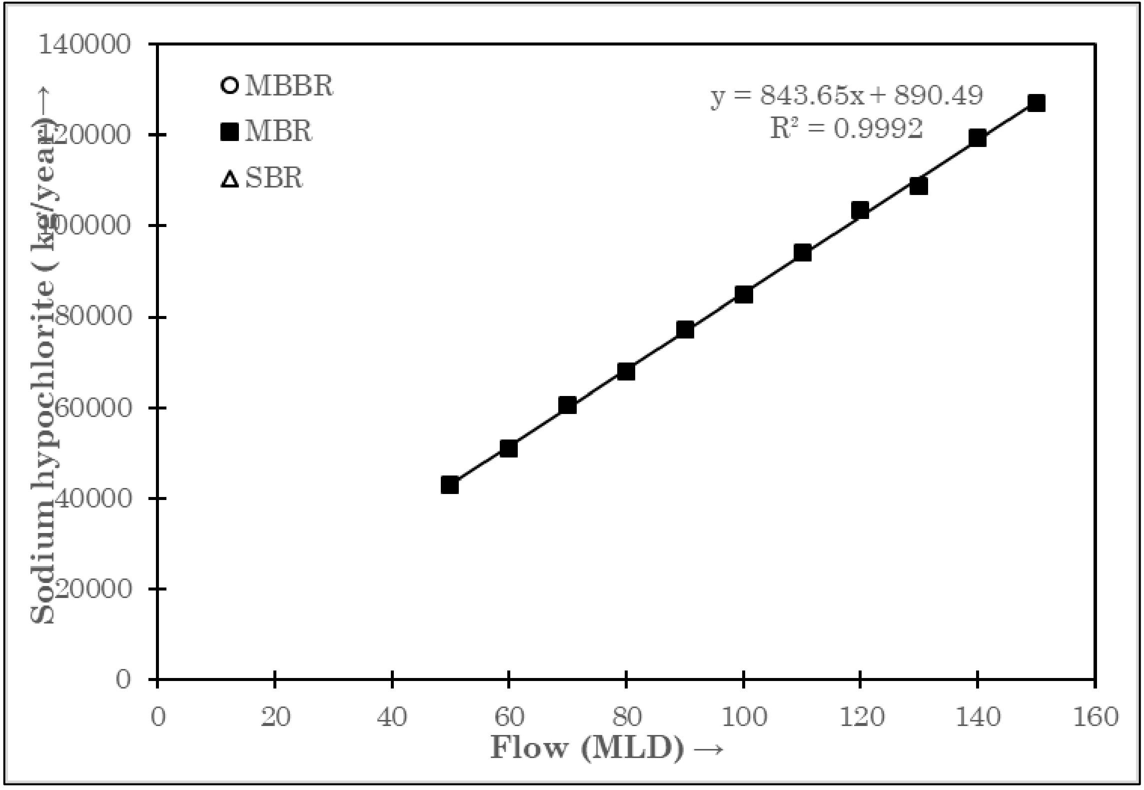


Figure 77: Sodium hypochlorite curve for large range WWTPs with MBR

Figure 77 illustrates the co-efficient of sodium hypochlorite required for large-scale WWTPs using MBR technology. SBR and MBBR technologies do not require sodium hypochlorite and therefore curve is shown only for MBR technology. The observed trends closely resemble those in Figures 57 and 37. With a high R² value of 0.999, indicating a perfect correlation between the data and the regression line, this curve enables precise prediction of the total cost associated with sodium hypochlorite for WWTPs with flow rates ranging from 50 MLD to 150 MLD, thereby simplifying the cost estimation process.

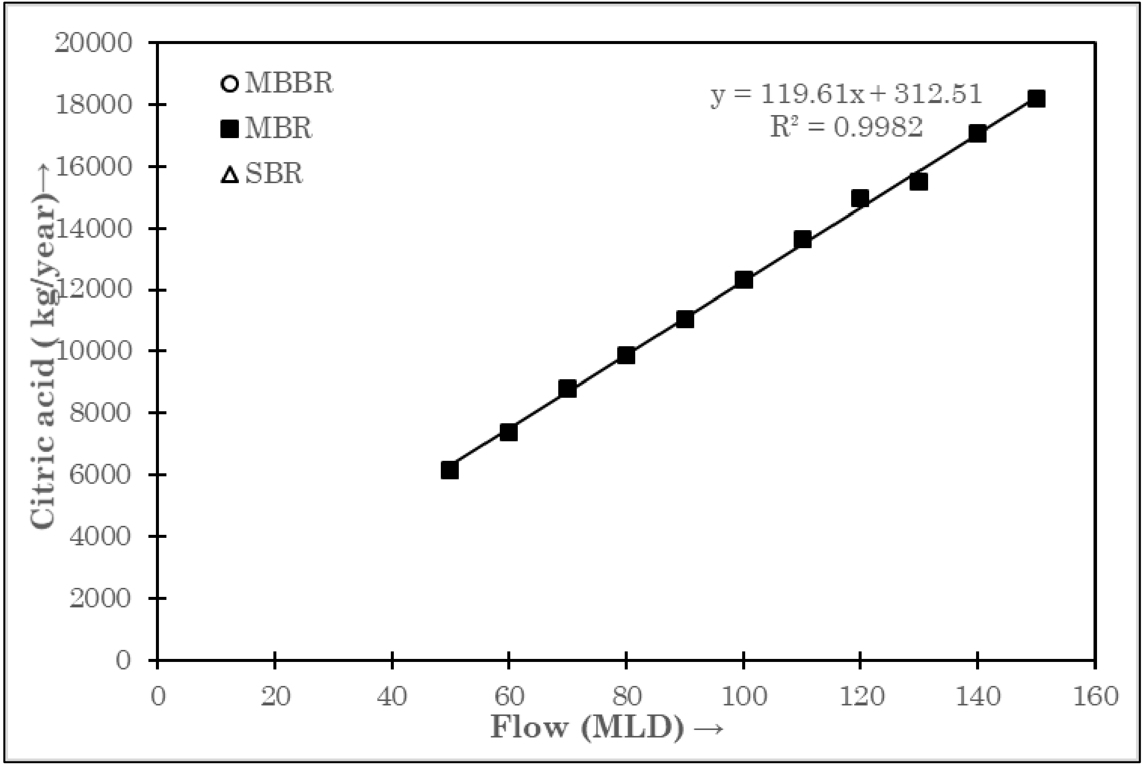


Figure 78: Acid curve for large range WWTPs with MBR

Figure 78 depicts the co-efficient of citric acid needed for large-scale WWTPs employing MBR technology. SBR and MBBR technologies do not require citric acid and therefore curve is shown only for MBR technology. The observed trends closely mirror those in Figures 58 and 38. With a high R² value of 0.998, indicating a perfect correlation between the data and the regression line, this curve allows for accurate prediction of the total cost associated with citric acid for WWTPs with flow rates ranging from 50 MLD to 150 MLD, thus simplifying the cost estimation process.

The unit cost co-efficient functions for different items of large range WWTPs with MBR technology as displayed in the Figures 59 to 78 are tabulated in Table 27:

Table 27: Large range WWTPs with MBR - Functions for calculations of cost

Large range WWTPs with MBR - Functions for calculations of total bare construction cost							
Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient function for unit cost (y)**	**Cost for x mld capacity WWTP with MBBR**	
			Value	***Unit***		***Value***	***Unit***
1	x	Cost of total earthwork	C_1	per ft^3	$y_1 = (5203.3*x) + 72731$	C_1*y_1	currency
2	x	Cost of total quantity of RCC	C_2	per ft^3	$y_2 = (2316.9*x) + 34926$	C_2*y_2	currency
3	x	Cost of total quantity of handrails	C_3	per ft	$y_3 = (65.287*x) + 1183.8$	C_3*y_3	currency
4	x	Cost of houses or buildings	C_4	per ft^2	$y_4 = (19.734*x) + 2351.2$	C_4*y_4	currency
5	x	Cost of blowers	C_5	per blower	$y_5 = (0.2193*x) + 5.9573$	C_6*y_6	currency
6	x	Cost of installation man-hours	C_6	per hr	$y_6 = (48.586*x) + 106.06$	C_7*y_7	currency
7	x	Cost of crane requirements for installation	C_7	per hr	$y_7 = (4.955*x)$	C_8*y_8	currency
8	x	Cost of pumps	C_8	Purchase cost of standard pump (3000 gpm)	$y_8 = (0.3506*x) + 5.3255$	C_9*y_9	currency
9	x	Cost of diffusers	C_9	per diffuser	$y_9 = (42.787*x) - 0.4455$	$C_{10}*y_{10}$	currency
10	x	Cost of swing arm diffuser headers	C_{10}	per header	$y_{10} = (2.1802*x)$	$C_{11}*y_{11}$	currency
11	x	Cost of membrane modules	C_{11}	per module	$y_{11} = (159.86*x)$	$C_{12}*y_{12}$	currency
12	x	Cost of air piping	C_{12}	cost index	$y_{12} = (490.18*x) + 9054.2$	$C_{13}*y_{13}$	currency

Table 27: Large range WWTPs with MBR - Functions for calculations of cost (continued)

Large range WWTPs with MBR - Functions for calculations of levelized cost for 25 years of operation							
Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient function for unit cost (y)**	**Cost for x mld capacity WWTP with MBBR**	
			Value	***Unit***		***Value***	***Unit***
13	x	Cost of operation and maintenance material costs			$y_{13} = [(3.0174*x) + 102.02]*10^5$	y_{13}	currency
14	x	Cost of energy requirement	C_{15}	per kwhr	$y_{14} = (148265*x) + 10196$	$C_{14}*y_{14}$	currency
15	x	Cost of operation and maintenance hours	C_{16}	per hr	$y_{15} = (83.118*x) + 5862.6$	$C_{15}*y_{15}$	currency
16	x	Cost of chemical for maintenance - sodium hypochlorite	C_{15}	per kg of solution	$y_{16} = (843.65*x) + 890.49$	$C_{16}*y_{16}$	currency
17	x	Cost of chemical for maintenance - citric acid	C_{16}	per kg of solution	$y_{17} = (119.61*x) + 312.51$	$C_{17}*y_{17}$	currency
		Present worth factor considered				9.82	
		Levelized cost for 25 years of operation			$9.82 * [y_{13} + (C_{14}*y_{14}) + (C_{15}*y_{15}) + (C_{16}*y_{16}) + (C_{17}*y_{17})]$		currency

The co-efficients for respective unit costs have been calculated based on derived functions for a case of 100 mld capacity WWTP with MBR technology and costs with unit cost base in India at year 2021 are furnished in Table – 28:

Table 28: Large range WWTPs with MBR - Validation for calculated costs

Large range WWTPs with MBR - Validation for calculated total bare construction cost

Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient function for unit cost (y)**	**Cost for 100.0 mld capacity WWTP with MBR**
			Value	***Unit***		***Value***
1	100.0	Cost of total earthwork	₹ 10.38	per ft^3	593061	₹ 6,157,378.01
2	100.0	Cost of total quantity of RCC	₹ 243.72	per ft^3	266616	₹ 64,980,836.23
3	100.0	Cost of total quantity of handrails	₹ 600.00	per ft	7712.5	₹ 4,627,500.00
4	100.0	Cost of houses or buildings	₹ 7,500.00	per ft^2	4324.6	₹ 32,434,500.00
5	100.0	Cost of blowers	₹ 53,00,895.04	per blower	27.8873	₹ 147,827,650.15
6	100.0	Cost of installation man-hours	₹ 125.00	per hr	4964.66	₹ 620,582.50
7	100.0	Cost of crane requirements for installation	₹ 1,000.00	per hr	495.5	₹ 495,500.00
8	100.0	Cost of pumps	₹ 12,93,750.00	Purchase cost of standard pump (3000 gpm)	40.3855	₹ 52,248,740.63
9	100.0	Cost of diffusers	₹ 1,200.00	per diffuser	4278.2545	₹ 5,133,905.40
10	100.0	Cost of swing arm diffuser headers	₹ 35,000.00	per header	218.02	₹ 7,630,700.00
11	100.0	Cost of membrane modules	₹ 1,63,506.94	per module	15986	₹ 2,613,822,013.89
12	100.0	Cost of air piping	₹ 750.00	cost index	58072.2	₹ 43,554,150.00
		Consolidated bare cost				₹ 2,979,533,456.81

Table 28: Large range WWTPs with MBR - Validation for calculated costs (continued)

Large range WWTPs with MBR - Validation for calculated levelized cost for 25 years of operation						
Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient function for unit cost (y)**	**Cost for 100.0 mld capacity WWTP with MBR**
			Value	***Unit***		***Value***
13	100.0	Cost of operation and maintenance material costs			40376000	₹ 40,376,000.00
14	100.0	Cost of energy requirement	₹ 6.00	per kwhr	14836696	₹ 89,020,176.00
15	100.0	Cost of operation and maintenance hours	₹ 250.00	per hr	14174.4	₹ 3,543,600.00
16	100.0	Cost of chemical for maintenance - sodium hypochlorite	₹ 30.00	per kg of solution	85255.49	₹ 2,557,664.70
17	100.0	Cost of chemical for maintenance - citric acid	₹ 90.00	per kg of solution	12273.51	₹ 1,104,615.90
		Present worth factor considered				9.82
		Levelized cost for 25 years of operation			$9.82 * [y_{13} + (C_{14}*y_{14}) + (C_{15}*y_{15}) + (C_{16}*y_{16}) + (C_{17}*y_{17})]$	₹ 1,341,784,575.15

It is noted that variation is within 1 % for each of estimated total bare construction cost and levelized cost of 25 years of operation.

The unit cost co-efficient functions for different items of medium range WWTPs with MBBR technology as displayed in the Figures 59 to 78 are tabulated in Table 29:

Table 29: Large range WWTPs with MBBR - Functions for calculations of cost

Large range WWTPs with MBBR - Functions for calculations of total bare construction cost

Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient function for unit cost (y)**	**Cost for x mld capacity WWTP with MBBR**	
			Value	***Unit***		***Value***	***Unit***
1	x	Cost of total earthwork	C_1	per ft^3	$y_1 = (29401*x) + 261939$	C_1*y_1	currency
2	x	Cost of total quantity of RCC	C_2	per ft^3	$y_2 = (3976.8*x) + 73716$	C_2*y_2	currency
3	x	Cost of total quantity of handrails	C_3	per / ft	$y_3 = (18.418*x) + 882.41$	C_3*y_3	currency
4	x	Cost of houses or buildings	C_4	per f^{t2}	$y_4 = (10.243*x) + 2925.5$	C_4*y_4	currency
5	x	Cost of clarifier mechanisms	C_5	per mechanism	$y_5 = (0.1762*x) + 4.3918$	C_5*y_5	currency
6	x	Cost of blowers	C_6	per blower	$y_6 = (0.1672*x) + 2.5745$	C_6*y_6	currency
7	x	Cost of installation man-hours	C_7	per hr	$y_7 = (63.415*x) + 725.33$	C_7*y_7	currency
8	x	Cost of crane requirements for installation	C_8	per hr	$y_8 = (6.3415*x) + 72.534$	C_8*y_8	currency
9	x	Cost of pumps	C_9	Purchase cost of standard pump (3000 gpm)	$y_9 = (0.1592*x) + 4.5645$	C_9*y_9	currency
10	x	Cost of diffusers	C_{10}	per diffuser	$y_{10} = (28.796*x) + 2.002$	$C_{10}*y_{10}$	currency
11	x	Cost of swing arm diffuser headers	C_{11}	per header	$y_{11} = 1.4834*x$	$C_{11}*y_{11}$	currency
12	x	Cost of carrier media	C_{12}	per m^3	$y_{12} = (38.651*x)$	$C_{12}*y_{12}$	currency
13	x	Cost of air piping	C_{13}	cost index	$y_{13} = (382.59*x)$	$C_{13}*y_{13}$	currency

Table 29: Large range WWTPs with MBBR - Functions for calculations of cost (continued)

Large range WWTPs with MBBR - Functions for calculations of levelized cost for 25 years of operation							
Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient function for unit cost (y)**	**Cost for x mld capacity WWTP with MBBR**	
			Value	***Unit***		***Value***	***Unit***
14	x	Cost of operation and maintenance material costs			$y_{14} = [(0.3599*x) + 11.988]*10^5$	y_{14}	currency
15	x	Cost of energy requirement	C_{15}	per kwhr	$y_{15} = (82795*x) + 29326$	$C_{15}*y_{15}$	currency
16	x	Cost of operation and maintenance hours	C_{16}	per hr	$y_{16} = (117.94*x) + 10723$	$C_{16}*y_{16}$	currency
		Present worth factor considered				9.82	
		Levelized cost for 25 years of operation			$9.82 * [y_{14} + (C_{15}*y_{15}) + (C_{16}*y_{16})]$		currency

The co-efficients for respective unit costs have been calculated based on derived functions for a case of 100 mld capacity WWTP with MBBR technology and costs with unit cost base in India at year 2021 are furnished in Table – 30:

Table 30: Large range WWTPs with MBBR - Validation for calculated costs

Large range WWTPs with MBBR - Validation for calculated total bare construction cost

Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient function for unit cost (y)**	**Cost for 100.0 mld capacity WWTP with MBBR**
			Value	***Unit***		***Value***
1	100.0	Cost of total earthwork	₹ 10.38	per ft^3	3202039	₹ 33,244,749.75
2	100.0	Cost of total quantity of RCC	₹ 243.72	per ft^3	471396	₹ 114,890,727.78
3	100.0	Cost of total quantity of handrails	₹ 600.00	per / ft	2724.21	₹ 1,634,526.00
4	100.0	Cost of houses or buildings	₹ 7,500.00	per ft^2	3949.8	₹ 29,623,500.00
5	100.0	Cost of clarifier mechanisms	₹ 75,00,000.00	per mechanism	22.0118	₹ 165,088,500.00
6	100.0	Cost of blowers	₹ 53,00,895.04	per blower	19.2945	₹ 102,278,119.28
7	100.0	Cost of installation man-hours	₹ 125.00	per hr	7066.83	₹ 883,353.75
8	100.0	Cost of crane requirements for installation	₹ 1,000.00	per hr	706.684	₹ 706,684.00
9	100.0	Cost of pumps	₹ 12,93,750.00	Purchase cost of standard pump (3000 gpm)	20.4845	₹ 26,501,821.88
10	100.0	Cost of diffusers	₹ 1,200.00	per diffuser	2881.602	₹ 3,457,922.40
11	100.0	Cost of swing arm diffuser headers	₹ 35,000.00	per header	148.34	₹ 5,191,900.00
12	100.0	Cost of carrier media	₹ 11,000.00	per m^3	3865.1	₹ 42,516,100.00
13	100.0	Cost of air piping	₹ 750.00	cost index	38259	₹ 28,694,250.00
		Consolidated bare cost				₹ 554,712,154.84

Table 30: Large range WWTPs with MBBR - Validation for calculated costs (continued)

Large range WWTPs with MBBR - Validation for calculated levelized cost of 25 years operation						
Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient function for unit cost (y)**	**Cost for 100.0 mld capacity WWTP with MBBR**
			Value	***Unit***		***Value***
14	100.0	Cost of operation and maintenance material costs			4797800	₹ 4,797,800.00
15	100.0	Cost of energy requirement	₹ 6.00	per kwhr	8308826	₹ 49,852,956.00
16	100.0	Cost of operation and maintenance hours	₹ 250.00	per hr	22517	₹ 5,629,250.00
		Present worth factor considered				9.82
		Levelized cost for 25 years of operation			$9.82 * [y_{14} + (C_{15}*y_{15}) + (C_{16}*y_{16})]$	₹ 592,105,157.52

It is noted that variation is around5 % of estimated total bare construction cost and around1 % of estimated levelized cost of 25 years of operation with reference to those predicted earlier through cost functions.

The unit cost co-efficient functions for different items of large range WWTPs with SBR technology as displayed in the Figures 59 to 78 are tabulated in Table 31.

Table 31: Large range WWTPs with SBR - Functions for calculations of cost

Large range WWTPs with SBR - Functions for calculations of total bare construction cost

Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient function for unit cost (y)**	**Cost for x mld capacity WWTP with SBR**	
			Value	***Unit***		***Value***	***Unit***
1	x	Cost of total earthwork	C1	per ft^3	$y_1 =(23277*x) + 87946$	C_1*y_1	currency
2	x	Cost of total quantity of RCC	C2	per ft^3	$y_2 = (9633.8*x) + 39843$	C_2*y_2	currency
3	x	Cost of total quantity of handrails	C3	per / ft	$y_3 = (237.24*x) + 1791.2$	C_3*y_3	currency
4	x	Cost of houses or buildings	C4	per ft^2	$y_4 = (6.0531*x) + 2441.3$	C_4*y_4	currency
5	x	Cost of blowers	C_5	per blower	$y_5 = (0.2151*x) + 8.47$	C_5*y_5	currency
6	x	Cost of installation man-hours	C_6	per hr	$y_6 = (6369.8*x)$	C_6*y_6	currency
7	x	Cost of crane requirements for installation	C_7	per hr	$y_7 = (289.58*x) - 12545$	C_7*y_7	currency
8	x	Cost of pumps	C_8	Purchase cost of standard pump (3000 gpm)	$y_8 = 0.58$	C_8*y_8	currency
9	x	Cost of diffusers	C_9	per diffuser	$y_9 = (2545.8*x) - 110361$	C_9*y_9	currency
10	x	Cost of swing arm diffuser headers	C_{10}	per header	$y_{10} = (127.41*x) - 5520$	$C_{10}*y_{10}$	currency
11	x	Cost of decanters	C_{11}	per m^3	$y_{11} = (706.44*x)$	$C_{11}*y_{11}$	currency
12	x	Cost of air piping	C_{12}	cost index	$y_{12} = (472.77*x) + 14348$	$C_{12}*y_{12}$	currency

Table 31: Large range WWTPs with SBR - Functions for calculations of cost (continued)

Functions for calculations of levelized cost for 25 years of operation of large range WWTP with SBR

Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient function for unit cost (y)**	**Cost for x mld capacity WWTP with SBR**	
			Value	***Unit***		***Value***	***Unit***
13	x	Cost of operation and maintenance material costs			$y_{13} = [(1.546*x) - 15.569]*10^5$	y_{13}	currency
14	x	Cost of energy requirement	C_{14}	per kwhr	$y_{14} = (113972*x) + 770413$	$C_{14}*y_{15}$	currency
15	x	Cost of operation and maintenance hours	C_{15}	per hr	$y_{15} = (54.661*x) + 5611.7$	$C_{15}*y_{15}$	currency
		Present worth factor considered				9.82	
		Levelized cost for 25 years of operation			$9.82 * [y_{13} + (C_{14}*y_{14}) + (C_{15}*y_{15})]$		currency

The co-efficients for respective unit costs have been calculated based on derived functions for a case of 100 mld capacity WWTP with SBR technology and costs with unit cost base in India at year 2021 are furnished in Table – 32.

Table 32: Large range WWTPs with SBR - Validation for calculated costs

Large range WWTPs with SBR - Validation for calculated total bare construction cost						
Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient for unit cost (y)**	**Cost for 100.0 mld capacity WWTP with SBR**
			Value	***Unit***		***Value***
1	100.0	Cost of total earthwork	₹ 10.38	per ft^3	2415646	₹ 25,080,127.62
2	100.0	Cost of total quantity of RCC	₹ 243.72	per ft^3	1003223	₹ 244,509,967.40
3	100.0	Cost of total quantity of handrails	₹ 600.00	per ft	25515.2	₹ 15,309,120.00
4	100.0	Cost of houses or buildings	₹ 7,500.00	per ft^2	3046.61	₹ 22,849,575.00
5	100.0	Cost of blowers	₹ 53,00,895.04	per blower	29.98	₹ 158,920,833.20
6	100.0	Cost of installation man-hours	₹ 125.00	per hr	636980	₹ 79,622,500.00
7	100.0	Cost of crane requirements for installation	₹ 1,000.00	per hr	16413	₹ 16,413,000.00
8	100.0	Cost of pumps	₹ 12,93,750.00	Purchase cost of standard pump (3000 gpm)	0.58	₹ 750,375.00
9	100.0	Cost of diffusers	₹ 1,200.00	per diffuser	144219	₹ 173,062,800.00
10	100.0	Cost of swing arm diffuser headers	₹ 35,000.00	per header	7221	₹ 252,735,000.00
11	100.0	Cost of decanters	₹ 2,400.00	per m^3/h	70644	₹ 169,545,600.00
12	100.0	Cost of air piping	₹ 750.00	cost index	61625	₹ 46,218,750.00
		Consolidated bare cost				₹ 1,205,017,648.22

Table 32: Large range WWTPs with SBR - Validation for calculated costs (continued)

Large range WWTPs with SBR - Validation for calculated levelized cost for 25 years of operation						
Sl. no.	**Capacity in mld**	**Cost component**	**Unit cost**		**Co-efficient for unit cost (y)**	**Cost for 100.0 mld capacity WWTP with SBR**
			Value	***Unit***		***Value***
13	100.0	Cost of operation and maintenance material costs			13903100	₹ 13,903,100.00
14	100.0	Cost of energy requirement	₹ 6.00	kwhr/year	12167613	₹ 73,005,678.00
15	100.0	Cost of operation and maintenance hours	₹ 250.00	per hr	11077.8	₹ 2,769,450.00
		Present worth factor considered				9.82
		Levelized cost for 25 years of operation			$9.82 * [y_{13} + (C_{14}*y_{14}) + (C_{15}*y_{15})]$	₹ 880,871,533.36

It has been scrutinized and noted that variation is within 9 % for estimated total bare construction cost and within 1 % for estimated levelized cost of 25 years of operation.

CHAPTER – 6:

CONCLUSIONS

6.0 Conclusions

It is concluded that accurate cost forecasts applicable in India can be achieved using the cost functions developed for three different capacity groups of WWTPs employing MBR, MBBR, and SBR technologies. The approach of utilizing basic engineering design and cost estimations based on schedules of rates ensures high accuracy. This method bypasses the difficulties and time-consuming process of collecting historical cost data. The procedure outlined in this study can be adopted to develop cost functions for any region, either by using region-specific schedules of rates for precise forecasts or by adjusting the projected costs (from the developed cost functions) using the specific currency conversion factor of the concerned country for approximate forecasts.

The 3-D cost response maps, developed based on applicable engineering design criteria and devoid of any historical references, predict overall costs, including capital, operation, and maintenance expenditures, for WWTPs with MBR technology within specified ranges of capacity and inlet BOD. These maps, generated without historical references, enable accurate cost forecasting for the specified technologies and conditions.

Creating 3-D surface or contour cost response maps for any location is possible by developing the cost functions illustrated in this study. However, the schedules of rates and quotes for non-scheduled items need to be considered as applicable to the specific location.

Sensitivity analysis has been conducted and validated, ensuring the worldwide applicability of the developed cost functions.

Policy-makers and stakeholders related to construction and operation of WWTPs with MBR, MBBR and SBR technologies may use the above cost functions and cost response maps in respect of BOD removal for rapid cost estimate at any place in India subject to adjustments based on applicable cost indices since these functions and maps are based on the schedule of rates and quotes for non-scheduled items specific to the year 2021. As an alternative, co--efficient functions for unit costs as developed may also be used to predict tentative costs for construction and operation of WWTPs with MBR, MBBR and SBR technologies

For places other than India, co-efficient functions for unit costs as developed may be used.

Further research study may be taken up as follows:

a) To develop cost functions as well as cost response maps and conduct sensitivity analysis with due consideration of nitrification and denitrification in addition to removal of BOD by use of MBR, MBBR & SBR technologies based on costs estimated through rational engineering methodology as elaborated in this research thesis.

b) To develop cost functions as well as cost response maps and conduct sensitivity analysis for the proven technologies other than MBR, MBBR & SBR based on methodology as elaborated in this research thesis.

Such future research initiative would also enrich the archive of rapid cost estimation methodologies and tools. This would enable policy-makers and stakeholders to adopt a prudent decision for selection of most cost-efficient technology in respect of construction and operation of WWTP.

REFERENCES

References

[1] United Nations Environment Programme. (2015). Economic Valuation of Wastewater - The cost of action and the cost of no action.

[2] Budget, Government of India. (2021-2022).

[3] Central Pollution Control Board – Government of India. (2021). National inventory of Sewage Treatment Plant.

[4] Central Public Health and Environmental Engineering Organization in collaboration with JICA. (2013). Manual on Sewerage and Sewage Treatment Systems.

[5] L. Li, G. Yan, H. Wang, Z. Chu, Z. Li, Y. Ling, T. Wu, Denitrification and microbial community in MBBR using A. donax as carbon source and biofilm carriers for reverse osmosis concentrate treatment, J. Environ. Sci. 84 (2019) 133–143, https://doi.org/10.1016/j.jes.2019.04.030 (China).

[6] [A. di Biase, M.S. Kowalski, T.R. Devlin, J.A. Oleszkiewicz, Moving bed biofilm reactor technology in municipal wastewater treatment: a review, J. Environ. Manag. 247 (2019) 849–866, https://doi.org/10.1016/j.jenvman.2019.06.053.

[7] A. Abdelfattah, I. Hossain, L. Cheng, High-strength wastewater treatment using microbial biofilm reactor: a critical review, World J. Microbiol. Biotechnol. 36 (2020) 1–10, https://doi.org/10.1007/s11274-020-02853-y.

[8] A. Barwal, R. Chaudhary, To study the performance of biocarriers in moving bed biofilm reactor (MBBR) technology and kinetics of biofilm for retrofitting the existing aerobic treatment systems: a review, Rev. Environ. Sci. Biotechnol. 13 (2014) 285–299, https://doi.org/10.1007/s11157-014-9333-7.

[9] A. Ding, F. Qu, H. Liang, J. Ma, Z. Han, H. Yu, S. Guo, G. Li, A novel integrated vertical membrane bioreactor (IVMBR) for removal of nitrogen from synthetic wastewater/domestic sewage, Chem. Eng. J. 223 (2013) 908–914, https://doi. org/10.1016/j.cej.2013.01.096.

[10] A. Joss, S. Zabczynski, A. G¨obel, B. Hoffmann, D. L¨offler, C.S. McArdell, T. A. Ternes, A. Thomsen, H. Siegrist, Biological degradation of pharmaceuticals in municipal wastewater treatment: proposing a classification scheme, Water Res. 40 (2006) 1686–1696, https://doi.org/10.1016/j.watres.2006.02.014.

[11] A. Majumder, A.K. Gupta, Enhanced photocatalytic degradation of 17β-estradiol by polythiophene modified Al-doped ZnO: optimization of synthesis parameters using multivariate optimization techniques, J. Environ. Chem. Eng. 8 (2020), 104463, https://doi.org/10.1016/j.jece.2020.104463.

[12] A. Majumder, A.K. Gupta, P.S. Ghosal, M. Varma, A review on hospital wastewater treatment: a special emphasis on occurrence and removal of pharmaceutically active compounds, resistant microorganisms, and SARS-CoV-2, J. Environ. Chem. Eng. 9 (2021), 104812, https://doi.org/10.1016/j. jece.2020.104812.

[13] A. Majumder, B. Gupta, A.K. Gupta, Pharmaceutically active compounds in aqueous environment: a status, toxicity and insights of remediation, Environ. Res. 176 (2019), 108542, https://doi.org/10.1016/j.envres.2019.108542.

[14] A. Majumder, D. Saidulu, A.K. Gupta, P.S. Ghosal, Predicting the trend and utility of different photocatalysts for degradation of pharmaceutically active compounds: a special emphasis on photocatalytic materials, modifications, and performance comparison, J. Environ. Manag. 293 (2021), 112858, https://doi. org/10.1016/j.jenvman.2021.112858.

[15] A. Rodríguez-Calvo, J. Gonzalez-Lopez, L.M. Ruiz, M.´A. G´omez-Nieto, B. Mu˜noz- Palazon, Effect of ultrasonic frequency on the bacterial community structure during biofouling formation in microfiltration membrane bioreactors for wastewater treatment, Int. Biodeterior. Biodegrad. 155 (2020), 105102, https:// doi.org/10.1016/j.ibiod.2020.105102.

[16] A. Rodriguez-Sanchez, B. Mu˜noz-Palazon, M. Hurtado-Martinez, A. Mikola, J. Gonzalez-Lopez, R. Vahala, A. Gonzalez-Martinez, Analysis of microbial communities involved in organic matter and nitrogen removal in a full-scale moving bed biofilm reactor located near the Polar Arctic Circle, Int. Biodeterior. Biodegrad. 146 (2020), 104830, https://doi.org/10.1016/j.ibiod.2019.104830.

[17] A. Rodriguez-Sanchez, J.C. Leyva-Diaz, J. Gonzalez-Lopez, J.M. Poyatos, Membrane bioreactor and hybrid moving bed biofilm reactor-membrane bioreactor for the treatment of variable salinity wastewater: influence of biomass concentration and hydraulic retention time, Chem. Eng. J. 336 (2018) 102–111, https://doi.org/10.1016/j.cej.2017.10.118.

[18] A. Sepehri, M. Sarrafzadeh, Effect of nitrifiers community on fouling mitigation and nitrification efficiency in a membrane bioreactor, Chem. Eng. Process. Process Intensif. 128 (2018) 10–18, https://doi.org/10.1016/j.cep.2018.04.006.

[19] A. Sepehri, M. Sarrafzadeh, M. Avateffazeli, Interaction between Chlorella vulgaris and nitrifying-enriched activated sludge in the treatment of wastewater with low C/N ratio, J. Clean. Prod. 247 (2020), 119164, https://doi.org/ 10.1016/j.jclepro.2019.119164.

[20] A. Singh, S.J. Kamble, M. Sawant, Y. Chakravarthy, A. Kazmi, E. Aymerich, M. Starkl, M. Ghangrekar, L. Philip, Technical, hygiene, economic, and life cycle assessment of full-scale moving bed biofilm reactors for wastewater treatment in India, Environ. Sci. Pollut. Res. 25 (2018) 2552–2569, https://doi.org/10.1007/ s11356-017-0605-y.

[21] A. Srivastava, V.K. Parida, A. Majumder, B. Gupta, A.K. Gupta, Treatment of saline wastewater using physicochemical, biological, and hybrid processes: Insights into inhibition mechanisms, treatment efficiencies and performance enhancement, J. Environ. Chem. Eng. 9 (2021), 105775, https://doi.org/ 10.1016/j.jece.2021.105775.

[22] A.A.L. Zinatizadeh, E. Ghaytooli, Simultaneous nitrogen and carbon removal from wastewater at different operating conditions in a moving bed biofilm reactor (MBBR): process modeling and optimization, J. Taiwan Inst. Chem. Eng. 53 (2015) 98–111, https://doi.org/10.1016/j.jtice.2015.02.034.

[23] A.B. Rostam, M. Taghizadeh, Advanced oxidation processes integrated by membrane reactors and bioreactors for various wastewater treatments: a critical review, J. Environ. Chem. Eng. 8 (2020), 104566, https://doi.org/10.1016/j. jece.2020.104566.

[24] A.D. Santos, R.C. Martins, R.M. Quinta-ferreira, L.M. Castro, Moving bed biofilm reactor (MBBR) for dairy wastewater treatment, Energy Rep. 6 (2020) 340–344, https://doi.org/10.1016/j.egyr.2020.11.158.

[25] A.F. Viero, T.M. de Melo, A.P.R. Torres, N.R. Ferreira, G.L. Sant'Anna, C. P. Borges, V.M.J. Santiago, The effects of long-term feeding of high organic loading in a submerged membrane bioreactor treating oil refinery wastewater, J. Membr. Sci. 319 (2008) 223–230, https://doi.org/10.1016/j. memsci.2008.03.038.

[26] A.H. Khan, H. Abdul Aziz, N.A. Khan, S. Ahmed, M.S. Mehtab, S. Vambol, V. Vambol, F. Changani, S. Islam, Pharmaceuticals of emerging concern in hospital wastewater: removal of ibuprofen and ofloxacin drugs using MBBR method, Int. J. Environ. Anal. Chem. 185533 (2020) 1–15, https://doi.org/ 10.1080/03067319.2020.1855333.

[27] A.H. Khan, H.A. Aziz, N.A. Khan, M.A. Hasan, S. Ahmed, I.H. Farooqi, A. Dhingra, V. Vambol, F. Changani, M. Yousefi, S. Islam, N. Mozaffari, M.S. Mahtab, Impact, disease outbreak and the eco-hazards associated with pharmaceutical residues: a critical review, Int. J. Environ. Sci. Technol. (2021), https://doi.org/10.1007/ s13762-021-03158-9.

[28] A.K.M. Ashadullah, M. Shafiquzzaman, H. Haider, M. Alresheedi, M.S. Azam, A. R. Ghumman, Wastewater treatment by microalgal membrane bioreactor: evaluating the effect of organic loading rate and hydraulic residence time, J. Environ. Manag. 278 (2021), 111548, https://doi.org/10.1016/j. jenvman.2020.111548.

[29] A.L. Carlson, G.T. Daigger, N.G. Love, E. Hart, Multi-year diagnosis of unpredictable fouling occurrences in a full-scale membrane bioreactor, Water Sci. Technol. 82 (2020) 524–536, https://doi.org/10.2166/wst.2020.354.

[30] Abu-Ghunmi, L.N. and Jamrah, A.I. (2006). Biological treatment of textile wastewater using sequencing batch reactor technology. Environmental Modeling & Assessment, 11(4), pp. 333-343.

[31] Akunna, J.C. and Shepherd, W. (2001). Comparison of RBC and SBR systems for the treatment of sewage from small communities. Water and Environment Journal, 15(2), pp. 147-151.

[32] Arora, M.L., Barth, E.F. and Umphres, M.B. (1985). Technology evaluation of sequencing batch reactors. Journal of Water Pollution Control Federation, 57(8), pp. 867-875.

[33] Artan, N. and Orhon D. (2005). Mechanism and Design of Sequencing Batch Reactors for Nutrient Removal. Vol. 19. IWA Publishing, London.

[34] Artan, N., Wilderer, P., Orhon, D., Morgenroth, E. and Özgür, N. (2001). The mechanism and design of sequencing batch reactor systems for nutrient removal-the state of the art. Water Science and Technology, 43(3), pp. 53-60.

[35] Artan, N., Wilderer, P., Orhon, D., Tasli, R. and Morgenroth, E. (2002). Model evaluation and optimisation of nutrient removal potential for sequencing batch reactors. Water SA, 28(4), pp. 423-432.

[36] B. Dong, H. Chen, Y. Yang, Q. He, X. Dai, Treatment of printing and dyeing wastewater using MBBR followed by membrane separation process, Desalin. Water Treat. 52 (2014) 4562–4567, https://doi.org/10.1080/ 19443994.2013.803780.

[37] B. Hou, H. Han, S. Jia, H. Zhuang, Q. Zhao, P. Xu, Effect of alkalinity on nitrite accumulation in treatment of coal chemical industry wastewater using moving bed biofilm reactor, J. Environ. Sci. 26 (2014) 1014–1022, https://doi.org/ 10.1016/S1001-0742(13)60517-3.

[38] B. Lesjean, S. Rosenberger, C. Laabs, M. Jekel, R. Gnirss, G. Amy, Correlation between membrane fouling and soluble/colloidal organic substances in membrane bioreactors for municipal wastewater treatment, Water Sci. Technol. 51 (2018) 1–8, https://doi.org/10.2166/wst.2005.0615.

[39] B. Rusten, B. Eikebrokk, Y. Ulgenes, E. Lygren, Design and operations of the Kaldnes moving bed biofilm reactors, Aquac. Eng. 34 (2006) 322–331, https:// doi.org/10.1016/j.aquaeng.2005.04.002.

[40] Beun, J.J., Dircks, K., Van Loosdrecht, M.C.M. and Heijnen, J.J. (2002). Poly-β-hydroxybutyrate metabolism in dynamically fed mixed microbial cultures. Water Research, 36(5), pp. 1167-1180.

[41] Brenner, A., Chozick, R. and Irvine, R.L. (1992). Treatment of a high ‐ strength, mixed phenolic waste in an SBR. Water Environment Research, 64(2), pp. 128-133.

[42] Buitrón, G., Schoeb, M.E. and Moreno, J. (2003). Automated sequencing batch bioreactor under extreme peaks of 4-chlorophenol. Water Science and Technology, 47(10), pp. 175-181.

[43] C. Chen, M. Sun, Z. Liu, J. Zhang, K. Xiao, X. Zhang, G. Song, J. Chang, G. Liu, H. Wang, X. Huang, Robustness of granular activated carbon-synergized anaerobic membrane bioreactor for pilot-scale application over a wide seasonal temperature change, Water Res. 189 (2021), 116552, https://doi.org/10.1016/j. watres.2020.116552.

[44] C. Valderrama, G. Ribera, N. Bahí, M. Rovira, T. Gim´enez, R. Nomen, S. Lluch, M. Yuste, X. Martinex-Lado, Winery wastewater treatment for water reuse purpose: conventional activated sludge versus membrane bioreactor (MBR) a comparative case study, Desalination 306 (2012) 1–7, https://doi.org/10.1016/j. desal.2012.08.016.

[45] Cervantes, F. J., Pavlostathis, S. G. and van Haandel, A. (2006). Advanced Biological Treatment Processes for Industrial Wastewaters. IWA Publishing. London

[46] Chiesa, S.C. and Irvine, R.L. (1985). Growth and control of filamentous microbes in activated sludge: an integrated hypothesis. Water Research, 19(4), pp. 471-479.

[47] Coelho, M.A.Z., Russo, C. and Araujo, O.Q.F. (2000). Optimization of a sequencing batch reactor for biological nitrogen removal. Water Research, 34(10), pp. 2809-2817.

[48] D. Di Trapani, G. Di Bella, G. Mannina, M. Torregrossa, G. Viviani, Comparison between moving bed-membrane bioreactor (MB-MBR) and membrane bioreactor (MBR) systems: influence of wastewater salinity variation, Bioresour. Technol. 162 (2014) 60–69, https://doi.org/10.1016/j.biortech.2014.03.126.

[49] D. Hu, Z. Zhou, X. Shen, H. Wei, L. Jiang, Y. Lv, Effects of alkalinity on membrane bioreactors for reject water treatment: performance improvement, fouling mitigation and microbial structures, Bioresour. Technol. 197 (2015) 217–226, https://doi.org/10.1016/j.biortech.2015.08.082.

[50] D. Saidulu, B. Gupta, A.K. Gupta, P.S. Ghosal, A review on occurrences, eco-toxic effects, and remediation of emerging contaminants from wastewater: special emphasis on biological treatment based hybrid systems, J. Environ. Chem. Eng. 9 (2021), 105282, https://doi.org/10.1016/j.jece.2021.105282.

[51] D. Zhao, C. Fu, X. Bi, H. Yong, X. Shi, Effects of coarse and fine bubble aeration on performances of membrane filtration and denitrification in moving bed membrane bioreactors, Sci. Total Environ. 772 (2021), 145513, https://doi.org/ 10.1016/j.scitotenv.2021.145513.

[52] D.M. Warsinger, S. Chakraborty, E.W. Tow, M.H. Plumlee, C. Bellona, S. Loutatidou, L. Karimi, A.M. Mikelonis, A. Achilli, A. Ghassemi, L.P. Padhye, S. A. Snyder, S. Curcio, C.D. Vecitis, H.A. Arafat, J.H. Lienhard, A review of polymeric membranes and processes for potable water reuse, Prog. Polym. Sci. 81 (2018) 209–237, https://doi.org/10.1016/j.progpolymsci.2018.01.004.

[53] Demuynck, C., Vanrolleghem, P., Mingneau, C., Liessens, J. and Verstraete, W. (1994). NDBEPR process optimization in SBRs: reduction of external carbon-source and oxygen supply. Water Science and Technology, 30(4), pp. 169-179

[54] Dionisi, D. (2017). Biological Wastewater Treatment Processes: Mass and Heat Balances. CRC press, Florida.

[55] Dionisi, D., Majone, M., Levantesi, C., Bellani, A. and Fuoco, A. (2006). Effect of feed length on settleability, substrate uptake and storage in a sequencing batch reactor treating an industrial wastewater. Environmental Technology, 27(8), pp. 901-908.

[56] Dionisi, D., Majone, M., Tandoi, V. and Beccari, M. (2001). Sequencing batch reactor: influence of periodic operation on physiological state, microbial composition and performance of activated sludge in biological wastewater treatment. Industrial and Engineering Chemistry Research, 40, pp. 5110-5119.

[57] Dionisi, D., Rasheed, A.A. and Majumder, A. (2016). A new method to calculate the periodic steady state of sequencing batch reactors for biological wastewater treatment: model development and applications. Journal of Environmental Chemical Engineering, 4(3), pp. 3665-3680.

[58] E. Baddour, N. Farhoud, M. Sharholy, I. Mohammed, A. Magid, Biological treatment of poultry slaughterhouses wastewater by using aerobic moving bed biofilm reactor, Int. Res. J. Public Environ. Health 3 (2016) 96–106.

[59] E. Katsou, S. Malamis, M. Loizidou, Performance of a membrane bioreactor used for the treatment of wastewater contaminated with heavy metals, Bioresour. Technol. 102 (2011) 4325–4332, https://doi.org/10.1016/j. biortech.2010.10.118.

[60] E. Kora, D. Theodorelou, G. Gatidou, M.S. Fountoulakis, Removal of polar micropollutants from domestic wastewater using a methanogenic – aerobic moving bed biofilm reactor system, Chem. Eng. J. 382 (2020), 122983, https:// doi.org/10.1016/j.cej.2019.122983.

[61] F. Meng, S.R. Chae, A. Drews, M. Kraume, H.S. Shin, F. Yang, Recent advances in membrane bioreactors (MBRs): membrane fouling and membrane material, Water Res. 43 (2009) 1489–1512, https://doi.org/10.1016/j.watres.2008.12.044.

[62] F. Morgan-Sagastume, S. Jacobsson, L.E. Olsson, M. Carlsson, M. Gyllenhammar, I. S´arv´ari Horv´ath, Anaerobic treatment of oil-contaminated wastewater with methane production using anaerobic moving bed biofilm reactors, Water Res. 163 (2019), 114851, https://doi.org/10.1016/j.watres.2019.07.018.

[63] F. Perreault, H. Jaramillo, M. Xie, M. Ude, L.D. Nghiem, M. Elimelech, Biofouling mitigation in forward osmosis using graphene oxide functionalized thin-film composite membranes, Environ. Sci. Technol. 50 (2016) 5840–5848, https://doi. org/10.1021/acs.est.5b06364.

[64] Fernandes, L., Kennedy, K.J. and Ning, Z. (1993). Dynamic modelling of substrate degradation in sequencing batch anaerobic reactors (SBAR). Water Research, 27(11), pp. 1619-1628.

[65] G. Mannina, G.A. Ekama, M. Capodici, A. Cosenza, D. Di, H. Ødegaard, Moving bed membrane bioreactors for carbon and nutrient removal: the effect of C/N variation, Biochem. Eng. J. 125 (2017) 31–40, https://doi.org/10.1016/j. bej.2017.05.005.

[66] G. Mao, H. Hu, X. Liu, J. Crittenden, N. Huang, A bibliometric analysis of industrial wastewater treatments from 1998 to 2019, Environ. Pollut. 275 (2021), 115785, https://doi.org/10.1016/j.envpol.2020.115785.

[67] G. Pozo, C.A. Villamar, M. Martínez, G. Vidal, Effect of organic load and nutrient ratio on the operation stability of the moving bed bioreactor for kraft mill wastewater treatment and the incidence of polyhydroxyalkanoate biosynthesis, Water Sci. Technol. 66 (2012) 370–376, https://doi.org/10.2166/wst.2012.204.

[68] G.S. Colares, N. Dell'Osbel, P.G. Wiesel, G.A. Oliveira, P.H.Z. Lemos, F.P. da Silva, C.A. Lutterbeck, L.T. Kist, ˆE.L. Machado, Floating treatment wetlands: a review and bibliometric analysis, Sci. Total Environ. 714 (2020), 136776, https://doi. org/10.1016/j.scitotenv.2020.136776.

[69] G.T.H. Ooi, K. Tang, R.K. Chhetri, K.M.S. Kaarsholm, K. Sundmark, C. Kragelund, K. Litty, A. Christensen, S. Lindholst, C. Sund, M. Christensson, K. Bester, H. R. Andersen, Biological removal of pharmaceuticals from hospital wastewater in a pilot-scale staged moving bed biofilm reactor (MBBR) utilising nitrifying and denitrifying processes, Bioresour. Technol. 267 (2018) 677–687, https://doi.org/ 10.1016/j.biortech.2018.07.077.

[70] Ge, H., Batstone, D.J. and Keller, J. (2013). Operating aerobic wastewater treatment at very short sludge ages enables treatment and energy recovery through anaerobic sludge digestion. Water Research, 47(17), pp. 6546-6557.

[71] Gerardi, M.H. (2011). Troubleshooting the Sequencing Batch Reactor. Vol. 11. John Wiley and Sons, New Jersey.

[72] Geselbracht, J. (2007). Spreadsheet Implementation of Activated Sludge Model# 1 for Sequencing Batch Reactors. Proceedings of the Water Environment Federation, 2007(17), pp. 1597-1606.

[73] González-Martinez, S. and Wilderer, P.A. (1991). Phosphate removal in a biofilm reactor. Water Science and Technology, 23(7-9), pp. 1405-1415.

[74] Grady Jr, C.L., Daigger, G.T., Love, N.G. and Filipe, C.D. (2011). Biological Wastewater Treatment. CRC press, Florida.

[75] Gujer, W., Henze, M., Mino, T. and Van Loosdrecht, M. (1999). Activated sludge model no. 3. Water Science and Technology, 39(1), pp. 183-193.

[76] H. Du, D. Liu, Z. Lu, J. Crittenden, G. Mao, S. Wang, H. Zou, Research development on sustainable urban infrastructure from 1991 to 2017: a bibliometric analysis to inform future innovations, Earth's Future 7 (2019) 718–733, https://doi.org/10.1029/2018EF001117.

[77] H. Ødegaard, A road-map for energy-neutral wastewater treatment plants of the future based on compact technologies (including MBBR), Front. Environ. Sci. Eng. 10 (2016) 2, https://doi.org/10.1007/s11783-016-0835-0.

[78] H. Ødegaard, Innovations in wastewater treatment: the moving bed biofilm process, Water Sci. Technol. 53 (2006) 17–33, https://doi.org/10.2166/ wst.2006.284.

[79] H. Sun, H. Liu, M. Zhang, Y. Liu, A novel single-stage ceramic membrane moving bed biofilm reactor coupled with reverse osmosis for reclamation of municipal wastewater to NEWater-like product water, Chemosphere 268 (2021), 128836, https://doi.org/10.1016/j.chemosphere.2020.128836.

[80] H. Wang, Z. Liu, S. Luo, R. Khan, P. Dai, P. Liang, X. Zhang, K. Xiao, X. Huang, Membrane autopsy deciphering keystone microorganisms stubborn against online NaOCl cleaning in a full-scale MBR, Water Res. 171 (2020), 115390, https://doi. org/10.1016/j.watres.2019.115390.

[81] H.T. Nhut, N.T.Q. Hung, T.C. Sac, N.H.K. Bang, T.Q. Tri, N.T. Hiep, N.M. Ky, Removal of nutrients and organic pollutants from domestic wastewater treatment by sponge-based moving bed biofilm reactor, Environ. Eng. Res. 25 (2020)

[82] Hajiabadi, H., Moghaddam, M. A. and Hashemi, S. (2009). Effect of sludge retention time on treating high Load synthetic wastewater using aerobic sequencing. Journal of Environmental Health Science and Engineering, 6(4), pp. 217-222.

[83] Henze, M., Grady Jr, C.L., Gujer, W., Marais, G.V.R. and Matsuo, T. (1987). A general model for single-sludge wastewater treatment systems. Water Research, 21(5), pp. 505-515.

[84] Henze, M., Gujer, W., Mino, T. and van Loosdrecht, M.C. (2000). Activated Sludge Models ASM1, ASM2, ASM2d and ASM3. IWA Publishing, London.

[85] Henze, M., Gujer, W., Mino, T., Matsuo, T., Wentzel, M. C. and Marais, G. (1995). Activated Sludge Model No. 2: IAWQ Scientific and Technical Reports. No. 3. IAWQ, London.

[86] Hoepker, E.C. and Schroeder, E.D. (1979). The effect of loading rate on batch-activated sludge effluent quality. Journal of Water Pollution Control Federation, 51(2), pp. 264-273.

[87] Hsu, E.H. (1986). Treatment of a petrochemical wastewater in sequencing batch reactors. Environmental Progress, 5(2), pp.71-81.

[88] I. Dimitrova, A. Dabrowska, S. Ekstr¨om, Start-up of a full-scale partial nitritation-anammox MBBR without inoculum at Klagshamn WWTP, Water Sci. Technol. 81 (2020) 2033–2042, https://doi.org/10.2166/wst.2020.271.

[89] Irvine, R.L. and Busch, A.W. (1979). Sequencing batch biological reactors: an overview. Journal of Water Pollution Control Federation, 51(2), pp. 235-243.

[90] Irvine, R.L., Ketchum Jr, L.H. and Asano, T. (1989). Sequencing batch reactors for biological wastewater treatment. Critical Reviews in Environmental Science and Technology, 18(4), pp. 255-294.

[91] Irvine, R.L., Wilderer, P.A. and Flemming, H.C. (1997). Controlled unsteady state processes and technologies-an overview. Water Science and Technology, 35(1), pp. 1-10.

[92] J. Cornejo, D.M. Gonz´alez-P´erez, J.I. P´erez, M.A. G´omez, Ibuprofen removal by a microfiltration membrane bioreactor during the startup phase, J. Environ. Sci. Health Part A Toxic/Hazard. Subst. Environ. Eng. 55 (2020) 374–384, https:// doi.org/10.1080/10934529.2019.1697587.

[93] J. Liu, F. Sun, P. Zhang, Y. Zhou, Integrated powdered activated carbon and quorum quenching strategy for biofouling control in industrial wastewater membrane bioreactor, J. Clean. Prod. 279 (2021), 123551, https://doi.org/ 10.1016/j.jclepro.2020.123551.

[94] J. Martín-Pascual, P. Reboleiro-Rivas, C. L´opez-L´opez, J.C. Leyva-Díaz, M. Jover, M.M. Mu˜nio, J. Gonz´alez-L´opez, J.M. Poyatos, Effect of the filling ratio, MLSS, hydraulic retention time, and temperature on the behavior of the hybrid biomass in a hybrid moving bed membrane bioreactor plant to treat urban wastewater, J. Environ. Eng. 141 (2015), 04015007, https://doi.org/10.1061/(asce)ee.1943- 7870.0000939.

[95] J. Ni, J. Ji, Y.-Y. Li, K. Kubota, Microbial characteristics in anaerobic membrane bioreactor treating domestic sewage: effects of HRT and process performance, J. Environ. Sci. 111 (2022) 392–399, https://doi.org/10.1016/j.jes.2021.04.022.

[96] J. Radjenovi´c, M. Petrovi´c, D. Barcel´o, Fate and distribution of pharmaceuticals in wastewater and sewage sludge of the conventional activated sludge (CAS) and advanced membrane bioreactor (MBR) treatment, Water Res. 43 (2009) 831–841, https://doi.org/10.1016/j.watres.2008.11.043.

[97] J. Teng, M. Zhang, K. Leung, J. Chen, H. Hong, H. Lin, B. Liao, A unified thermodynamic mechanism underlying fouling behaviors of soluble microbial products (SMPs) in a membrane bioreactor, Water Res. 149 (2019) 477–487, https://doi.org/10.1016/j.watres.2018.11.043.

[98] J. Wang, F. Bi, H.H. Ngo, W. Guo, H. Jia, H. Zhang, X. Zhang, Evaluation of energy-distribution of a hybrid microbial fuel cell-membrane bioreactor (MFC-MBR) for cost-effective wastewater treatment, Bioresour. Technol. 200 (2016) 420–425, https://doi.org/10.1016/j.biortech.2015.10.042.

[99] J.C. Leyva-díaz, A. Gonz´alez-martínez, J. Gonz´alez-l´opez, M.M. Mu˜nío, J. M. Poyatos, Kinetic modeling and microbiological study of two-step nitrification in a membrane bioreactor and hybrid moving bed biofilm reactor – membrane bioreactor for wastewater treatment, Chem. Eng. J. 259 (2015) 692–702, https:// doi.org/10.1016/j.cej.2014.07.136.

[100] J.C. Leyva-Díaz, A. Monteoliva-García, J. Martín-Pascual, M.M. Munio, J. J. García-Mesa, J.M. Poyatos, Moving bed biofilm reactor as an alternative wastewater treatment process for nutrient removal and recovery in the circular economy model, Bioresour. Technol. 299 (2020), 122631, https://doi.org/ 10.1016/j.biortech.2019.122631.

[101] J.C. Leyva-Díaz, J. Martín-Pascual, M.M. Mu˜nío, J. Gonz´alez-L´opez, E. Hontoria, J.M. Poyatos, Comparative kinetics of hybrid and pure moving bed reactor-membrane bioreactors, Ecol. Eng. 70 (2014) 227–234, https://doi.org/10.1016/j. ecoleng.2014.05.017.

[102] J.C. Leyva-Díaz, K. Calder´on, F.A. Rodríguez, J. Gonz´alez-L´opez, E. Hontoria, J. M. Poyatos, Comparative kinetic study between moving bed biofilm reactor-membrane bioreactor and membrane bioreactor systems and their influence on organic matter and nutrients removal, Biochem. Eng. J. 77 (2013) 28–40, https:// doi.org/10.1016/j.bej.2013.04.023.

[103] J.C. Leyva-Diaz, M. Munio, J. Gonz´alez-l´opez, J.M. Poyatos, Anaerobic/anoxic/ oxic configuration in hybrid moving bed biofilm reactor-membrane bioreactor for nutrient removal from municipal wastewater, Ecol. Eng. 91 (2016) 449–458, https://doi.org/10.1016/j.ecoleng.2016.03.006.

[104] J.P. Bassin, M. Dezotti, Moving bed biofilm reactor. Advanced Biological Processes for Wastewater Treatment, Springer, Cham, 2018, pp. 37–74, https:// doi.org/10.1007/978-3-319-58835-3.

[105] K. Lenz, S.N. Mahnik, N. Weissenbacher, R.M. Mader, P. Krenn, S. Hann, G. Koellensperger, M. Uhl, S. Knasmüller, F. Ferk, W. Bursch, M. Fuerhacker, Monitoring, removal and risk assessment of cytostatic drugs in hospital wastewater, Water Sci. Technol. 56 (2007) 141–149, https://doi.org/10.2166/ wst.2007.828.

[106] K. Tang, G.T.H. Ooi, K. Litty, K. Sundmark, K.M.S. Kaarsholm, C. Sund, C. Kragelund, M. Christensson, K. Bester, H.R. Andersen, Removal of pharmaceuticals in conventionally treated wastewater by a polishing moving bed biofilm reactor (MBBR) with intermittent feeding, Bioresour. Technol. 236 (2017) 77–86, https://doi.org/10.1016/j.biortech.2017.03.159.

[107] K. Xiao, S. Liang, X. Wang, C. Chen, X. Huang, Current state and challenges of full-scale membrane bioreactor applications: a critical review, Bioresour. Technol. 271 (2019) 473–481, https://doi.org/10.1016/j.biortech.2018.09.061.

[108] K. Xiao, Y. Xu, S. Liang, T. Lei, J. Sun, X. Wen, H. Zhang, C. Chen, X. Huang, Engineering application of membrane bioreactor for wastewater treatment in China: current state and future prospect, Front. Environ. Sci. Eng. 8 (2014) 805–819, https://doi.org/10.1007/s11783-014-0756-8.

[109] K.M. Jabri, E. Nolde, A. Ciroth, L. Bousselmi, Life cycle assessment of a decentralized greywater treatment alternative for non-potable reuse application, Int. J. Environ. Sci. Technol. 17 (2020) 433–444, https://doi.org/10.1007/ s13762-019-02511-3.

[110] Keller, J., Watts, S., Battye-Smith, W. and Chong, R. (2001). Full-scale demonstration of biological nutrient removal in a single tank SBR process. Water Science and Technology, 43(3), pp. 355-362.

[111] Ketchum Jr, L.H. (1997). Design and physical features of sequencing batch reactors. Water Science and Technology, 35(1), pp. 11-18.

[112] L. Borea, V. Naddeo, V. Belgiorno, An electro moving bed membrane bioreactor (eMB-MBR) as a novel technology for wastewater treatment and reuse, in: G. Mannina (Ed.), Frontiers in Wastewater Treatment and Modelling, Springer International Publishing, Cham, 2017, pp. 159–164, https://doi.org/10.1007/ 978-3-319-58421-8_24.

[113] L. Chu, J. Wang, F. Quan, X.H. Xing, L. Tang, C. Zhang, Modification of polyurethane foam carriers and application in a moving bed biofilm reactor, Process Biochem. 49 (2014) 1979–1982, https://doi.org/10.1016/j. procbio.2014.07.018.

[114] L. Defrance, M.Y. Jaffrin, B. Gupta, P. Paullier, V. Geaugey, Contribution of various constituents of activated sludge to membrane bioreactor fouling, Bioresour. Technol. 73 (2000) 4–11, https://doi.org/doi.org/10.1016/S0960- 8524(99)00163-7.

[115] L. Deng, W. Guo, H. Hao, X. Zhang, X.C. Wang, Q. Zhang, R. Chen, New functional biocarriers for enhancing the performance of a hybrid moving bed biofilm reactor – membrane bioreactor system, Bioresour. Technol. 208 (2016) 87–93, https:// doi.org/10.1016/j.biortech.2016.02.057.

[116] L. Duan, W. Jiang, Y. Song, S. Xia, S.W. Hermanowicz, The characteristics of extracellular polymeric substances and soluble microbial products in moving bed biofilm reactor-membrane bioreactor, Bioresour. Technol. 148 (2013) 436–442, https://doi.org/10.1016/j.biortech.2013.08.147.

[117] L. Høibye, H. Wenzel, H.F. Larsen, B.N. Jacobsen, O. Dalgaard, Sustainability assessment of advanced wastewater treatment technologies, Water Sci. Technol. 58 (2008) 963–968, https://doi.org/10.2166/wst.2008.450.

[118] L. Jin, S.L. Ong, H.Y. Ng, Comparison of fouling characteristics in different pore-sized submerged ceramic membrane bioreactors, Water Res. 44 (2010) 5907–5918, https://doi.org/10.1016/j.watres.2010.07.014.

[119] L. Qin, M. Gao, M. Zhang, L. Feng, Q. Liu, G. Zhang, Application of encapsulated algae into MBR for high-ammonia nitrogen wastewater treatment and biofouling control, Water Res. 187 (2020), 116430, https://doi.org/10.1016/j. watres.2020.116430.

[120] L. Qin, Y. Zhang, Z. Xu, G. Zhang, Advanced membrane bioreactors systems: new materials and hybrid process design, Bioresour. Technol. 269 (2018) 476–488, https://doi.org/10.1016/j.biortech.2018.08.062.

[121] L. Ramrakhiani, A. Halder, A. Majumder, A.K. Mandal, S. Majumdar, S. Ghosh, Industrial waste derived biosorbent for toxic metal remediation: mechanism studies and spent biosorbent management, Chem. Eng. J. 308 (2017) 1048–1064, https://doi.org/10.1016/J.CEJ.2016.09.145.

[122] L. Zhang, H. Liu, Y. Wang, Y. Peng, Compositional characteristics of dissolved organic matter during coal liquefaction wastewater treatment and its environmental implications, Sci. Total Environ. 704 (2020), 135409, https://doi. org/10.1016/j.scitotenv.2019.135409.

[123] L.W. Jaroszynski, N. Cicek, R. Sparling, J.A. Oleszkiewicz, Importance of the operating pH in maintaining the stability of anoxic ammonium oxidation (anammox) activity in moving bed biofilm reactors, Bioresour. Technol. 102 (2011) 7051–7056, https://doi.org/10.1016/j.biortech.2011.04.069.

[124] Li, J.P., Healy, M.G., Zhan, X.M. and Rodgers, M. (2008). Nutrient removal from slaughterhouse wastewater in an intermittently aerated sequencing batch reactor. Bioresource Technology, 99(16), pp. 7644-7650.

[125] M. Germec, A. Demirci, I. Turhan, Biofilm reactors for value-added products production: an in-depth review, Biocatal. Agric. Biotechnol. 27 (2020), 101662, https://doi.org/10.1016/j.bcab.2020.101662.

[126] M. Herrera-Robledo, J.M. Morgan-Sagastume, A. Noyola, Biofouling and pollutant removal during long-term operation of an anaerobic membrane bioreactor treating municipal wastewater, Biofouling 26 (2010) 23–30, https:// doi.org/10.1080/08927010903243923.

[127] M. Jain, A. Majumder, P.S. Ghosal, A.K. Gupta, A review on treatment of petroleum refinery and petrochemical plant wastewater: a special emphasis on constructed wetlands, J. Environ. Manag. 272 (2020), 111057, https://doi.org/ 10.1016/j.jenvman.2020.111057.

[128] M. Kashif, A. Kashif, P. Ranjan, M. Aslam, A. Fuwad, Y. Choi, Rajesh Banu J, J. Hoon, G. Kumar, A brief review of anaerobic membrane bioreactors emphasizing recent advancements, fouling issues and future perspectives, J. Environ. Manag. 270 (2020), 110909, https://doi.org/10.1016/j. jenvman.2020.110909.

[129] M. Kermani, B. Bina, H. Movahedian, M.M. Amin, M. Nikaein, Application of moving bed biofilm process for biological organics and nutrients removal from municipal wastewater, Am. J. Environ. Sci. 4 (2008) 675–682.

[130] M. Laureni, P. Falås, O. Robin, A. Wick, D.G. Weissbrodt, J. Lund, T.A. Ternes, E. Morgenroth, A. Joss, Mainstream partial nitritation and anammox: long-term process stability and effluent quality at low temperatures, Water Res. 101 (2016) 628–639, https://doi.org/10.1016/j.watres.2016.05.005.

[131] M. Maaz, M. Yasin, M. Aslam, G. Kumar, A.E. Atabani, M. Idrees, F. Anjum, F. Jamil, R. Ahmad, A. Laeeq, G. Lesage, M. Heran, J. Kim, Anaerobic membrane bioreactors for wastewater treatment: novel configurations, fouling control and energy considerations, Bioresour. Technol. 283 (2019) 358–372, https://doi.org/ 10.1016/j.biortech.2019.03.061.

[132] M. Ortiz, R.G. Raluy, L. Serra, J. Uche, Life cycle assessment of water treatment technologies: wastewater and water-reuse in a small town, Desalination 204 (2007) 121–131, https://doi.org/10.1016/j.desal.2006.04.026.

[133] M. Qi, Y. Yang, X. Zhang, X. Zhang, M. Wang, W. Zhang, X. Lu, Y. Tong, Pollution reduction and operating cost analysis of municipal wastewater treatment in China and implication for future wastewater management, J. Clean. Prod. 253 (2020), 120003, https://doi.org/10.1016/j.jclepro.2020.120003.

[134] M. Starkl, J. Anthony, E. Aymerich, N. Brunner, C. Chubilleau, S. Das, M. M. Ghangrekar, A. Ahmad, L. Philip, A. Singh, Interpreting best available technologies more flexibly: a policy perspective for municipal wastewater management in India and other developing countries, Environ. Impact Assess. Rev. 71 (2018) 132–141, https://doi.org/10.1016/j.eiar.2018.03.002.

[135] M. Varma, A.K. Gupta, P.S. Ghosal, A. Majumder, A review on performance of constructed wetlands in tropical and cold climate: insights of mechanism, role of influencing factors, and system modification in low temperature, Sci. Total Environ. 755 (2021), 142540, https://doi.org/10.1016/j.scitotenv.2020.142540.

[136] M. Wu, Y. Chen, H. Lin, L. Zhao, L. Shen, R. Li, Y. Xu, H. Hong, Y. He, Membrane fouling caused by biological foams in a submerged membrane bioreactor: mechanism insights, Water Res. 181 (2020), 115932, https://doi.org/10.1016/j. watres.2020.115932.

[137] M. Xu, M. Bernards, Z. Hu, Algae-facilitated chemical phosphorus removal during high-density Chlorella emersonii cultivation in a membrane bioreactor, Bioresour. Technol. 153 (2014) 383–387, https://doi.org/10.1016/j.biortech.2013.12.026.

[138] M. Xu, P. Li, T. Tang, Z. Hu, Roles of SRT and HRT of an algal membrane bioreactor system with a tanks-in-series configuration for secondary wastewater effluent polishing, Ecol. Eng. 85 (2015) 257–264, https://doi.org/10.1016/j. ecoleng.2015.09.064.

[139] M. Zhang, C. Zhu, T. Pan, Y. Fan, Y. Liu, C. He, X. Gu, J. Wu, Elucidating sludge characteristic, substrate transformation and microbial evolution in a two-sludge denitrifying phosphorus removal system under the impact of HRT, J. Environ. Manag. 262 (2020), 110391, https://doi.org/10.1016/j.jenvman.2020.110391.

[140] M.A. Mazhar, N.A. Khan, A.H. Khan, S. Ahmed, A.A. Siddiqui, A. Husain, Rahisuddin, V. Tirth, S. Islam, N.K. Shukla, F. Changani, M. Yousefi, A. E. Hassaballa, N. Radwan, Upgrading combined anaerobic-aerobic UASB-FPU to UASB-DHS system: cost comparison and performance perspective for developing countries, J. Clean. Prod. 284 (2021), 124723, https://doi.org/10.1016/j. jclepro.2020.124723.

[141] M.C. Chrispim, M.A. Nolasco, Greywater treatment using a moving bed biofilm reactor at a university campus in Brazil, J. Clean. Prod. 142 (2017) 290–296, https://doi.org/10.1016/j.jclepro.2016.07.162.

[142] M.C. Matheus, G.R. Lourenço, B.A. Solano, M.W.C. Dezotti, J.P. Bassin, Assessing the impact of hydraulic conditions and absence of pretreatment on the treatability of pesticide formulation plant wastewater in a moving bed biofilm reactor, J. Water Process Eng. 36 (2020), 101243, https://doi.org/10.1016/j. jwpe.2020.101243.

[143] M.E. Casas, R.K. Chhetri, G. Ooi, K.M.S. Hansen, K. Litty, M. Christensson, C. Kragelund, H.R. Andersen, K. Bester, Biodegradation of pharmaceuticals in hospital wastewater by staged moving bed biofilm reactors (MBBR), Water Res. 83 (2015) 293–302, https://doi.org/10.1016/j.watres.2015.06.042.

[144] M.K. Perera, J.D. Englehardt, A.C. Dvorak, Technologies for recovering nutrients from wastewater: a critical review, Environ. Eng. Sci. 36 (2019) 511–529, https://doi.org/10.1089/ees.2018.0436.

[145] M.S. Fountoulakis, N. Markakis, I. Petousi, T. Manios, Single house on-site greywater treatment using a submerged membrane bioreactor for toilet flushing, Sci. Total Environ. 551–552 (2016) 706–711, https://doi.org/10.1016/j. scitotenv.2016.02.057.

[146] M.S. Kowalski, T.R. Devlin, A. di Biase, J.A. Oleszkiewicz, Controlling cold temperature partial nitritation in moving bed biofilm reactor, Chemosphere 227 (2019) 216–224, https://doi.org/10.1016/j.chemosphere.2019.04.025.

[147] N.C. Cinperi, E. Ozturk, N.O. Yigit, M. Kitis, Treatment of woolen textile wastewater using membrane bioreactor, nanofiltration and reverse osmosis for reuse in production processes, J. Clean. Prod. 223 (2019) 837–848, https://doi. org/10.1016/j.jclepro.2019.03.166.

[148] N.C. Nguyen, S.S. Chen, H.T. Nguyen, S.S. Ray, H.H. Ngo, W. Guo, P.H. Lin, Innovative sponge-based moving bed-osmotic membrane bioreactor hybrid system using a new class of draw solution for municipal wastewater treatment, Water Res. 91 (2016) 305–313, https://doi.org/10.1016/j.watres.2016.01.024.

[149] N.J. van Eck, L. Waltman, Software survey: VOSviewer, a computer program for bibliometric mapping, Scientometrics 84 (2010) 523–538, https://doi.org/ 10.1007/s11192-009-0146-3.

[150] N.O. Yigit, N. Uzal, H. Koseoglu, I. Harman, H. Yukseler, U. Yetis, G. Civelekoglu, M. Kitis, Treatment of a denim producing textile industry wastewater using pilot-scale membrane bioreactor, Desalination 240 (2009) 143–150, https://doi.org/ 10.1016/j.desal.2007.11.071.

[151] N.-qi Ren, X.-feng Yan, Z.-bo Chen, D.-xue Hu, M.-li Gong, W.-qian Guo, Feasibility and simulation model of a pilot scale membrane bioreactor for wastewater treatment and reuse from Chinese traditional medicine, J. Environ. Sci. 19 (2007) 129–134, https://doi.org/10.1016/S1001-0742(07)60021-7.

[152] N.S.A. Mutamim, Z.Z. Noor, M.A.A. Hassan, G. Olsson, Application of membrane bioreactor technology in treating high strength industrial wastewater: a performance review, Desalination 305 (2012) 1–11, https://doi.org/10.1016/j. desal.2012.07.033.

[153] Nakhla, G., Liu, V. and Bassi, A. (2006). Kinetic modeling of aerobic biodegradation of high oil and grease rendering wastewater. Bioresource Technology, 97(1), pp. 131-139.

[154] Ni, B.J., Xie, W.M., Liu, S.G., Yu, H.Q., Wang, Y.Z., Wang, G. and Dai, X.L. (2009). Granulation of activated sludge in a pilot-scale sequencing batch reactor for the treatment of low-strength municipal wastewater. Water Research, 43(3), pp. 751-761.

[155] O.T. Iorhemen, R.A. Hamza, J.H. Tay, Membrane bioreactor (MBR) technology for wastewater treatment and reclamation: membrane fouling, Membranes 33 (2016) 13–16, https://doi.org/10.3390/membranes6020033 (Basel).

[156] O.T. Iorhemen, R.A. Hamza, J.H. Tay, Membrane fouling control in membrane bioreactors (MBRs) using granular materials, Bioresour. Technol. 240 (2017) 9–24, https://doi.org/10.1016/j.biortech.2017.03.005.

[157] O.T. Iorhemen, R.A. Hamza, Z. Sheng, J.H. Tay, Submerged aerobic granular sludge membrane bioreactor (AGMBR): organics and nutrients (nitrogen and phosphorus) removal, Bioresour. Technol. Rep. 6 (2019) 260–267, https://doi. org/10.1016/j.biteb.2019.03.015.

[158] Oles, J. and Wilderer, P.A. (1991). Computer aided design of sequencing batch reactors based on the IAWPRC activated sludge model. Water Science and Technology, 23(4-6), pp. 1087-1095.

[159] P. Artiga, E. Ficara, F. Malpei, J.M. Garrido, R. M´endez, Treatment of two industrial wastewaters in a submerged membrane bioreactor, Desalination 179 (2005) 161–169, https://doi.org/10.1016/j.desal.2004.11.064.

[160] P. Cartagena, M. El Kaddouri, V. Cases, A. Trapote, D. Prats, Reduction of emerging micropollutants, organic matter, nutrients and salinity from real wastewater by combined MBR-NF/RO treatment, Sep. Purif. Technol. 110 (2013) 132–143, https://doi.org/10.1016/j.seppur.2013.03.024.

[161] P. Krzeminski, J.H.J.M. van der Graaf, J.B. van Lier, Specific energy consumption of membrane bioreactor (MBR) for sewage treatment, Water Sci. Technol. 65 (2012) 380–392.

[162] P. Krzeminski, L. Leverette, S. Malamis, E. Katsou, Membrane bioreactors – a review on recent developments in energy reduction, fouling control, novel configurations, LCA and market prospects, J. Membr. Sci. 527 (2017) 207–227, https://doi.org/10.1016/j.memsci.2016.12.010.

[163] P. Krzeminski, M.C. Tomei, P. Karaolia, A. Langenhoff, C.M.R. Almeida, E. Felis, F. Gritten, H.R. Andersen, T. Fernandes, C.M. Manaia, L. Rizzo, D. Fatta-Kassinos, Performance of secondary wastewater treatment methods for the removal of contaminants of emerging concern implicated in crop uptake and antibiotic resistance spread: a review, Sci. Total Environ. 648 (2019) 1052–1081, https:// doi.org/10.1016/j.scitotenv.2018.08.130.

[164] P. Reboleiro-rivas, J. Martín-pascual, B. Ju´arez-jim´enez, J.M. Poyatos, R. Vílchez-vargas, Nitrogen removal in a moving bed membrane bioreactor for municipal sewage treatment: community differentiation in attached biofilm and suspended biomass, Chem. Eng. J. 277 (2015) 209–218, https://doi.org/10.1016/j. cej.2015.04.141.

[165] P. Stanchev, E. Katsou, F. Fatone, A.L. Eusebi, Comparative life cycle environmental and economic assessment of anaerobic membrane bioreactor and disinfection for reclaimed water reuse in agricultural irrigation: a case study in Italy, J. Clean. Prod. 293 (2021), 126201, https://doi.org/10.1016/j. jclepro.2021.126201.

[166] P.B. Moser, B.C. Ricci, B.G. Reis, L.S.F. Neta, A.C. Cerqueira, M.C.S. Amaral, Effect of MBR-H2O2/UV Hybrid pre-treatment on nanofiltration performance for the treatment of petroleum refinery wastewater, Sep. Purif. Technol. 192 (2018) 176–184, https://doi.org/10.1016/j.seppur.2017.09.070.

[167] P.M. Sutton, Membrane bioreactors for industrial wastewater treatment: applicability and selection of optimal system configuration, Proc. Water Environ. Fed. 2006 (2006) 3233–3248, https://doi.org/10.2175/193864706783751636.

[168] Q. Jiang, H.H. Ngo, L.D. Nghiem, F.I. Hai, W.E. Price, J. Zhang, S. Liang, L. Deng, W. Guo, Effect of hydraulic retention time on the performance of a hybrid moving bed biofilm reactor-membrane

bioreactor system for micropollutants removal from municipal wastewater, Bioresour. Technol. 247 (2018) 1228–1232, https:// doi.org/10.1016/j.biortech.2017.09.114.

[169] Q. Liu, J. Wang, R. He, H. Hu, B. Wu, H. Ren, Bacterial assembly during the initial adhesion phase in wastewater treatment biofilms, Water Res. 184 (2020), 116147, https://doi.org/10.1016/j.watres.2020.116147.

[170] R. Canziani, V. Emondi, M. Garavaglia, F. Malpei, E. Pasinetti, G. Buttiglieri, Effect of oxygen concentration on biological nitrification and microbial kinetics in a cross-flow membrane bioreactor (MBR) and moving-bed biofilm reactor (MBBR) treating old landfill leachate, J. Membr. Sci. 286 (2006) 202–212, https://doi.org/10.1016/j.memsci.2006.09.044.

[171] R. Iglesias, P. Sim´on, L. Moragas, U. Arce, I. Rodriguez-Roda, Cost comparison of full-scale water reclamation technologies with an emphasis on membrane bioreactors, Water Sci. Technol. 75 (2017) 2562–2570, https://doi.org/10.2166/ wst.2017.132. D. Saidulu et al.

[172] R. Shokoohi, G. Asgari, M. Leili, M. Khiadani, M. Foroughi, M. Sedighi Hemmat, Modelling of moving bed biofilm reactor (MBBR) efficiency on hospital wastewater (HW) treatment: a comprehensive analysis on BOD and COD removal, Int. J. Environ. Sci. Technol. 14 (2017) 841–852, https://doi.org/10.1007/ s13762-017-1255-9.

[173] R.M. Ahl, T. Leiknes, H. Ødegaard, Tracking particle size distributions in a moving bed biofilm membrane reactor for treatment of municipal wastewater, Water Sci. Technol. 53 (2006) 33–42, https://doi.org/10.2166/wst.2006.205.

[174] R.M. Chaudhry, K.L. Nelson, J.E. Drewes, Mechanisms of pathogenic virus removal in a full-scale membrane bioreactor, Environ. Sci. Technol. 49 (2015) 2815–2822, https://doi.org/10.1021/es505332n.

[175] Rodríguez, D.C., Lara, P.A. and Peñuela, G. (2014). Pilot study of a sequencing batch reactor for the treatment of wastewater from an animal food factory. Afinidad, 71(565), pp. 43-48

[176] S. Al-Asheh, M. Bagheri, A. Aidan, Membrane bioreactor for wastewater treatment: a review, Case Stud. Chem. Environ. Eng. 4 (2021), 100109, https:// doi.org/10.1016/j.cscee.2021.100109.

[177] S. Arefi-Oskoui, A. Khataee, M. Safarpour, Y. Orooji, V. Vatanpour, A review on the applications of ultrasonic technology in membrane bioreactors, Ultrason. Sonochem. 58 (2019), 104633, https://doi.org/10.1016/j.ultsonch.2019.104633.

[178] S. Bering, J. Mazur, K. Tarnowski, M. Janus, S. Mozia, A.W. Morawski, The application of moving bed bio-reactor (MBBR) in commercial laundry wastewater treatment, Sci. Total Environ. 627 (2018) 1638–1643, https://doi.org/10.1016/j. scitotenv.2018.02.029.

[179] S. Gabarr´on, G. Ferrero, M. Dalmau, J. Comas, I. Rodriguez-roda, Assessment of energy-saving strategies and operational costs in full-scale membrane bioreactors, J. Environ. Manag. 134 (2014) 8–14, https://doi.org/10.1016/j. jenvman.2013.12.023.

[180] S. Jabornig, E. Favero, Single household greywater treatment with a moving bed biofilm membrane reactor (MBBMR), J. Membr. Sci. 446 (2013) 277–285, https://doi.org/10.1016/j.memsci.2013.06.049.

[181] S. Jia, H. Han, B. Hou, H. Zhuang, F. Fang, Q. Zhao, Treatment of coal gasification wastewater by membrane bioreactor hybrid powdered activated carbon (MBR-PAC) system, Chemosphere 117 (2014) 753–759, https://doi.org/10.1016/j. chemosphere.2014.09.085.

[182] S. Mozia, M. Janus, P. Bro˙ zek, S. Bering, K. Tarnowski, J. Mazur, A.W. Morawski, A system coupling hybrid biological method with UV/O3 oxidation and membrane separation for treatment and reuse of industrial laundry wastewater, Environ. Sci. Pollut. Res. 23 (2016) 19145–19155, https://doi.org/10.1007/ s11356-016-7111-5.

[183] S. Phanwilai, N. Kangwannarakul, P. (Lek) Noophan, T. Kasahara, A. Terada, J. Munakata-Marr, L.A. Figueroa, Nitrogen removal efficiencies and microbial communities in full-scale IFAS and MBBR municipal wastewater treatment plants at high COD:N ratio, Front. Environ. Sci. Eng. 14 (2020) 115, https://doi.org/ 10.1007/s11783-020-1374-2.

[184] S. Prasertkulsak, C. Chiemchaisri, W. Chiemchaisri, T. Itonaga, K. Yamamoto, Removals of pharmaceutical compounds from hospital wastewater in membrane bioreactor operated under short hydraulic retention time, Chemosphere 150 (2016) 624–631, https://doi.org/10.1016/j.chemosphere.2016.01.031.

[185] S. Shao, Y. Hu, C. Cheng, J. Cheng, Y. Chen, Simultaneous degradation of tetracycline and denitrification by a novel bacterium, Klebsiella sp. SQY5, Chemosphere 209 (2018) 35–43, https://doi.org/10.1016/j. chemosphere.2018.06.093.

[186] S. Shao, Y. Hu, J. Cheng, Y. Chen, Action of oxytetracycline (OTC) degrading bacterium and its application in moving bed biofilm reactor (MBBR) for aquaculture wastewater pre-treatment, Ecotoxicol. Environ. Saf. 171 (2019) 833–842, https://doi.org/10.1016/j.ecoenv.2019.01.040.

[187] S. Wang, L. Zou, H. Li, K. Zheng, Y. Wang, G. Zheng, J. Li, Full-scale membrane bioreactor process WWTPs in East Taihu basin: wastewater characteristics, energy consumption and sustainability, Sci. Total Environ. 723 (2020), 137983, https:// doi.org/10.1016/j.scitotenv.2020.137983.

[188] S. Wang, X. Ma, Y. Liu, X. Yi, G. Du, J. Li, Fate of antibiotics, antibiotic-resistant bacteria, and cell-free antibiotic-resistant genes in full-scale membrane bioreactor wastewater treatment plants, Bioresour. Technol. 302 (2020), 122825, https:// doi.org/10.1016/j.biortech.2020.122825.

[189] S. Yang, F. Yang, Z. Fu, R. Lei, Comparison between a moving bed membrane bioreactor and a conventional membrane bioreactor on organic carbon and nitrogen removal, Bioresour. Technol. 100 (2009) 2369–2374, https://doi.org/ 10.1016/j.biortech.2008.11.022.

[190] S. Yang, F. Yang, Z. Fu, T. Wang, R. Lei, Simultaneous nitrogen and phosphorus removal by a novel sequencing batch moving bed membrane bioreactor for wastewater treatment, J. Hazard. Mater. 175 (2010) 551–557, https://doi.org/ 10.1016/j.jhazmat.2009.10.040.

[191] S.H. Hansen, M. Nierychlo, M.L. Christensen, P.H. Nielsen, M.K. Jørgensen, Fouling of membranes in membrane bioreactors for wastewater treatment: planktonic bacteria can have a significant contribution, Water Environ. Res. 93 (2020) 207–216, https://doi.org/10.1002/wer.1392.

[192] S.J. Judd, The status of industrial and municipal effluent treatment with membrane bioreactor technology, Chem. Eng. J. 305 (2016) 37–45, https://doi. org/10.1016/j.cej.2015.08.141.

[193] S.K. Behera, H.W. Kim, J.E. Oh, H.S. Park, Occurrence and removal of antibiotics, hormones and several other pharmaceuticals in wastewater treatment plants of the largest industrial city of Korea, Sci. Total Environ. 409 (2011) 4351–4360, https://doi.org/10.1016/j.scitotenv.2011.07.015.

[194] S.K. Gupta, S.K. Gupta, G. Singh, Biodegradation of distillery spent wash in anaerobic hybrid reactor, Water Res. 41 (2007) 721–730, https://doi.org/ 10.1016/j.watres.2006.11.039.

[195] S.M.A. Abuabdou, W. Ahmad, N.C. Aun, M.J.K. Bashir, A review of anaerobic membrane bioreactors (AnMBR) for the treatment of highly contaminated landfill leachate and biogas production: effectiveness, limitations and future perspectives, J. Clean. Prod. 255 (2020), 120215, https://doi.org/10.1016/j. jclepro.2020.120215.

[196] S.M.R. Razavi, T. Miri, A real petroleum refinery wastewater treatment using hollow fiber membrane bioreactor (HF-MBR), J. Water Process Eng. 8 (2015) 136–141, https://doi.org/10.1016/j.jwpe.2015.09.011.

[197] Schwarzenbeck, N., Borges, J.M. and Wilderer, P.A. (2005). Treatment of dairy effluents in an aerobic granular sludge sequencing batch reactor. Applied Microbiology and Biotechnology, 66(6), pp. 711-718.

[198] Serafim, L.S., Lemos, P.C., Oliveira, R. and Reis, M.A. (2004). Optimization of polyhydroxybutyrate production by mixed cultures submitted to aerobic dynamic feeding conditions. Biotechnology and Bioengineering, 87(2), pp.145-160.

[199] Spellman, F.R. (2013). Handbook of Water and Wastewater Treatment Plant Operations. CRC Press, Florida.

[200] T. Sakcharoen, C. Ratanatamskul, A. Chandrachai, Factors affecting technology selection, techno-economic and environmental sustainability assessment of a novel zero-waste system for food waste and wastewater management, J. Clean. Prod. 314 (2021), 128103, https://doi.org/10.1016/j.jclepro.2021.128103.

[201] T. Zsirai, P. Buzatu, P. Aerts, S. Judd, Efficacy of relaxation, backflushing, chemical cleaning and clogging removal for an immersed hollow fibre membrane bioreactor, Water Res. 46 (2012) 4499–4507, https://doi.org/10.1016/j. watres.2012.05.004.

[202] T.O. Leiknes, H. Ødegaard, The development of a biofilm membrane bioreactor, Desalination 202 (2007) 135–143, https://doi.org/10.1016/j.desal.2005.12.049.

[203] V. Hoang, R. Delatolla, T. Abujamel, W. Mottawea, A. Gadbois, E. Laflamme, A. Stintzi, Nitrifying moving bed biofilm reactor (MBBR) biofilm and biomass response to long term exposure to 1◦C, Water Res. 49 (2014) 215–224, https:// doi.org/10.1016/j.watres.2013.11.018.

[204] V.K. Parida, D. Saidulu, A. Majumder, A. Srivastava, B. Gupta, A.K. Gupta, Emerging contaminants in wastewater: a critical review on occurrence, existing legislations, risk assessment, and sustainable treatment alternatives, J. Environ. Chem. Eng. 9 (2021), 105966, https://doi.org/10.1016/j.jece.2021.105966.

[205] Velmurugan, S., Clarkson, W.W. and Veenstra, J.N., 2010. Model‐based design of sequencing batch reactor for removal of biodegradable organics and nitrogen. Water Environment Research, 82(5), pp.462-474.

[206] Von Sperling, M. (2007). Activated Sludge and Aerobic Biofilm Reactors. IWA Publishing, London.

[207] W. Yang, N. Cicek, J. Ilg, State-of-the-art of membrane bioreactors: worldwide research and commercial applications in North America, J. Membr. Sci. 270 (2006) 201–211, https://doi.org/10.1016/j.memsci.2005.07.010.

[208] W.N. Lee, I.J. Kang, C.H. Lee, Factors affecting filtration characteristics in membrane-coupled moving bed biofilm reactor, Water Res. 40 (2006) 1827–1835, https://doi.org/10.1016/j.watres.2006.03.007.

[209] Wang, L.K., Shammas, N.K. and Hung, Y.T. (2010). Advanced biological treatment processes. Vol. 9. Springer Science & Business Media, Berlin.

[210] Water Environment Federation (WEF) (2012). Wastewater Treatment Plant Design Handbook. Alexandria, VA, USA.

[211] Wilderer, P.A., Irvine, R.L. and Goronszy, M.C. (2001). Sequencing Batch Reactor Technology.Vol. 10. IWA Publishing, London.

[212] X. Sheng, R. Liu, L. Chen, J. Zhu, Z. Yin, Enrichment and application of nitrifying activated sludge in membrane bioreactors, Water Sci. Technol. 76 (2017) 2888–2894, https://doi.org/10.2166/wst.2017.421.

[213] X. Tan, I. Acquah, H. Liu, W. Li, S. Tan, A critical review on saline wastewater treatment by membrane bioreactor (MBR) from a microbial perspective, Chemosphere 220 (2019) 1150–1162, https://doi.org/10.1016/j. chemosphere.2019.01.027.

[214] X. Xu, G. Wang, L. Zhou, H. Yu, F. Yang, Start-up of a full-scale SNAD-MBBR process for treating sludge digester liquor, Chem. Eng. J. 343 (2018) 477–483, https://doi.org/10.1016/j.cej.2018.03.032.

[215] X. Yang, V. Lopez-Grimau, M. Vilaseca, M. Crespi, Treatment of textile wastewater by CAS, MBR, and MBBR: a comparative study from technical, economic, and environmental perspectives, Water 12 (2020) 1–17, https://doi. org/10.3390/w12051306.

[216] X. Zhang, Z. Zhang, Y. Liu, H. Hao Ngo, W. Guo, H. Wang, Y. Zhang, D. Zhang, Impacts of sulfadiazine on the performance and membrane fouling of a hybrid moving bed biofilm reactor-membrane bioreactor system at different C/N ratios, Bioresour. Technol. 318 (2020), 124180, https://doi.org/10.1016/j. biortech.2020.124180.

[217] X.J. Wang, S.Q. Xia, L. Chen, J.F. Zhao, N.J. Renault, J.M. Chovelon, Nutrients removal from municipal wastewater by chemical precipitation in a moving bed biofilm reactor, Process Biochem. 41 (2006) 824–828, https://doi.org/10.1016/ J.PROCBIO.2005.10.015.

[218] Y. Luo, Q. Jiang, H.H. Ngo, L.D. Nghiem, F.I. Hai, W.E. Price, J. Wang, W. Guo, Evaluation of micropollutant removal and fouling reduction in a hybrid moving bed biofilm reactor – membrane bioreactor system, Bioresour. Technol. 191 (2015) 355–359, https://doi.org/10.1016/j.biortech.2015.05.073.

[219] Y. Xu, N. Zhu, J. Sun, P. Liang, K. Xiao, X. Huang, Evaluating oxygen mass transfer parameters for large-scale engineering application of membrane bioreactors, Process Biochem. 60 (2017) 13–18, https://doi.org/10.1016/j. procbio.2017.05.020.

[220] Y. Zhang, J. Zhou, J. Zhang, S. Yuan, An innovative membrane bioreactor and packed-bed biofilm reactor combined system for shortcut nitrification-denitrification, J. Environ. Sci. 21 (2009) 568–574, https://doi.org/10.1016/ S1001-0742(08)62309-8.

[221] Y.X. Cui, D. Wu, H.R. Mackey, H.K. Chui, G.H. Chen, Application of a moving-bed biofilm reactor for sulfur-oxidizing autotrophic denitrification, Water Sci. Technol. 77 (2018) 1027–1034, https://doi.org/10.2166/wst.2017.617.

[222] Yoong, E.T., Lant, P.A. and Greenfield, P.F. (2000). In situ respirometry in an SBR treating wastewater with high phenol concentrations. Water Research, 34(1), pp. 239-245.

[223] Z. Badani, H. Ait-Amar, A. Si-Salah, M. Brik, W. Fuchs, Treatment of textile waste water by membrane bioreactor and reuse, Desalination 185 (2005) 411–417, https://doi.org/10.1016/j.desal.2005.03.088.

[224] Z. Li, M. Hu, H. Song, D. Lin, Y. Wang, Toxic effects of nano-TiO2 in bivalves — a synthesis of meta-analysis and bibliometric analysis, J. Environ. Sci. 104 (2021) 188–203, https://doi.org/10.1016/j.jes.2020.11.013.

[225] Z. Niu, H. Guo, Y. Zhou, S. Xia, Unraveling membrane fouling in anoxic/oxic membrane bioreactors treating anaerobically digested piggery wastewater, J. Environ. Chem. Eng. 9 (2021), 104985, https://doi.org/10.1016/j. jece.2020.104985.

[226] Z. Wang, X.-L. Liu, C.-N. Bu, S.-Q. Ni, S. Sung, Microbial diversity reveals the partial denitrification-anammox process serves as a new pathway in the first mainstream anammox plant, Sci. Total Environ. 764 (2021), 142917, https://doi. org/10.1016/j.scitotenv.2020.142917.

[227] Z. Yu, W. Li, S. Tan, Real-time monitoring of the membrane biofouling based on spectroscopic analysis in a marine MBBR-MBR (moving bed biofilm reactor-membrane bioreactor) for saline wastewater treatment, Chemosphere 235 (2019) 1154–1161, https://doi.org/10.1016/j.chemosphere.2019.07.005.

[228] Shah, K.L. & Reid, G. W (1970). Techniques for Estimating Construction Costs of Waste Treatment Plants. J (WPCF). Vol. 42, No. 5, Part I (May, 1970), pp. 776-793

[229] USEPA. (1976). An analysis of construction cost experiences for wastewater treatment plants. EPA 430-9-76-002.

[230] Qasim, S.R., Lim, S.W., Motley, E.M., and Heung, K. G. (1992). Estimating costs for treatment plant construction. J. Am. Wat. Work. Ass. vol.84, pp.56-62.

[231] Vanrolleghem, P. A., Jeppsson, U., Carstensen, J., Carlsson, B., and Olsson, G. (1996). Integration of wastewater treatment plant design and operation – a systematic approach using cost functions. Wat. Sci. Tech., vol.34, pp.159-171.

[232] Gillot, S., De Clercq, B., Defour, D., Simoens, F., Gernaey, K., and Vanrolleghem, P.A. (1999). Optimization of wastewater treatment plant design and operation using simulation and cost analysis. 72nd annual conference WEFTEC, New Orleans, USA.

[233] Tsagarakis, K. P., Mara, D. D., and Angelakis, A. N. (2003). Application of Cost Criteria for Selection of Municipal Wastewater Treatment Systems. Water Air and Soil Pollution - January Issue.

[234] Gratziou, M.K., Tsalkatidou, M., and Kotsovinos, N.E. (2006). Economic evaluation of small capacity sewage processing units. Global Nest Jl. vol.8, no.1, pp. 52-60.

[235] Friedier, E. and Pisanty, E. (2006). Effects of design flow and treatment level on construction and operation costs of municipal wastewater treatment plants and their implications on policy making. Water Res. vol.40, no.2, pp.3751-3758.

[236] Nogueira, R., Ferreira, I., Janknecht, P., Rodriguez, J. J., Oliveria, P., and Brito, A. G. (2007). Energy-saving wastewater treatment systems: formulation of cost functions. Water Sci. Tech., vol. 56, no.3, pp.85-92.

[237] Sato, N., Okubo, T., Onodera, T., Agrawal, L. K., Ohashi, A., and Harada, H. (2007). Economic evaluation of sewage treatment processes in India. J. Env. Manage. vol. 84, pp.447-460.

[238] Papadopoulos, B., Konstantinos, P., Tsagarakis, and Yannopoulos, A. (2007). Cost and land functions for wastewater treatment projects: Typical simple linear regression versus Fuzzy linear regression. ASCE. J. Env. Eng. vol.133, pp.581.

[239] Dysert, L. R. (2008). An Introduction to Parametric Estimating. AACE International Transactions

[240] Singhirunnusorn, W and Stenstrom, M. K. (2010). A Critical Analysis of Economic Factors for Diverse Wastewater Treatment Processes: Case Studies in Thailand. Sustain. Environ. Res., 20(4), 263-268

[241] Hernandez, S.F., Senante, M.M., and Garrido, R.S. (2011). Cost Modeling in Wastewater Treatment Processes. Desalination', vol.268, pp.1-5.

[242] Yengejeh, R. J. Z., Davideh, K., and Baqeri, A. (2014). Cost/Benefit Evaluation of Wastewater Treatment Plant Types (SBR, MLE, Oxidation Ditch), Case Study: Khouzestan, Iran. Bulletin of Environment, Pharmacology and Life Sciences - Vol 4 [1] December: 55-60.

[243] Pannirselvam, R. and Gopalakrishnan, A.N. (2015). Development of Cost Functions for Sewage Treatment Plants based on Conventional Activated Sludge Process. Indian Journal of Science and Technology, Vol 8(30), DOI:10.17485/ijst/2015/v8i30/76062, November 2015

[244] Koul, A. and John, S. (2015). A Life Cycle Cost Approach for Evaluation of Sewage Treatment Plants. International Journal of Innovative Research in Advanced Engineering (IJIRAE) ISSN: 2349-2163 Issue 7, Volume 2, July 2015.

[245] Panaitescu, M., Panaitescu, F. V., and Anton, I. A. (2015). Theoretical and experimental researches on the operating costs of a wastewater treatment plant. IOP Conf. Series: Materials Science and Engineering 95 (2015) 012131.

[246] Jafarinejad, S. (2016). Cost estimation and economical evaluation of three configurations of activated sludge process for a wastewater treatment plant (WWTP) using simulation. Applied Water Science | Springer – July.

[247] Gautam, S., Ahmed, S., Dhingra, A., and Fatima, Z. (2017). Cost-Effective Treatment Technology for Small Size Sewage Treatment Plants in India. Journal of Scientific & Industrial Research - Vol. 76, April 2017, pp. 249-254.

[248] Doherty, E. (2017). Development of new benchmarking systems for wastewater treatment facilities. A thesis submitted to the College of Engineering and Informatics, National University of Ireland, Galway, in partial fulfilment of the requirements for the Degree of Doctor of Philosophy. Dysert, L. R. (2008). An Introduction to Parametric Estimating. AACE International Transactions

[249] Sekandari, A. W. (2019). Cost Comparison Analysis of Wastewater Treatment Plants. International Journal of Science Technology & Engineering| Volume 6 | Issue 1.

[250] Acampa, G., Giustra, M. G., and Parisi, C. M. (2019). Water Treatment Emergency: Cost Evaluation Tools' MDPI – 07 May.

[251] Arif, A. U. A., Sorour, M. T., and Aly, S. A. (2020). Cost analysis of activated sludge and membrane bioreactor WWTPs using CapdetWorks simulation program: Case study of Tikrit WWTP (middle Iraq). Alexandria Engineering Journal: Hosted by ELSEVIER.

[252] Altın S, Altın A, Doğru S. Investigation of operating costs at an urban wastewater treatment plant. Turk Hij Den Biyol Derg, 2020; 77(EK4: Su ve Sağlık): 49-56.

[253] Karolinczak Beata, Milaszewski Rafal, Dabrowski Wojciech: Cost Optimization of Wastewater and Septage Treatment Process, Energies, MDPI, vol. 13, no. 23,2020, Article number: 6406, pp. 1-13, DOI:10.3390 /enl3236406.

[254] H. Ozgun*, B. Cicekalan, Y. Akdag, I. Koyuncu, I. Ozturk (2021). Comparative evaluation of cost for preliminary and tertiary municipal wastewater treatment plants in Istanbul. Article number – 146258, Journal - Science of the Total Environment, Volume – 778, Published - 15 Jul 2021.

[255] Rosalie Rivera (2022). Cost-Saving Strategies for Municipal Wastewater Treatment Plant Managers. Doctoral Study Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Business Administration, Walden University, July 2022.

[256] P Rathore, D J Killedar, D Parde and A Sahare (2022). Life cycle cost analysis of wastewater treatment technologies, IOP Conf. Ser.: Earth Environ. Sci. 1032 012006

[257] A Maziotis, M Molinos-Senante (2023). A Comprehensive Eco-Efficiency Analysis of Wastewater Treatment Plants: Estimation of Optimal Operational Costs and Greenhouse Gas Emissions. Water Research 243 (2023) 120354

[258] S. U. Sayyad, P. V. Patil and P. R. Attar (2024). Cost Comparison of a Sewage Treatment Plant Unit by Conventional Method and BIM Approach, ASEAN Engineering Journal - November 2024, DOI: 10.11113/aej.v14.21303

[259] K. Limbore and Dr. R. D. Shinde (2024). Planning of Sewage Treatment Plant (STP) and Sewer Network with Operations-Maintenance, Service Problems. IJIRSET - Volume 13, Issue 4, April 2024

[260] Metcalf & Eddy, Inc. (Fourth Edition). Wastewater Engineering – Treatment and Reuse.

[261] "Process Design and Cost Estimating Algorithms for The Computer Assisted Procedure for Design and Evaluation of Wastewater Treatment Systems (CAPDET)" – USEPA, 1982.

[262] "Schedule of Rates" (latest publication) of Public Works Department (PWD), Government of India, 2021

Appendix - I

Summary of data obtained for small group WWTPs with MBR

DESIGN SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM
BOD REMOVAL

		Capacity in mld									
		0.5	***1***	***1.5***	***2***	***2.5***	***3***	***3.5***	***4***	***4.5***	***5***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Average wastewater flow rate	m^3/d	500.00	1000.00	1500.00	2000.00	2500.00	3000.00	3500.00	4000.00	4500.00	5000.00
Influent flow rate to reactor basins	m^3/d	578.00	1156.00	1734.00	2312.00	2890.00	3468.00	4046.00	4624.00	5202.00	5780.00
Average BOD load	kg/d	163.64	327.28	490.92	654.56	818.20	981.84	1145.48	1309.12	1472.76	1636.40
Number of reactor basins	number	2	2	2	2	2	2	2	2	2	2
Aerobic solids residence time - design value	d	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Total volume of each reactor basin	m^3	50.80	101.59	152.39	203.19	253.98	304.78	355.58	406.37	457.17	507.97
Hydraulic detention time of each reactor basin	h	4.22	4.22	4.22	4.22	4.22	4.22	4.22	4.22	4.22	4.22
MLSS (X_{MLSS})	g TSS/m^3	8000.00	8000.00	8000.00	8000.00	8000.00	8000.00	8000.00	8000.00	8000.00	8000.00
MLVSS (X_{MLVSS})	g VSS/m^3	3400.14	3400.14	3400.14	3400.14	3400.14	3400.14	3400.14	3400.14	3400.14	3400.14
F/M	(g BOD/d)/g bVSS	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
Volumetric BOD loading	(kg BOD/d)/m^3	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61
Total sludge (TSS) purged per day	kg TSS/d	162.55	325.10	487.65	650.20	812.74	975.29	1137.84	1300.39	1462.94	1625.49
Observed yield based on VSS	g b VSS/g bCOD	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29
	g b VSS/g BOD	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
Observed yield based on TSS	g TSS/g bCOD	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62
	g TSS/g BOD	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Summary of data obtained for small group WWTPs with MBR (continued)

DESIGN SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM (continued)

BOD REMOVAL

		Capacity in mld									
		0.5	***1***	***1.5***	***2***	***2.5***	***3***	***3.5***	***4***	***4.5***	***5***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Overall oxygen demand	kg oxygen/h	6.79	13.57	20.36	27.14	33.93	40.71	47.50	54.28	61.07	67.86
Air flow rate at average wastewater flow rate	m^3/min	5.78	11.57	17.35	23.14	28.92	34.70	40.49	46.27	52.06	57.84
RAS recycle ratio	-	1.93	1.93	1.93	1.93	1.93	1.93	1.93	1.93	1.93	1.93
Concentration of BOD of effluent	g/m^3	9.66	9.66	9.66	9.66	9.66	9.66	9.66	9.66	9.66	9.66
Concentration of TSS of effluent	g/m^3	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00

Summary of data obtained for small group WWTPs with MBR (continued)

EQUIPMENT SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM BOD REMOVAL											
		Capacity in mld									
		0.50	***1***	***1.50***	***2***	***2.50***	***3***	***3.50***	***4***	***4.50***	***5***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
AEROBIC REACTOR BASINS & ACCESSORIES											
Number of reactor basins		2	2	2	2	2	2	2	2	2	2
Length of each reactor basin	m	1.36	2.73	4.09	5.46	6.82	8.19	9.55	10.91	12.28	13.64
Width of each reactor basin	m	9.14	9.14	9.14	9.14	9.14	9.14	9.14	9.14	9.14	9.14
Depth of each reactor basin	m	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57
Number of swing arm headers of each reactor basin		1	1	2	2	3	3	4	4	4	5
MEMBRANE CHAMBERS & ACCESSORIES											
Number of membrane chambers		2	2	2	2	2	2	2	2	2	2
Length of each membrane chamber	m	1.78	3.02	3.33	3.95	5.19	5.50	6.12	7.36	7.67	8.29
Width of each membrane chamber	m	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26
Depth of each membrane chamber	m	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57
Number of membrane modules provided for membrane chambers		96	144	192	240	288	336	384	432	480	528
MIXED LIQUOR RECIRCULATION PUMPS AND PUMP-HOUSE											
Total number of pumps required		2	2	2	2	2	2	2	2	2	2
Capacity of each pump	m^3/h	50.00	100.00	150.00	190.00	240.00	290.00	330.00	380.00	430.00	480.00
Area required for pump house	m ^2	61.00	61.00	62.00	62.00	63.00	63.00	64.00	64.00	65.00	65.00
BLOWERS AND BLOWER BUILDING											
Total number of blowers required		2	2	2	2	2	2	2	2	2	2
Capacity of each blower	scfm	255.00	488.00	720.00	953.00	1185.00	1417.00	1650.00	1882.00	2114.00	2347.00
Area required for blower building	m ^2	50.00	59.00	65.00	69.00	73.00	77.00	80.00	83.00	85.00	87.00

Summary of data obtained for small group WWTPs with MBR (continued)

ESTIMATED COST SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM
BOD REMOVAL

		Capacity in mld									
		0.5	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
AEROBIC REACTOR BASINS & ACCESSORIES											
Total bare construction cost (CAPEX)	Crore ₹	2.17	3.18	4.19	5.18	6.19	7.21	8.23	9.25	10.26	11.29
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of reaction basins and accessories (OPEX)	Crore ₹	1.73	2.36	2.99	3.59	4.18	4.77	5.34	5.90	6.46	7.01
Overall cost inclusive of CAPEX & OPEX	Crore ₹	3.90	5.54	7.17	8.77	10.38	11.97	13.57	15.15	16.72	18.30
MEMBRANE CHAMBERS & ACCESSORIES											
Total bare construction cost (CAPEX)	Crore ₹	2.11	3.09	4.06	5.03	6.01	6.98	7.95	8.93	9.89	10.86
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of membrane chambers and accessories (OPEX)	Crore ₹	1.43	1.78	2.12	2.45	2.78	3.08	3.39	3.70	3.98	4.26
Overall cost inclusive of CAPEX & OPEX	Crore ₹	3.53	4.87	6.17	7.48	8.79	10.06	11.33	12.62	13.87	15.12
MIXED LIQUOR RECIRCULATION PUMPS AND PUMP-HOUSE											
Total bare construction cost (CAPEX)	Crore ₹	0.77	0.84	0.90	0.94	0.98	1.02	1.05	1.08	1.11	1.14
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of pumps and pump-house (OPEX)	Crore ₹	0.34	0.48	0.61	0.74	0.86	0.99	1.11	1.24	1.36	1.48
Overall cost inclusive of CAPEX & OPEX	Crore ₹	1.11	1.32	1.51	1.67	1.84	2.01	2.16	2.32	2.47	2.62

Summary of data obtained for small group WWTPs with MBR (continued)

ESTIMATED COST SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM

BOD REMOVAL

		Capacity in mld									
		0.5	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
ESTIMATED CONSOLIDATED COSTS											
Total bare construction cost (CAPEX)	Crore ₹	5.99	8.38	10.67	12.90	15.13	17.34	19.53	21.72	23.88	26.05
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of STP	Crore ₹	3.49	4.62	5.71	6.77	7.83	8.84	9.84	10.84	11.79	12.75
Overall cost inclusive of CAPEX & OPEX	Crore ₹	9.48	13.00	16.38	19.67	22.96	26.17	29.37	32.55	35.67	38.80
COST OF LAND											
Cost of land	Crore ₹	0.69	0.79	0.86	0.93	1.01	1.08	1.15	1.23	1.29	1.36
OVERALL COST											
Overall cost	Crore ₹	10.18	13.79	17.24	20.60	23.98	27.25	30.52	33.78	36.97	40.16
Overall cost	Million $	1.27	1.72	2.15	2.58	3.00	3.41	3.81	4.22	4.62	5.02

Summary of data obtained for small group WWTPs with MBR (continued)

REGRESSION ANALYSIS AND DETERMINATION OF MAPE
BOD REMOVAL

		Capacity in mld									
		0.5	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
(as per exponential cost function)											
Predicted value	Crore ₹	12.20	14.10	16.30	18.85	21.79	25.19	29.12	33.67	38.93	45.00
Value of R^2		0.9573									
Absolute percentage error	%	19.87	2.29	5.41	8.52	9.12	7.56	4.56	0.33	5.30	12.05
Mean absolute percentage error (MAPE)	%	7.50									
(as per linear cost function)											
Predicted value	Crore ₹	10.51	13.83	17.15	20.47	23.79	27.11	30.43	33.75	37.07	40.39
Value of R^2		0.9997									
Absolute percentage error	%	3.25	0.29	0.52	0.66	0.79	0.53	0.30	0.11	0.27	0.56
Mean absolute percentage error (MAPE)	%	0.73									
(as per logarithmic cost function)											
Predicted value	Crore ₹	5.62	14.72	20.04	23.82	26.75	29.14	31.16	32.91	34.46	35.84
Value of R^2		0.9152									
Absolute percentage error	%	44.73	6.78	16.27	15.60	11.55	6.92	2.11	2.58	6.78	10.76
Mean absolute percentage error (MAPE)	%	12.41									

Summary of data obtained for small group WWTPs with MBR (continued)

REGRESSION ANALYSIS AND DETERMINATION OF MAPE
BOD REMOVAL

		Capacity in mld									
		0.5	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
(as per polynomial cost function)											
Predicted value	Crore ₹	10.24	13.74	17.19	20.60	23.96	27.28	30.56	33.79	36.98	40.13
Value of R^2		1.00									
Absolute percentage error	%	0.65	0.36	0.28	0.03	0.07	0.11	0.13	0.02	0.04	0.09
Mean absolute percentage error (MAPE)	%	0.18									
(as per power cost function)											
Predicted value	Crore ₹	9.34	14.25	18.23	21.72	24.88	27.80	30.54	33.13	35.59	37.95
Value of R^2		0.9883									
Absolute percentage error	%	8.20	3.33	5.79	5.44	3.79	2.03	0.07	1.95	3.73	5.52
Mean absolute percentage error (MAPE)	%	3.98									

Where

CAPEX : Total bare construction cost

OPEX : Levelized cost based on energy requirement, operation and maintenance for 25 years of life of WWTP

MAPE : Mean absolute percentage error

R : Determination coefficient

Conversion rate : 80.00 ₹ is equivalent to 1.00 $

NOTE: The above are applicable for each of subsequent appendices.

Summary of data obtained for small group WWTPs with MBR (continued)

95 % CONFIDENCE INTERVAL FOR MEAN OF ABSOLUTE PERCENTAGE ERROR AS PER SELECTED COST FUNCTION

BOD REMOVAL

		Capacity in mld									
		0.5	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
		(as per linear cost function)									
Absolute percentage error	%	3.25	0.29	0.52	0.66	0.79	0.53	0.30	0.11	0.27	0.56
MAPE	%	0.73									
Standard deviation	%	0.91									
Alpha value for 95% confidence level		0.05									
Confidence		0.56									
Upper limit of MAPE	%	1.29									
Lower limit of MAPE	%	0.16									

Appendix - II

Summary of data obtained for medium group WWTPs with MBR

DESIGN SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM
BOD REMOVAL

		Capacity in mld									
		5	***10***	***15***	***20***	***25***	***30***	***35***	***40***	***45***	***50***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Average wastewater flow rate	m^3/d	5000.0	10000.0	15000.0	20000.0	25000.0	30000.0	35000.0	40000.0	45000.0	50000.0
Influent flow rate to reactor basins	m^3/d	5780.0	11560.0	17340.0	23120.0	28900.0	34680.0	40460.0	46240.0	52020.0	57800.0
Average BOD load	kg/d	1636.4	3272.8	4909.2	6545.6	8182.0	9818.4	11454.8	13091.2	14727.6	16364.0
Number of reactor basins	number	2	3	4	4	4	4	6	6	6	6
Aerobic solids residence time - design value	d	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Total volume of each reactor basin	m^3	507.97	677.29	761.95	1015.93	1269.91	1523.90	1185.25	1354.57	1523.90	1693.22
Hydraulic detention time of each reactor basin	h	4.22	4.22	4.22	4.22	4.22	4.22	4.22	4.22	4.22	4.22
MLSS (X_{MLSS})	g TSS/m^3	8000.00	8000.00	8000.00	8000.00	8000.00	8000.00	8000.00	8000.00	8000.00	8000.00
MLVSS (X_{MLVSS})	g VSS/m^3	3400.14	3400.14	3400.14	3400.14	3400.14	3400.14	3400.14	3400.14	3400.14	3400.14
F/M	(g BOD/d)/g bVSS	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
Volumetric BOD loading	(kg BOD/d)/m^3	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61
Total sludge (TSS) purged per day	kg TSS/d	1625.49	3250.98	4876.47	6501.95	8127.44	9752.93	11378.42	13003.91	14629.40	16254.88

Summary of data obtained for medium group WWTPs with MBR (continued)

DESIGN SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM(continued)

BOD REMOVAL

		Capacity in mld									
		5	***10***	***15***	***20***	***25***	***30***	***35***	***40***	***45***	***50***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Observed yield based on VSS	g b VSS/g bCOD	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29
	g b VSS/g BOD	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
Observed yield based on TSS	g TSS/g bCOD	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62
	g TSS/g BOD	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Overall oxygen demand	kg oxygen/h	67.86	135.71	203.57	271.42	339.28	407.13	474.99	542.85	610.70	678.56
Air flow rate at average wastewater flow rate	m^3/min	57.84	115.68	173.52	231.36	289.20	347.04	404.88	462.72	520.56	578.40
RAS recycle ratio	-	1.93	1.93	1.93	1.93	1.93	1.93	1.93	1.93	1.93	1.93
Concentration of BOD of effluent	g/m^3	9.66	9.66	9.66	9.66	9.66	9.66	9.66	9.66	9.66	9.66
Concentration of TSS of effluent	g/m^3	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
Concentration of NH_4-N of effluent	g/m^3	40.95	40.95	40.95	40.95	40.95	40.95	40.95	40.95	40.95	40.95
Concentration of NO_3-N of effluent	g/m^3	≤ 5	≤ 5	≤ 5	≤ 5	≤ 5	≤ 5	≤ 5	≤ 5	≤ 5	≤ 5

Summary of data obtained for medium group WWTPs with MBR (continued)

EQUIPMENT SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM BOD REMOVAL											
		Capacity in mld									
		5	***10***	***15***	***20***	***25***	***30***	***35***	***40***	***45***	***50***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Number of batteries		1	1	1	1	1	1	1	1	1	1
AEROBIC REACTOR BASINS & ACCESSORIES											
Number of reactor basins		2	3	4	4	4	4	6	6	6	6
Length of each reactor basin	m	13.64	18.19	20.46	27.28	34.11	40.93	31.83	36.38	40.93	45.47
Width of each reactor basin	m	9.14	9.14	9.14	9.14	9.14	9.14	9.14	9.14	9.14	9.14
Depth of each reactor basin	m	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57
Number of swing arm headers of each reactor basin		5	6	7	9	11	14	11	12	14	15
MEMBRANE CHAMBERS & ACCESSORIES											
Number of membrane chambers		2	3	4	4	4	4	6	6	6	6
Length of each membrane chamber	m	8.29	8.29	8.29	10.46	12.63	16.04	12.01	13.87	16.04	16.97
Width of each membrane chamber	m	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26
Depth of each membrane chamber	m	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57
Number of membrane modules provided for membrane chambers		528	792	1056	1344	1632	2016	2304	2592	3024	3312

Summary of data obtained for medium group WWTPs with MBR (continued)

EQUIPMENT SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM(continued)

BOD REMOVAL

		Capacity in mld									
		5	***10***	***15***	***20***	***25***	***30***	***35***	***40***	***45***	***50***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
MIXED LIQUOR RECIRCULATION PUMPS AND PUMP-HOUSE											
Total number of pumps required		2	2	2	2	2	2	2	2	2	3
Capacity of each pump	m^3/h	480.00	950.00	1420.00	1890.00	2360.00	2830.00	3300.00	3770.00	4240.00	2360.00
Area required for pump house	m ^2	65.00	71.00	76.00	82.00	87.00	93.00	98.00	104.00	109.00	115.00
BLOWERS AND BLOWER BUILDING											
Total number of blowers required		2	2	2	3	3	3	4	4	4	5
Capacity of each blower	scfm	2347.00	4569.00	6791.00	4512.00	5629.00	6768.00	5257.00	6001.00	6768.00	5635.00
Area required for blower building	m ^2	87.00	103.00	114.00	123.00	130.00	136.00	142.00	147.00	151.00	155.00

Summary of data obtained for medium group WWTPs with MBR (continued)

ESTIMATED COST SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM
BOD REMOVAL

		Capacity in mld									
		5	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
AEROBIC REACTOR BASINS & ACCESSORIES											
CAPEX	Crore ₹	11.29	17.20	23.31	29.72	36.11	44.38	50.68	56.97	66.15	72.42
OPEX	Crore ₹	7.01	11.15	15.29	19.42	23.49	27.87	31.81	35.72	40.11	43.95
CAPEX & OPEX	Crore ₹	18.30	28.34	38.60	49.14	59.60	72.25	82.49	92.68	106.26	116.37
MEMBRANE CHAMBERS & ACCESSORIES											
CAPEX	Crore ₹	10.86	16.24	21.65	27.47	33.30	41.09	46.94	52.79	61.53	67.34
OPEX	Crore ₹	4.26	5.46	6.67	7.95	9.19	10.92	12.07	13.23	15.03	16.08
CAPEX & OPEX	Crore ₹	15.12	21.70	28.31	35.42	42.49	52.00	59.01	66.01	76.57	83.42
MIXED LIQUOR RECIRCULATION PUMPS AND PUMP-HOUSE											
CAPEX	Crore ₹	1.14	1.38	1.72	2.16	2.61	3.08	3.56	4.05	4.55	3.76
OPEX	Crore ₹	1.48	2.69	3.91	5.14	6.36	7.58	8.80	10.01	11.23	12.35
CAPEX & OPEX	Crore ₹	2.62	4.07	5.63	7.29	8.97	10.66	12.36	14.07	15.78	16.12
BLOWERS AND BLOWER BUILDING											
CAPEX	Crore ₹	2.76	3.91	4.83	5.54	6.26	6.92	7.78	8.38	8.96	9.88

Summary of data obtained for medium group WWTPs with MBR (continued)

ESTIMATED COST SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM ***BOD REMOVAL***											
		Capacity in mld									
		5	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
ESTIMATED CONSOLIDATED COSTS											
CAPEX	Crore ₹	26.05	38.72	51.51	64.89	78.28	95.47	108.96	122.18	141.19	153.41
OPEX	Crore ₹	12.75	19.30	25.87	32.51	39.03	46.37	52.68	58.95	66.37	72.38
CAPEX & OPEX	Crore ₹	38.80	58.02	77.37	97.40	117.32	141.84	161.64	181.14	207.57	225.79
COST OF LAND											
Cost of land	Crore ₹	1.36	2.06	3.04	3.68	4.32	5.01	5.64	6.26	6.89	7.46
OVERALL COST											
Overall cost	Crore ₹	40.16	60.09	80.41	101.08	121.64	146.85	167.28	187.39	214.46	233.24
Overall cost	Million $	5.02	7.51	10.05	12.64	15.20	18.36	20.91	23.42	26.81	29.16

Summary of data obtained for medium group WWTPs with MBR (continued)

REGRESSION ANALYSIS AND DETERMINATION OF MAPE

BOD REMOVAL

		Capacity in mld									
		5	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
(as per exponential cost function)											
Predicted value	Crore ₹	51.38	61.88	74.53	89.77	108.12	130.22	156.85	188.91	227.53	274.04
Value of R^2		0.9521									
Absolute percentage error	%	27.93	2.99	7.31	11.19	11.11	11.32	6.24	0.81	6.09	17.49
MAPE	%	10.25									
(as per linear cost function)											
Predicted value	Crore ₹	37.71	59.38	81.06	102.74	124.42	146.10	167.78	189.46	211.14	232.82
Value of R^2		0.9991									
Absolute percentage error	%	6.12	1.17	0.81	1.64	2.29	0.51	0.30	1.10	1.55	0.18
MAPE	%	1.57									
(as per logarithmic cost function)											
Predicted value	Crore ₹	7.37	66.06	100.39	124.75	143.64	159.08	172.13	183.43	193.40	202.33
Value of R^2		0.8933									
Absolute percentage error	%	81.64	9.94	24.84	23.41	18.09	8.33	2.90	2.11	9.82	13.26
MAPE	%	19.43									

Summary of data obtained for medium group WWTPs with MBR (continued)

REGRESSION ANALYSIS AND DETERMINATION OF MAPE

BOD REMOVAL

		Capacity in mld									
		5	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
(as per polynomial cost function)											
Predicted value	Crore ₹	39.65	60.03	80.75	101.78	123.15	144.83	166.85	189.18	211.85	234.83
Value of R^2		0.9995									
Absolute percentage error	%	1.29	0.09	0.41	0.70	1.24	1.37	0.26	0.95	1.22	0.68
MAPE	%	0.82									
(as per power cost function)											
Predicted value	Crore ₹	36.34	62.53	85.90	107.60	128.14	147.80	166.76	185.14	203.03	220.49
Value of R^2		0.9903									
Absolute percentage error	%	9.52	4.07	6.82	6.45	5.34	0.65	0.31	1.20	5.33	5.47
MAPE	%	4.52									

Summary of data obtained for medium group WWTPs with MBR (continued)

95 % CONFIDENCE INTERVAL FOR MEAN OF ABSOLUTE PERCENTAGE ERROR AS PER SELECTED COST FUNCTION

BOD REMOVAL

		Capacity in mld									
		5	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
		(as per linear cost function)									
Absolute percentage error	%	6.12	1.17	0.81	1.64	2.29	0.51	0.30	1.10	1.55	0.18
MAPE	%	1.57									
Standard deviation	%	1.73									
Alpha value for 95% confidence level		0.05									
Confidence		1.07									
Upper limit of MAPE	%	2.64									
Lower limit of MAPE	%	0.50									

Appendix - III

Summary of data obtained for large group WWTPs with MBR

DESIGN SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM
BOD REMOVAL

		Capacity in mld										
		50	***60***	***70***	***80***	***90***	***100***	***110***	***120***	***130***	***140***	***150***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Average wastewater flow rate	m^3/d	50000.00	60000.00	70000.00	80000.00	90000.00	100000.00	110000.00	120000.00	130000.00	140000.00	150000.00
Influent flow rate to reactor basins	m^3/d	57800.00	69360.00	80920.00	92480.00	104040.00	115600.00	127160.00	138720.00	150280.00	161840.00	173400.00
Average BOD load	kg/d	16364.00	19636.80	22909.60	26182.40	29455.20	32728.00	36000.80	39273.60	42546.40	45819.20	49092.00
Number of reactor basins	number	6	6	8	8	8	10	10	10	10	12	12
Aerobic solids residence time - design value	d	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Total volume of each reactor basin	m^3	1693.22	2031.86	1777.88	2031.86	2285.84	2031.86	2235.05	2438.23	2641.42	2370.50	2539.83
Hydraulic detention time of each reactor basin	h	4.22	4.22	4.22	4.22	4.22	4.22	4.22	4.22	4.22	4.22	4.22
MLSS (X_{MLSS})	g TSS/m^3	8000.00	8000.00	8000.00	8000.00	8000.00	8000.00	8000.00	8000.00	8000.00	8000.00	8000.00
MLVSS (X_{MLVSS})	g VSS/m^3	3400.14	3400.14	3400.14	3400.14	3400.14	3400.14	3400.14	3400.14	3400.14	3400.14	3400.14
F/M	(g BOD/d)/g bVSS	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
Volumetric BOD loading	(kg BOD/d)/m^3	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61
Total sludge (TSS) purged per day	kg TSS/d	16254.88	19505.86	22756.84	26007.81	29258.79	32509.77	35760.74	39011.72	42262.70	45513.67	48764.65
Observed yield based on VSS	g b VSS/g bCOD	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29
	g b VSS/g BOD	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
Observed yield based on TSS	g TSS/g bCOD	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62
	g TSS/g BOD	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Summary of data obtained for large group WWTPs with MBR (continued)

DESIGN SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM(continued)
BOD REMOVAL

		Capacity in mld										
		50	***60***	***70***	***80***	***90***	***100***	***110***	***120***	***130***	***140***	***150***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Overall oxygen demand	kg oxygen/h	678.56	814.27	949.98	1085.69	1221.40	1357.12	1492.83	1628.54	1764.25	1899.96	2035.67
Air flow rate at average wastewater flow rate	m^3/min	578.40	694.08	809.76	925.44	1041.11	1156.79	1272.47	1388.15	1503.83	1619.51	1735.19
RAS recycle ratio	-	1.93	1.93	1.93	1.93	1.93	1.93	1.93	1.93	1.93	1.93	1.93
Concentration of BOD of effluent	g/m^3	9.66	9.66	9.66	9.66	9.66	9.66	9.66	9.66	9.66	9.66	9.66
Concentration of TSS of effluent	g/m^3	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00

Summary of data obtained for large group WWTPs with MBR (continued)

EQUIPMENT SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM

BOD REMOVAL

		Capacity in mld										
		50	***60***	***70***	***80***	***90***	***100***	***110***	***120***	***130***	***140***	***150***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
AEROBIC REACTOR BASINS & ACCESSORIES												
Number of reactor basins		6	6	8	8	8	10	10	10	10	12	12
Length of each reactor basin	m	45.47	54.57	47.75	54.57	61.39	54.57	60.03	65.48	70.94	63.66	68.21
Width of each reactor basin	m	9.14	9.14	9.14	9.14	9.14	9.14	9.14	9.14	9.14	9.14	9.14
Depth of each reactor basin	m	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57
Number of swing arm headers of each reactor basin		15	18	16	18	20	18	20	21	23	21	22
MEMBRANE CHAMBERS & ACCESSORIES												
Number of membrane chambers		6	6	8	8	8	10	10	10	10	12	12
Length of each membrane chamber	m	16.97	20.38	18.21	20.38	22.86	20.38	22.55	24.72	25.65	23.48	25.03
Width of each membrane chamber	m	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26
Depth of each membrane chamber	m	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57
Number of membrane modules provided for membrane chambers		3312	3888	4608	5184	5952	6480	7200	7920	8400	9216	9792
MIXED LIQUOR RECIRCULATION PUMPS AND PUMP-HOUSE												
Total number of pumps required		3	3	3	3	3	4	4	4	4	4	5
Capacity of each pump	m^3/h	2360.00	2830.00	3300.00	3770.00	4240.00	3140.00	3450.00	3770.00	4080.00	4400.00	3530.00
Area required for pump house	m ^2	115.00	126.00	137.00	147.00	158.00	169.00	180.00	191.00	202.00	213.00	224.00

Summary of data obtained for large group WWTPs with MBR (continued)

EQUIPMENT SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM(continued)

BOD REMOVAL

		Capacity in mld										
		50	**60**	**70**	**80**	**90**	**100**	**110**	**120**	**130**	**140**	**150**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
BLOWERS AND BLOWER BUILDING												
Total number of blowers required		5	5	3	4	4	4	4	5	5	5	5
Capacity of each blower	scfm	5635.00	6751.00	15769.00	12002.00	13521.00	15002.00	16513.00	13519.00	14624.00	15769.00	16886.00
Area required for blower building	m ^2	155.00	163.00	169.00	175.00	180.00	185.00	190.00	194.00	198.00	202.00	205.00

Summary of data obtained for large group WWTPs with MBR (continued)

ESTIMATED COST SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM
BOD REMOVAL

		Capacity in mld										
		50	**60**	**70**	**80**	**90**	**100**	**110**	**120**	**130**	**140**	**150**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
AEROBIC REACTOR BASINS & ACCESSORIES												
Total bare construction cost (CAPEX)	Crore ₹	72.42	84.99	100.41	112.92	129.26	140.83	156.20	171.52	182.08	199.40	211.83
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of reaction basins and accessories (OPEX)	Crore ₹	43.95	51.58	59.59	67.07	75.08	82.33	90.09	97.80	104.82	112.72	119.94
Overall cost inclusive of CAPEX & OPEX	Crore ₹	116.37	136.56	160.00	179.99	204.34	223.16	246.29	269.31	286.90	312.12	331.77
MEMBRANE CHAMBERS & ACCESSORIES												
Total bare construction cost (CAPEX)	Crore ₹	67.34	79.02	93.63	105.29	120.81	131.56	146.12	160.68	170.36	186.91	198.57
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of membrane chambers and accessories (OPEX)	Crore ₹	16.08	18.22	20.94	22.93	25.67	27.45	29.94	32.38	33.78	36.55	38.36
Overall cost inclusive of CAPEX & OPEX	Crore ₹	83.42	97.24	114.57	128.22	146.48	159.01	176.06	193.07	204.14	223.47	236.93

Summary of data obtained for large group WWTPs with MBR (continued)

ESTIMATED COST SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM(continued)

BOD REMOVAL

		Capacity in mld										
		50	**60**	**70**	**80**	**90**	**100**	**110**	**120**	**130**	**140**	**150**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
MIXED LIQUOR RECIRCULATION PUMPS AND PUMP-HOUSE												
Total bare construction cost (CAPEX)	Crore ₹	3.76	4.49	5.24	6.00	6.78	6.57	7.25	7.95	8.65	9.37	9.24
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of pumps and pump-house (OPEX)	Crore ₹	12.35	14.75	17.19	19.62	22.05	24.41	26.83	29.25	31.67	34.10	36.47
Overall cost inclusive of CAPEX & OPEX	Crore ₹	16.12	19.25	22.43	25.62	28.83	30.99	34.08	37.21	40.32	43.46	45.71
ESTIMATED CONSOLIDATED COSTS												
Total bare construction cost (CAPEX)	Crore ₹	153.41	179.45	212.34	238.86	272.50	295.55	327.08	359.45	381.26	416.71	441.50
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of STP	Crore ₹	72.38	84.54	97.71	109.63	122.81	134.19	146.86	159.43	170.27	183.37	194.77
Overall cost inclusive of CAPEX & OPEX	Crore ₹	225.79	264.00	310.05	348.49	395.31	429.74	473.94	518.88	551.53	600.09	636.27
COST OF LAND												
Cost of land	Crore ₹	7.46	8.67	9.94	11.09	12.25	13.53	14.69	15.85	16.92	18.26	19.38
OVERALL COST												
Overall cost	Crore ₹	233.24	272.67	319.99	359.58	407.56	443.28	488.63	534.73	568.44	618.34	655.65
Overall cost	Million $	29.16	34.08	40.00	44.95	50.94	55.41	61.08	66.84	71.06	77.29	81.96

Summary of data obtained for large group WWTPs with MBR (continued)

REGRESSION ANALYSIS AND DETERMINATION OF MAPE
BOD REMOVAL

		Capacity in mld										
		50	**60**	**70**	**80**	**90**	**100**	**110**	**120**	**130**	**140**	**150**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
(as per exponential cost function)												
Predicted value	Crore ₹	255.14	282.26	312.26	345.44	382.15	422.77	467.70	517.40	572.39	633.22	700.52
Value of R^2							0.9777					
Absolute percentage error	%	9.39	3.52	2.42	3.93	6.23	4.63	4.28	3.24	0.69	2.41	6.84
Mean absolute percentage error (MAPE)	%						4.07					
(as per linear cost function)												
Predicted value	Crore ₹	233.31	275.78	318.25	360.71	403.18	445.65	488.12	530.59	573.05	615.52	657.99
Value of R^2							0.9995					
Absolute percentage error	%	0.03	1.14	0.54	0.32	1.07	0.54	0.11	0.77	0.81	0.46	0.36
Mean absolute percentage error (MAPE)	%						0.58					
(as per logarithmic cost function)												
Predicted value	Crore ₹	197.66	268.54	328.46	380.37	426.16	467.11	504.16	537.99	569.11	597.91	624.73
Value of R^2							0.9782					
Absolute percentage error	%	15.26	1.51	2.65	5.78	4.56	5.38	3.18	0.61	0.12	3.30	4.72
Mean absolute percentage error (MAPE)	%						4.24					

Summary of data obtained for large group WWTPs with MBR (continued)

REGRESSION ANALYSIS AND DETERMINATION OF MAPE (continued)
BOD REMOVAL

		Capacity in mld										
		50	**60**	**70**	**80**	**90**	**100**	**110**	**120**	**130**	**140**	**150**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
(as per polynomial cost function)												
Predicted value	Crore ₹	231.91	275.09	318.10	360.92	403.56	446.03	488.31	530.42	572.34	614.08	655.65
Value of R^2		0.9996										
Absolute percentage error	%	0.57	0.89	0.59	0.37	0.98	0.62	0.07	0.81	0.69	0.69	0.00
Mean absolute percentage error (MAPE)	%	0.63										
(as per power cost function)												
Predicted value	Crore ₹	231.66	275.35	318.66	361.65	404.36	446.82	489.06	531.09	572.95	614.63	656.16
Value of R^2		0.9996										
Absolute percentage error	%	0.68	0.98	0.41	0.58	0.79	0.80	0.09	0.68	0.79	0.60	0.08
Mean absolute percentage error (MAPE)	%	0.64										

Summary of data obtained for large group WWTPs with MBR (continued)

95 % CONFIDENCE INTERVAL FOR MEAN OF ABSOLUTE PERCENTAGE ERROR AS PER SELECTED COST FUNCTION
BOD REMOVAL

		Capacity in mld										
		50	60	70	80	90	100	110	120	130	140	150
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
						(as per linear cost function)						
Absolute percentage error	%	0.03	1.14	0.54	0.32	1.07	0.54	0.11	0.77	0.81	0.46	0.36
MAPE	%						0.58					
Standard deviation	%						0.36					
Alpha value for 95% confidence level							0.05					
Confidence							0.21					
Upper limit of MAPE	%						0.79					
Lower limit of MAPE	%						0.37					

Appendix - IV

Summary of data obtained for small group WWTPs with MBBR

DESIGN SUMMARY FOR MOVING BED BIOFILM REACTOR BASINS - SMALL GROUP BOD REMOVAL											
		Capacity in mld									
		0.5	***1***	***1.5***	***2***	***2.5***	***3***	***3.5***	***4***	***4.5***	***5***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Average wastewater flow rate	m^3/d	500.00	1000.00	1500.00	2000.00	2500.00	3000.00	3500.00	4000.00	4500.00	5000.00
Influent flow rate to reactor basins	m^3/d	572.38	1144.75	1717.13	2289.50	2861.88	3434.25	4006.63	4579.00	5151.38	5723.75
Average BOD load	kg/d	119.89	239.78	359.67	479.56	599.45	719.34	839.23	959.12	1079.01	1198.90
MLSS (X_{MLSS})	g TSS/m^3	5000.00	5000.00	5000.00	5000.00	5000.00	5000.00	5000.00	5000.00	5000.00	5000.00
MLVSS (X_{MLVSS})	g VSS/m^3	2832.63	2832.63	2832.63	2832.63	2832.63	2832.63	2832.63	2832.63	2832.63	2832.63
F/M	(g BOD/d)/g VSS	1.27	1.27	1.27	1.27	1.27	1.27	1.27	1.27	1.27	1.27
Volumetric BOD loading	(kg BOD/d)/m^3	3.61	3.61	3.61	3.61	3.61	3.61	3.61	3.61	3.61	3.61
Total sludge (TSS) purged per day	kg TSS/d	114.54	229.09	343.63	458.17	572.72	687.26	801.80	916.34	1030.89	1145.43
Observed yield based on VSS	g bVSS/g bCOD	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34
	g bVSS/g BOD	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55
Observed yield based on TSS	g TSS/g bCOD	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61
	g TSS/g BOD	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97
Overall oxygen demand	kg oxygen/h	4.57	9.13	13.70	18.26	22.83	27.39	31.96	36.52	41.09	45.65
Air flow rate at average wastewater flow rate	m^3/min	3.89	7.78	11.67	15.57	19.46	23.35	27.24	31.13	35.02	38.92
RAS recycle ratio	number	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69
Concentration of BOD of effluent	g/m^3	9.99	9.99	9.99	9.99	9.99	9.99	9.99	9.99	9.99	9.99
Concentration of TSS of effluent	g/m^3	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00

Summary of data obtained for small group WWTPs with MBBR (continued)

EQUIPMENT SUMMARY FOR MOVING BED BIOLOGICAL REACTOR BASED SYSTEM - SMALL GROUP BOD REMOVAL											
		Capacity in mld									
		0.5	***1***	***1.5***	***2***	***2.5***	***3***	***3.5***	***4***	***4.5***	***5***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
PRIMARY CLARIFIERS											
Number of primary clarifiers	number	2	2	2	2	2	2	2	2	2	2
Diameter of each primary clarifier	m	3.50	4.90	6.00	7.00	7.80	7.80	8.40	9.00	9.50	10.00
Side water depth of each primary clarifier	m	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
PRIMARY CLARIFIER SLUDGE SUMP											
Number of sludge sumps	number	1	1	1	1	1	1	1	1	1	1
Length of each sludge sump	m	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10
Width of each sludge sump	m	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10
Depth of each sludge sump	m	3.10	3.10	3.10	3.10	3.10	3.10	3.10	3.10	3.10	3.10
PRIMARY CLARIFIER SLUDGE TRANSFER PUMPS & PUMP-HOUSE											
Number of pump-houses	number	1	1	1	1	1	1	1	1	1	1
Total number of pumps provided in each pump-house	number	2	2	2	2	2	2	2	2	2	2
Design capacity for each pump	m^3/h	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
Head to be developed by each pump	mlc	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00

Summary of data obtained for small group WWTPs with MBBR (continued)

EQUIPMENT SUMMARY FOR MOVING BED BIOLOGICAL REACTOR BASED SYSTEM - SMALL GROUP(continued)
BOD REMOVAL

		Capacity in mld									
		0.5	***1***	***1.5***	***2***	***2.5***	***3***	***3.5***	***4***	***4.5***	***5***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
STAGE - 1 OF DOUBLE STAGE BOD REMOVAL REACTION BASINS & ACCESSORIES											
Number of reactor basins	number	2	2	2	2	2	2	2	2	2	2
Length of each reactor basin	m	1.80	2.50	3.00	3.50	3.90	4.30	4.60	4.90	5.20	5.50
Width of each reactor basin	m	1.50	2.10	2.50	3.00	3.30	3.60	3.90	4.10	4.40	4.60
Depth of each reactor basin	m	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57
STAGE - 2 OF DOUBLE STAGE BOD REMOVAL REACTION BASINS & ACCESSORIES											
Number of reactor basins	number	2	2	2	2	2	2	2	2	2	2
Length of each reactor basin	m	1.70	2.30	2.90	3.30	3.70	4.10	4.40	4.70	5.00	5.30
Width of each reactor basin	m	1.50	2.10	2.50	3.00	3.30	3.60	3.90	4.10	4.40	4.60
Depth of each reactor basin	m	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57
SECONDARY CLARIFIERS											
Number of secondary clarifiers	number	2	2	2	2	2	2	2	2	2	2
Diameter of each secondary clarifier	m	7.20	10.20	12.50	14.40	16.10	16.20	17.50	18.70	19.80	20.90
Side water depth of each secondary clarifier	m	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50

Summary of data obtained for small group WWTPs with MBBR (continued)

EQUIPMENT SUMMARY FOR MOVING BED BIOLOGICAL REACTOR BASED SYSTEM - SMALL GROUP(continued)
BOD REMOVAL

		Capacity in mld									
		0.5	***1***	***1.5***	***2***	***2.5***	***3***	***3.5***	***4***	***4.5***	***5***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
SECONDARY CLARIFIER SLUDGE SUMP											
Number of sludge sumps	number	1	1	1	1	1	1	1	1	1	1
Length of each sludge sump	m	6.10	6.10	6.10	6.10	6.10	6.59	7.69	8.79	9.89	10.99
Width of each sludge sump	m	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10
Depth of each sludge sump	m	3.10	3.10	3.10	3.10	3.10	3.10	3.10	3.10	3.10	3.10
SECONDARY CLARIFIER SLUDGE TRANSFER PUMPS & PUMP-HOUSE											
Number of pump-houses	number	1	1	1	1	1	1	1	1	1	1
Total number of pumps provided in each pump-house	number	2	2	2	2	2	2	2	2	2	2
Design capacity for each pump	m^3/h	20.00	40.00	60.00	70.00	90.00	110.00	120.00	140.00	160.00	170.00
Head to be developed by each pump	mlc	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00

Summary of data obtained for small group WWTPs with MBBR (continued)

ESTIMATED COST SUMMARY FOR MOVING BED BIOLOGICAL REACTOR BASED SYSTEM - SMALL GROUP BOD REMOVAL											
		Capacity in mld									
		0.5	***1***	***1.5***	***2***	***2.5***	***3***	***3.5***	***4***	***4.5***	***5***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
PRIMARY CLARIFIERS											
Total bare construction cost (CAPEX)	Crore ₹	0.41	0.55	0.66	0.76	0.83	0.83	0.89	0.95	1.00	1.05
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of primary clarifiers (OPEX)	Crore ₹	0.22	0.23	0.24	0.25	0.26	0.26	0.27	0.29	0.30	0.31
Overall cost inclusive of CAPEX & OPEX	Crore ₹	0.63	0.78	0.90	1.01	1.10	1.10	1.17	1.24	1.30	1.36
PRIMARY CLARIFIER SLUDGE SUMP											
Total bare construction cost (CAPEX)	Crore ₹	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of primary clarifier sludge sump (OPEX)	Crore ₹	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Overall cost inclusive of CAPEX & OPEX	Crore ₹	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
PRIMARY CLARIFIER SLUDGE TRANSFER PUMPS & PUMP-HOUSE											
Total bare construction cost (CAPEX)	Crore ₹	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of primary clarifier sludge transfer pumps & pump-house (OPEX)	Crore ₹	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21
Overall cost inclusive of CAPEX & OPEX	Crore ₹	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87

Summary of data obtained for small group WWTPs with MBBR (continued)

ESTIMATED COST SUMMARY FOR MOVING BED BIOLOGICAL REACTOR BASED SYSTEM - SMALL GROUP (continued)
BOD REMOVAL

		Capacity in mld									
		0.5	***1***	***1.5***	***2***	***2.5***	***3***	***3.5***	***4***	***4.5***	***5***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
STAGE - 1 OF DOUBLE STAGE BOD REMOVAL REACTION BASINS & ACCESSORIES											
Total bare construction cost (CAPEX)	Crore ₹	0.21	0.25	0.28	0.32	0.35	0.37	0.41	0.44	0.47	0.51
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of stage - 1 of double stage bod removal reaction basins & accessories (OPEX)	Crore ₹	0.48	0.73	0.97	1.21	1.44	1.67	1.90	2.13	2.35	2.58
Overall cost inclusive of CAPEX & OPEX	Crore ₹	0.69	0.98	1.25	1.53	1.79	2.04	2.30	2.56	2.83	3.09
STAGE - 2 OF DOUBLE STAGE BOD REMOVAL REACTION BASINS & ACCESSORIES											
Total bare construction cost (CAPEX)	Crore ₹	0.14	0.16	0.19	0.21	0.23	0.25	0.27	0.28	0.30	0.32
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of stage - 2 of double stage bod removal reaction basins & accessories (OPEX)	Crore ₹	0.08	0.08	0.08	0.08	0.09	0.09	0.09	0.09	0.10	0.10
Overall cost inclusive of CAPEX & OPEX	Crore ₹	0.22	0.24	0.27	0.29	0.31	0.34	0.36	0.38	0.40	0.42
BLOWERS AND BLOWER-BUILDING											
Total bare construction cost (CAPEX)	Crore ₹	0.73	0.99	1.19	1.36	1.52	1.65	1.78	1.91	2.02	2.13
SECONDARY CLARIFIERS											
Total bare construction cost (CAPEX)	Crore ₹	0.79	1.09	1.32	1.52	1.69	1.71	1.84	1.97	2.09	2.21
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of secondary clarifiers (OPEX)	Crore ₹	0.26	0.31	0.36	0.41	0.46	0.46	0.50	0.53	0.56	0.60
Overall cost inclusive of CAPEX & OPEX	Crore ₹	1.05	1.40	1.68	1.92	2.15	2.16	2.34	2.50	2.66	2.81

Summary of data obtained for small group WWTPs with MBBR (continued)

ESTIMATED COST SUMMARY FOR MOVING BED BIOLOGICAL REACTOR BASED SYSTEM - SMALL GROUP (continued)
BOD REMOVAL

		Capacity in mld									
		0.5	***1***	***1.5***	***2***	***2.5***	***3***	***3.5***	***4***	***4.5***	***5***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
SECONDARY CLARIFIER SLUDGE SUMP											
Total bare construction cost (CAPEX)	Crore ₹	0.05	0.05	0.05	0.05	0.05	0.06	0.06	0.07	0.07	0.08
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of secondary clarifier sludge sump (OPEX)	Crore ₹	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Overall cost inclusive of CAPEX & OPEX	Crore ₹	0.19	0.19	0.19	0.19	0.19	0.20	0.20	0.21	0.21	0.22
SECONDARY CLARIFIER SLUDGE TRANSFER PUMPS & PUMP-HOUSE											
Total bare construction cost (CAPEX)	Crore ₹	0.70	0.75	0.79	0.80	0.83	0.86	0.87	0.89	0.91	0.92
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of secondary clarifier sludge transfer pumps & pump-house (OPEX)	Crore ₹	0.25	0.31	0.38	0.41	0.46	0.52	0.55	0.60	0.66	0.69
Overall cost inclusive of CAPEX & OPEX	Crore ₹	0.95	1.07	1.16	1.21	1.29	1.38	1.42	1.49	1.57	1.61
ESTIMATED CONSOLIDATED COSTS											
Total bare construction cost (CAPEX)	Crore ₹	3.76	4.57	5.20	5.74	6.22	6.44	6.84	7.23	7.59	7.94
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of WWTP (OPEX)	Crore ₹	1.77	2.16	2.52	2.85	3.20	3.49	3.80	4.13	4.46	4.76
Overall cost inclusive of CAPEX & OPEX	Crore ₹	5.53	6.72	7.72	8.59	9.42	9.93	10.64	11.36	12.05	12.70
COST OF LAND											
Cost of land	Crore ₹	1.48	1.82	2.12	2.42	2.69	2.75	2.99	3.23	3.46	3.70
OVERALL COST											
Overall cost	Crore ₹	7.00	8.54	9.84	11.00	12.11	12.68	13.63	14.59	15.51	16.39
Overall cost	Million $	0.88	1.07	1.23	1.38	1.51	1.59	1.70	1.82	1.94	2.05

Summary of data obtained for small group WWTPs with MBBR (continued)

REGRESSION ANALYSIS AND DETERMINATION OF MAPE											
BOD REMOVAL											
		Capacity in mld									
		0.5	***1***	***1.5***	***2***	***2.5***	***3***	***3.5***	***4***	***4.5***	***5***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
(as per exponential cost function)											
Predicted value		7.92	8.64	9.44	10.30	11.25	12.28	13.41	14.64	15.98	17.45
Value of R^2		0.9510									
Absolute percentage error		13.06	1.17	4.10	6.37	7.07	3.15	1.63	0.36	3.04	6.46
Mean absolute percentage error (MAPE)		4.64									
(as per linear cost function)											
Predicted value		7.62	8.62	9.62	10.62	11.63	12.63	13.63	14.64	15.64	16.64
Value of R^2		0.9894									
Absolute percentage error		8.73	0.86	2.24	3.46	3.95	0.40	0.02	0.34	0.82	1.53
Mean absolute percentage error (MAPE)		2.24									
(as per logarithmic cost function)											
Predicted value		5.99	8.81	10.46	11.63	12.53	13.27	13.90	14.44	14.92	15.35
Value of R^2		0.9533									
Absolute percentage error		14.47	3.08	6.24	5.64	3.53	4.68	1.98	0.99	3.80	6.35
Mean absolute percentage error (MAPE)		5.08									
(as per polynomial cost function)											
Predicted value		7.00	8.55	9.86	10.98	11.96	12.85	13.69	14.53	15.44	16.45
Value of R^2		0.9992									
Absolute percentage error		0.02	0.11	0.23	0.19	1.19	1.30	0.41	0.36	0.48	0.33
Mean absolute percentage error (MAPE)		0.46									
(as per power cost function)											
Predicted value		6.72	8.69	10.09	11.23	12.19	13.04	13.81	14.51	15.15	15.76
Value of R^2		0.9908									
Absolute percentage error		4.04	1.65	2.54	2.00	0.72	2.86	1.30	0.54	2.30	3.87
Mean absolute percentage error (MAPE)		2.18									

Summary of data obtained for small group WWTPs with MBBR (continued)

95 % CONFIDENCE INTERVAL FOR MEAN OF ABSOLUTE PERCENTAGE ERROR AS PER SELECTED COST FUNCTION

BOD REMOVAL

		Capacity in mld									
		0.5	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
		(as per linear cost function)									
Absolute percentage error	%	8.73	0.86	2.24	3.46	3.95	0.4	0.02	0.34	0.82	1.53
MAPE	%	2.24									
Standard deviation	%	2.64									
Alpha value for 95% confidence level		0.05									
Confidence		1.64									
Upper limit of MAPE	%	3.87									
Lower limit of MAPE	%	0.60									

Appendix- V

Summary of data obtained for medium group WWTPs with MBBR

DESIGN SUMMARY FOR MOVING BED BIOFILM REACTOR BASINS - MEDIUM GROUP BOD REMOVAL

		Capacity in mld									
		5	***10***	***15***	***20***	***25***	***30***	***35***	***40***	***45***	***50***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Average wastewater flow rate	m^3/d	5000.00	10000.00	15000.00	20000.00	25000.00	30000.00	35000.00	40000.00	45000.00	50000.00
Influent flow rate to reactor basins	m^3/d	5723.75	11447.50	17171.25	22895.00	28618.75	34342.50	40066.25	45790.00	51513.75	57237.50
Average BOD load	kg/d	1198.90	2397.80	3596.70	4795.60	5994.50	7193.40	8392.30	9591.20	10790.10	11989.00
MLSS (X_{MLSS})	g TSS/m^3	5000.00	5000.00	5000.00	5000.00	5000.00	5000.00	5000.00	5000.00	5000.00	5000.00
MLVSS (X_{MLVSS})	g VSS/m^3	2832.63	2832.63	2832.63	2832.63	2832.63	2832.63	2832.63	2832.63	2832.63	2832.63
F/M	(g BOD/d)/g VSS	1.27	1.27	1.27	1.27	1.27	1.27	1.27	1.27	1.27	1.27
Volumetric BOD loading	(kg BOD/d)/m^3	3.61	3.61	3.61	3.61	3.61	3.61	3.61	3.61	3.61	3.61
Total sludge (TSS) purged per day	kg TSS/d	1145.43	2290.86	3436.29	4581.72	5727.15	6872.58	8018.01	9163.44	10308.87	11454.30
Observed yield based on VSS	g bVSS/g bCOD	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34
	g bVSS/g BOD	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55
Observed yield based on TSS	g TSS/g bCOD	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61
	g TSS/g BOD	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97
Overall oxygen demand	kg oxygen/h	45.65	91.31	136.96	182.62	228.27	273.93	319.58	365.24	410.89	456.55
Air flow rate at average wastewater flow rate	m^3/min	38.92	77.83	116.75	155.66	194.58	233.50	272.41	311.33	350.24	389.16
RAS recycle ratio	number	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69
Concentration of BOD of effluent	g/m^3	9.99	9.99	9.99	9.99	9.99	9.99	9.99	9.99	9.99	9.99
Concentration of TSS of effluent	g/m^3	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00

Summary of data obtained for medium group WWTPs with MBBR (continued)

EQUIPMENT SUMMARY FOR MOVING BED BIOLOGICAL REACTOR BASED SYSTEM BOD REMOVAL											
		Capacity in mld									
		5	***10***	***15***	***20***	***25***	***30***	***35***	***40***	***45***	***50***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
PRIMARY CLARIFIERS											
Number of primary clarifiers	number	2	2	2	2	2	2	2	4	4	4
Diameter of each primary clarifier	m	10.00	13.50	16.60	19.10	21.40	23.40	25.30	19.10	20.30	21.40
Side water depth of each primary clarifier	m	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
PRIMARY CLARIFIER SLUDGE SUMP											
Number of sludge sumps	number	1	1	1	1	1	1	1	1	1	1
Length of each sludge sump	m	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10
Width of each sludge sump	m	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10
Depth of each sludge sump	m	3.10	3.10	3.10	3.10	3.10	3.10	3.10	3.10	3.10	3.10
PRIMARY CLARIFIER SLUDGE TRANSFER PUMPS & PUMP-HOUSE											
Number of pump-houses	number	1	1	1	1	1	1	1	1	1	1
Total number of pumps provided in each pump-house	number	2	2	2	2	2	2	2	2	2	2
Design capacity for each pump	m^3/h	10.00	10.00	10.00	10.00	20.00	20.00	20.00	20.00	30.00	30.00
Head to be developed by each pump	mlc	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
STAGE - 1 OF DOUBLE STAGE BOD REMOVAL REACTION BASINS & ACCESSORIES											
Number of reactor basins	number	2	3	4	4	4	4	6	6	6	6
Length of each reactor basin	m	5.50	6.30	6.70	7.70	8.60	9.40	8.30	8.90	9.40	10.00
Width of each reactor basin	m	4.60	5.30	5.60	6.50	7.20	7.90	7.00	7.50	7.90	8.40
Depth of each reactor basin	m	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57

Summary of data obtained for medium group WWTPs with MBBR (continued)

EQUIPMENT SUMMARY FOR MOVING BED BIOLOGICAL REACTOR BASED SYSTEM (continued)
BOD REMOVAL

		Capacity in mld									
		5	***10***	***15***	***20***	***25***	***30***	***35***	***40***	***45***	***50***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
STAGE - 2 OF DOUBLE STAGE BOD REMOVAL REACTION BASINS & ACCESSORIES											
Number of reactor basins	number	2	3	4	4	4	4	6	6	6	6
Length of each reactor basin	m	5.30	6.10	6.50	7.40	8.40	9.20	8.10	8.60	9.20	9.60
Width of each reactor basin	m	4.60	5.30	5.60	6.50	7.20	7.90	7.00	7.50	7.90	8.40
Depth of each reactor basin	m	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57
SECONDARY CLARIFIERS											
Number of secondary clarifiers	number	2	2	2	2	2	2	4	4	4	4
Diameter of each secondary clarifier	m	20.90	28.10	34.50	39.80	44.50	48.70	37.20	39.80	42.20	44.50
Side water depth of each secondary clarifier	m	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50
SECONDARY CLARIFIER SLUDGE SUMP											
Number of sludge sumps	number	1	1	1	1	1	1	1	2	2	2
Length of each sludge sump	m	10.99	21.98	32.97	43.97	54.96	65.95	76.94	43.97	49.46	54.96
Width of each sludge sump	m	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10
Depth of each sludge sump	m	3.10	3.10	3.10	3.10	3.10	3.10	3.10	3.10	3.10	3.10
SECONDARY CLARIFIER SLUDGE TRANSFER PUMPS & PUMP-HOUSE											
Number of pump-houses	number	1	1	1	1	1	1	1	1	1	1
Total number of pumps provided in each pump-house	number	2	2	2	2	2	2	2	2	2	2
Design capacity for each pump	m^3/h	170.00	340.00	510.00	680.00	840.00	1010.00	1180.00	1350.00	1510.00	1680.00
Head to be developed by each pump	mlc	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00

Summary of data obtained for medium group WWTPs with MBBR (continued)

ESTIMATED COST SUMMARY FOR MOVING BED BIOLOGICAL REACTOR BASED SYSTEM
BOD REMOVAL

		Capacity in mld									
		5	***10***	***15***	***20***	***25***	***30***	***35***	***40***	***45***	***50***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
PRIMARY CLARIFIERS											
Total bare construction cost (CAPEX)	Crore ₹	1.05	1.40	1.71	1.97	2.22	2.44	2.65	3.95	4.20	4.44
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of primary clarifiers (OPEX)	Crore ₹	0.31	0.38	0.47	0.54	0.61	0.67	0.73	0.89	0.95	1.01
Overall cost inclusive of CAPEX & OPEX	Crore ₹	1.36	1.77	2.18	2.51	2.83	3.11	3.38	4.84	5.16	5.45
PRIMARY CLARIFIER SLUDGE SUMP											
Total bare construction cost (CAPEX)	Crore ₹	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of primary clarifier sludge sump (OPEX)	Crore ₹	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Overall cost inclusive of CAPEX & OPEX	Crore ₹	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
PRIMARY CLARIFIER SLUDGE TRANSFER PUMPS & PUMP-HOUSE											
Total bare construction cost (CAPEX)	Crore ₹	0.67	0.67	0.67	0.67	0.70	0.70	0.70	0.70	0.73	0.73
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of primary clarifier sludge transfer pumps & pump-house (OPEX)	Crore ₹	0.21	0.21	0.21	0.21	0.25	0.25	0.25	0.25	0.28	0.28
Overall cost inclusive of CAPEX & OPEX	Crore ₹	0.87	0.87	0.87	0.87	0.95	0.95	0.95	0.95	1.01	1.01
STAGE - 1 OF DOUBLE STAGE BOD REMOVAL REACTION BASINS & ACCESSORIES											
Total bare construction cost (CAPEX)	Crore ₹	0.51	0.95	1.50	1.90	2.31	2.71	3.24	3.60	3.95	4.30
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of stage - 1 of double stage bod removal reaction basins & accessories (OPEX)	Crore ₹	2.58	4.81	7.05	9.23	11.41	13.56	15.74	17.87	20.00	22.12
Overall cost inclusive of CAPEX & OPEX	Crore ₹	3.09	5.75	8.56	11.13	13.72	16.27	18.98	21.48	23.95	26.42

Summary of data obtained for medium group WWTPs with MBBR (continued)

ESTIMATED COST SUMMARY FOR MOVING BED BIOLOGICAL REACTOR BASED SYSTEM (continued)
BOD REMOVAL

		Capacity in mld									
		5	***10***	***15***	***20***	***25***	***30***	***35***	***40***	***45***	***50***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
STAGE - 2 OF DOUBLE STAGE BOD REMOVAL REACTION BASINS & ACCESSORIES											
Total bare construction cost (CAPEX)	Crore ₹	0.32	0.54	0.86	1.02	1.19	1.35	1.64	1.79	1.96	2.11
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of stage - 2 of double stage bod removal reaction basins & accessories (OPEX)	Crore ₹	0.10	0.14	0.20	0.22	0.25	0.27	0.31	0.33	0.35	0.37
Overall cost inclusive of CAPEX & OPEX	Crore ₹	0.42	0.68	1.06	1.25	1.44	1.62	1.95	2.12	2.30	2.48
BLOWERS AND BLOWER-BUILDING											
Total bare construction cost (CAPEX)	Crore ₹	2.13	3.03	3.75	4.38	4.94	5.35	5.82	6.27	6.69	7.09
SECONDARY CLARIFIERS											
Total bare construction cost (CAPEX)	Crore ₹	2.21	3.04	3.85	4.56	5.25	5.89	8.41	9.13	9.82	10.49
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of secondary clarifiers (OPEX)	Crore ₹	0.60	0.83	1.04	1.24	1.42	1.59	1.94	2.10	2.26	2.41
Overall cost inclusive of CAPEX & OPEX	Crore ₹	2.81	3.87	4.89	5.81	6.67	7.48	10.35	11.23	12.07	12.90
SECONDARY CLARIFIER SLUDGE SUMP											
Total bare construction cost (CAPEX)	Crore ₹	0.08	0.13	0.18	0.24	0.29	0.34	0.40	0.42	0.47	0.52
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of secondary clarifier sludge sump (OPEX)	Crore ₹	0.14	0.16	0.19	0.21	0.24	0.27	0.30	0.32	0.35	0.37
Overall cost inclusive of CAPEX & OPEX	Crore ₹	0.22	0.29	0.37	0.45	0.53	0.61	0.70	0.74	0.82	0.89
SECONDARY CLARIFIER SLUDGE TRANSFER PUMPS & PUMP-HOUSE											
Total bare construction cost (CAPEX)	Crore ₹	0.92	1.06	1.16	1.25	1.33	1.41	1.50	1.65	1.80	1.96
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of secondary clarifier sludge transfer pumps & pump-house (OPEX)	Crore ₹	0.69	1.14	1.58	2.02	2.43	2.87	3.31	3.75	4.17	4.61
Overall cost inclusive of CAPEX & OPEX	Crore ₹	1.61	2.20	2.75	3.28	3.76	4.27	4.80	5.40	5.97	6.57

Summary of data obtained for medium group WWTPs with MBBR (continued)

ESTIMATED COST SUMMARY FOR MOVING BED BIOLOGICAL REACTOR BASED SYSTEM (continued) ***BOD REMOVAL***											
		Capacity in mld									
		5	***10***	***15***	***20***	***25***	***30***	***35***	***40***	***45***	***50***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
ESTIMATED CONSOLIDATED COSTS											
Total bare construction cost (CAPEX)	Crore ₹	7.94	10.87	13.74	16.05	18.28	20.26	24.42	27.58	29.66	31.70
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of WWTP (OPEX)	Crore ₹	4.76	7.80	10.89	13.82	16.74	19.61	22.70	25.65	28.49	31.30
Overall cost inclusive of CAPEX & OPEX	Crore ₹	12.70	18.67	24.63	29.87	35.02	39.87	47.12	53.23	58.15	63.00
COST OF LAND											
Cost of land	Crore ₹	3.70	5.65	7.90	9.82	11.72	13.57	16.23	18.57	20.45	22.36
OVERALL COST											
Overall cost	Crore ₹	16.39	24.32	32.52	39.69	46.74	53.44	63.35	71.80	78.60	85.36
Overall cost	Million $	2.05	3.04	4.07	4.96	5.84	6.68	7.92	8.97	9.83	10.67

Summary of data obtained for medium group WWTPs with MBBR (continued)

REGRESSION ANALYSIS AND DETERMINATION OF MAPE
BOD REMOVAL

		Capacity in mld									
		5	***10***	***15***	***20***	***25***	***30***	***35***	***40***	***45***	***50***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
(as per exponential cost function)											
Predicted value (as per exponential cost function)		20.94	24.90	29.60	35.19	41.84	49.74	59.13	70.30	83.58	99.37
Value of R^2		0.9488									
Absolute percentage error		27.77	2.38	8.98	11.32	10.49	6.93	6.66	2.08	6.33	16.40
Mean absolute percentage error (MAPE)		9.94									
(as per linear cost function)											
Predicted value (as per linear cost function)		10.79	19.41	28.03	36.65	45.27	53.89	62.51	71.13	79.75	88.37
Value of R^2		0.9709									
Absolute percentage error		34.16	20.18	13.80	7.64	3.15	0.84	1.33	0.92	1.46	3.53
Mean absolute percentage error (MAPE)		8.7									
(as per logarithmic cost function)											
Predicted value (as per logarithmic cost function)		5.39	26.42	38.73	47.46	54.23	59.76	64.44	68.49	72.06	75.26
Value of R^2		0.9032									
Absolute percentage error		67.14	8.64	19.08	19.58	16.01	11.82	1.71	4.61	8.32	11.83
Mean absolute percentage error (MAPE)		16.87									
(as per polynomial cost function)											
Predicted value (as per polynomial cost function)		16.55	24.21	31.88	39.57	47.27	54.99	62.72	70.47	78.23	86.01
Value of R^2		0.9988									
Absolute percentage error		0.99	0.45	1.97	0.29	1.13	2.89	1.00	1.85	0.48	0.75
Mean absolute percentage error (MAPE)		1.18									
(as per power cost function)											
Predicted value (as per power cost function)		15.13	25.11	33.77	41.68	49.06	56.05	62.74	69.17	75.39	81.42
Value of R^2		0.9918									
Absolute percentage error		7.69	3.25	3.85	5.01	4.95	4.88	0.97	3.66	4.09	4.62
Mean absolute percentage error (MAPE)		4.30									

Summary of data obtained for medium group WWTPs with MBBR (continued)

95 % CONFIDENCE INTERVAL FOR MEAN OF ABSOLUTE PERCENTAGE ERROR AS PER SELECTED COST FUNCTION

BOD REMOVAL

		Capacity in mld									
		5	***10***	***15***	***20***	***25***	***30***	***35***	***40***	***45***	***50***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
(as per linear cost function)											
Absolute percentage error	%	34.16	20.18	13.80	7.64	3.15	0.84	1.33	0.92	1.46	3.53
MAPE	%	8.70									
Standard deviation	%	11.02									
Alpha value for 95% confidence level		0.05									
Confidence		6.83									
Upper limit of MAPE	%	15.53									
Lower limit of MAPE	%	1.87									

Appendix- VI

Summary of data obtained for large group WWTPs with MBBR

DESIGN SUMMARY FOR MOVING BED BIOFILM REACTOR BASINS - LARGE GROUP

BOD REMOVAL

Capacity in mld

		50	***60***	***70***	***80***	***90***	***100***	***110***	***120***	***130***	***140***	***150***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Average wastewater flow rate	m^3/d	50000.00	60000.00	70000.00	80000.00	90000.00	100000.00	110000.00	120000.00	130000.00	140000.00	150000.00
Influent flow rate to reactor basins	m^3/d	57237.50	68685.00	80132.50	91580.00	103027.50	114475.00	125922.50	137370.00	148817.50	160265.00	171712.50
Average BOD load	kg/d	11989.00	14386.80	16784.60	19182.40	21580.20	23978.00	26375.80	28773.60	31171.40	33569.20	35967.00
Average TKN load	kg/d	2752.50	3303.00	3853.50	4404.00	4954.50	5505.00	6055.50	6606.00	7156.50	7707.00	8257.50
DESIGN FEATURES												
MLSS (X_{MLSS})	g TSS/m^3	5000.00	5000.00	5000.00	5000.00	5000.00	5000.00	5000.00	5000.00	5000.00	5000.00	5000.00
MLVSS (X_{MLVSS})	g VSS/m^3	2832.63	2832.63	2832.63	2832.63	2832.63	2832.63	2832.63	2832.63	2832.63	2832.63	2832.63
F/M	(g BOD/d)/g VSS	1.27	1.27	1.27	1.27	1.27	1.27	1.27	1.27	1.27	1.27	1.27
Volumetric BOD loading	(kg BOD/d)/m^3	3.61	3.61	3.61	3.61	3.61	3.61	3.61	3.61	3.61	3.61	3.61
Total sludge (TSS) purged per day	kg TSS/d	11454.30	13745.16	16036.02	18326.88	20617.75	22908.61	25199.47	27490.33	29781.19	32072.05	34362.91
Observed yield based on VSS	g bVSS/g bCOD	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34
	g bVSS/g BOD	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55
Observed yield based on TSS	g TSS/g bCOD	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61	0.61
	g TSS/g BOD	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97
Overall oxygen demand	kg oxygen/h	456.55	547.86	639.17	730.48	821.79	913.10	1004.41	1095.72	1187.03	1278.34	1369.65

Summary of data obtained for large group WWTPs with MBBR (continued)

DESIGN SUMMARY FOR MOVING BED BIOFILM REACTOR BASINS - LARGE GROUP (continued)												
BOD REMOVAL												
		Capacity in mld										
		50	***60***	***70***	***80***	***90***	***100***	***110***	***120***	***130***	***140***	***150***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Air flow rate at average wastewater flow rate	m^3/min	389.16	466.99	544.82	622.65	700.49	778.32	856.15	933.98	1011.81	1089.65	1167.48
RAS recycle ratio	number	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69
QUALITY OF EFFLUENT												
Concentration of BOD of effluent	g/m^3	9.99	9.99	9.99	9.99	9.99	9.99	9.99	9.99	9.99	9.99	9.99
Concentration of TSS of effluent	g/m^3	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00

Summary of data obtained for large group WWTPs with MBBR (continued)

EQUIPMENT SUMMARY FOR MOVING BED BIOLOGICAL REACTOR BASED SYSTEM- LARGE GROUP												
BOD REMOVAL												
		Capacity in mld										
		50	***60***	***70***	***80***	***90***	***100***	***110***	***120***	***130***	***140***	***150***
Description	**Unit**	Value	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
PRIMARY CLARIFIERS												
Number of primary clarifiers	number	4	4	4	4	4	8	8	8	8	8	8
Diameter of each primary clarifier	m	21.40	23.40	25.30	27.00	28.70	21.40	22.40	23.40	24.40	25.30	26.20
Side water depth of each primary clarifier	m	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
PRIMARY CLARIFIER SLUDGE SUMP												
Number of sludge sumps	number	1	1	1	1	1	1	1	1	1	1	1
Length of each sludge sump	m	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10
Width of each sludge sump	m	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10
Depth of each sludge sump	m	3.10	3.10	3.10	3.10	3.10	3.10	3.10	3.10	3.10	3.10	3.10
PRIMARY CLARIFIER SLUDGE TRANSFER PUMPS & PUMP-HOUSE												
Number of pump-houses	number	1	1	1	1	1	1	1	1	1	1	1
Total number of pumps provided in each pump-house	number	2	2	2	2	2	2	2	2	2	2	2
Design capacity for each pump	m^3/h	30.00	30.00	40.00	40.00	50.00	50.00	60.00	60.00	70.00	70.00	80.00
Head to be developed by each pump	mlc	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00

Summary of data obtained for large group WWTPs with MBBR (continued)

EQUIPMENT SUMMARY FOR MOVING BED BIOLOGICAL REACTOR BASED SYSTEM (continued)												
BOD REMOVAL												
		Capacity in mld										
		50	*60*	*70*	*80*	*90*	*100*	*110*	*120*	*130*	*140*	*150*
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
STAGE - 1 OF DOUBLE STAGE BOD REMOVAL REACTION BASINS & ACCESSORIES												
Number of reactor basins	number	6	6	8	8	8	10	10	10	10	12	12
Length of each reactor basin	m	10.00	10.90	10.20	10.90	11.60	10.90	11.40	11.90	12.40	11.80	12.20
Width of each reactor basin	m	8.40	9.10	8.50	9.10	9.70	9.10	9.50	10.00	10.40	9.90	10.20
Depth of each reactor basin	m	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57
STAGE - 2 OF DOUBLE STAGE BOD REMOVAL REACTION BASINS & ACCESSORIES												
Number of reactor basins	number	6	6	8	8	8	10	10	10	10	12	12
Length of each reactor basin	m	9.60	10.60	9.90	10.60	11.20	10.60	11.20	11.60	12.10	11.40	11.80
Width of each reactor basin	m	8.40	9.10	8.50	9.10	9.70	9.10	9.50	10.00	10.40	9.90	10.20
Depth of each reactor basin	m	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57

Summary of data obtained for large group WWTPs with MBBR (continued)

EQUIPMENT SUMMARY FOR MOVING BED BIOLOGICAL REACTOR BASED SYSTEM(continued)												
BOD REMOVAL												
		Capacity in mld										
		50	***60***	***70***	***80***	***90***	***100***	***110***	***120***	***130***	***140***	***150***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
SECONDARY CLARIFIERS												
Number of secondary clarifiers	number	4	4	4	8	8	8	8	8	8	8	8
Diameter of each secondary clarifier	m	44.50	48.70	52.60	39.80	42.20	44.50	44.10	46.10	48.00	49.80	51.50
Side water depth of each secondary clarifier	m	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50
SECONDARY CLARIFIER SLUDGE SUMP												
Number of sludge sumps	number	2	2	2	3	3	3	4	4	4	4	5
Length of each sludge sump	m	54.96	65.95	76.94	58.62	65.95	73.28	60.45	65.95	71.44	76.94	65.95
Width of each sludge sump	m	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10
Depth of each sludge sump	m	3.10	3.10	3.10	3.10	3.10	3.10	3.10	3.10	3.10	3.10	3.10
SECONDARY CLARIFIER SLUDGE TRANSFER PUMPS & PUMP-HOUSE												
Number of pump-houses	number	1	1	1	1	1	1	1	1	1	1	1
Total number of pumps provided in each pump-house	number	2	2	2	2	2	2	2	2	2	3	3
Design capacity for each pump	m^3/h	1680.00	2020.00	2350.00	2690.00	3020.00	3360.00	3690.00	4030.00	4360.00	2350.00	2520.00
Head to be developed by each pump	mlc	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00

Summary of data obtained for large group WWTPs with MBBR (continued)

ESTIMATED COST SUMMARY FOR MOVING BED BIOLOGICAL REACTOR BASED SYSTEM												
BOD REMOVAL												
		Capacity in mld										
		50	***60***	***70***	***80***	***90***	***100***	***110***	***120***	***130***	***140***	***150***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
PRIMARY CLARIFIERS												
Total bare construction cost (CAPEX)	Crore ₹	4.44	4.88	5.31	5.70	6.10	8.89	9.32	9.76	10.21	10.62	11.03
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of primary clarifiers (OPEX)	Crore ₹	1.01	1.11	1.22	1.31	1.41	1.74	1.83	1.92	2.02	2.10	2.19
Overall cost inclusive of CAPEX & OPEX	Crore ₹	5.45	5.99	6.53	7.01	7.51	10.62	11.15	11.69	12.23	12.72	13.22
PRIMARY CLARIFIER SLUDGE SUMP												
Total bare construction cost (CAPEX)	Crore ₹	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of primary clarifier sludge sump (OPEX)	Crore ₹	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Overall cost inclusive of CAPEX & OPEX	Crore ₹	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19

Summary of data obtained for large group WWTPs with MBBR (continued)

ESTIMATED COST SUMMARY FOR MOVING BED BIOLOGICAL REACTOR BASED SYSTEM (continued)												
BOD REMOVAL												
		Capacity in mld										
		50	***60***	***70***	***80***	***90***	***100***	***110***	***120***	***130***	***140***	***150***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
PRIMARY CLARIFIER SLUDGE TRANSFER PUMPS & PUMP-HOUSE												
Total bare construction cost (CAPEX)	Crore ₹	0.73	0.73	0.75	0.75	0.77	0.77	0.79	0.79	0.80	0.80	0.82
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of primary clarifier sludge transfer pumps & pump-house (OPEX)	Crore ₹	0.28	0.28	0.31	0.31	0.35	0.35	0.38	0.38	0.41	0.41	0.44
Overall cost inclusive of CAPEX & OPEX	Crore ₹	1.01	1.01	1.07	1.07	1.12	1.12	1.16	1.16	1.21	1.21	1.25
STAGE - 1 OF DOUBLE STAGE BOD REMOVAL REACTION BASINS & ACCESSORIES												
Total bare construction cost (CAPEX)	Crore ₹	4.30	4.98	5.80	6.45	7.13	7.91	8.54	9.23	9.86	10.65	11.27
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of stage - 1 of double stage bod removal reaction basins & accessories (OPEX)	Crore ₹	22.12	26.35	30.59	34.79	38.99	43.20	47.37	51.56	55.73	59.91	64.07
Overall cost inclusive of CAPEX & OPEX	Crore ₹	26.42	31.33	36.39	41.24	46.12	51.10	55.91	60.79	65.58	70.56	75.35

Summary of data obtained for large group WWTPs with MBBR (continued)

ESTIMATED COST SUMMARY FOR MOVING BED BIOLOGICAL REACTOR BASED SYSTEM (continued)

BOD REMOVAL												
		Capacity in mld										
		50	***60***	***70***	***80***	***90***	***100***	***110***	***120***	***130***	***140***	***150***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
STAGE - 2 OF DOUBLE STAGE BOD REMOVAL REACTION BASINS & ACCESSORIES												
Total bare construction cost (CAPEX)	Crore ₹	2.11	2.43	2.87	3.19	3.50	3.96	4.27	4.59	4.90	5.37	5.68
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of stage - 2 of double stage bod removal reaction basins & accessories (OPEX)	Crore ₹	0.37	0.40	0.46	0.49	0.52	0.57	0.60	0.63	0.66	0.71	0.74
Overall cost inclusive of CAPEX & OPEX	Crore ₹	2.48	2.83	3.33	3.68	4.02	4.53	4.88	5.22	5.56	6.08	6.41
BLOWERS AND BLOWER-BUILDING												
Total bare construction cost (CAPEX)	Crore ₹	7.09	8.09	8.82	9.89	10.58	11.23	12.94	13.58	14.81	15.43	16.04
SECONDARY CLARIFIERS												
Total bare construction cost (CAPEX)	Crore ₹	10.49	11.79	13.06	18.26	19.64	20.99	20.75	21.96	23.14	24.28	25.39
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of secondary clarifiers (OPEX)	Crore ₹	2.41	2.69	2.97	3.62	3.89	4.15	4.11	4.34	4.56	4.78	4.99
Overall cost inclusive of CAPEX & OPEX	Crore ₹	12.90	14.48	16.02	21.88	23.52	25.14	24.86	26.30	27.70	29.06	30.37

Summary of data obtained for large group WWTPs with MBBR (continued)

ESTIMATED COST SUMMARY FOR MOVING BED BIOLOGICAL REACTOR BASED SYSTEM (continued)												
BOD REMOVAL												
		Capacity in mld										
		50	***60***	***70***	***80***	***90***	***100***	***110***	***120***	***130***	***140***	***150***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
SECONDARY CLARIFIER SLUDGE SUMP												
Total bare construction cost (CAPEX)	Crore ₹	0.52	0.61	0.71	0.79	0.88	0.97	1.06	1.15	1.24	1.33	1.42
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of secondary clarifier sludge sump (OPEX)	Crore ₹	0.37	0.42	0.46	0.50	0.54	0.58	0.62	0.66	0.69	0.73	0.76
Overall cost inclusive of CAPEX & OPEX	Crore ₹	0.89	1.03	1.17	1.29	1.43	1.55	1.68	1.81	1.93	2.06	2.18
SECONDARY CLARIFIER SLUDGE TRANSFER PUMPS & PUMP-HOUSE												
Total bare construction cost (CAPEX)	Crore ₹	1.96	2.28	2.60	2.94	3.28	3.63	3.97	4.33	4.68	3.75	4.01
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of secondary clarifier sludge transfer pumps & pump-house (OPEX)	Crore ₹	4.61	5.50	6.35	7.24	8.09	8.97	9.82	10.70	11.55	12.34	13.19
Overall cost inclusive of CAPEX & OPEX	Crore ₹	6.57	7.78	8.96	10.18	11.37	12.60	13.79	15.03	16.24	16.09	17.20

Summary of data obtained for large group WWTPs with MBBR (continued)

ESTIMATED COST SUMMARY FOR MOVING BED BIOLOGICAL REACTOR BASED SYSTEM (continued)

BOD REMOVAL

		Capacity in mld										
		50	***60***	***70***	***80***	***90***	***100***	***110***	***120***	***130***	***140***	***150***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
ESTIMATED CONSOLIDATED COSTS												
Total bare construction cost (CAPEX)	Crore ₹	31.70	35.84	39.98	48.03	51.92	58.40	61.70	65.44	69.69	72.28	75.71
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of STP	Crore ₹	31.30	36.89	42.50	48.41	53.93	59.70	64.87	70.32	75.76	81.12	86.51
Overall cost inclusive of CAPEX & OPEX	Crore ₹	63.00	72.73	82.48	96.44	105.85	118.09	126.57	135.76	145.45	153.40	162.21
COST OF LAND												
Cost of land	Crore ₹	22.36	26.01	29.93	35.04	38.80	43.55	44.71	48.28	51.81	55.64	59.12
OVERALL COST												
Overall cost	Crore ₹	85.36	98.75	112.41	131.48	144.65	161.65	171.28	184.04	197.26	209.03	221.34
Overall cost	Million $	10.67	12.34	14.05	16.43	18.08	20.21	21.41	23.01	24.66	26.13	27.67

Summary of data obtained for large group WWTPs with MBBR (continued)

REGRESSION ANALYSIS AND DETERMINATION OF MAPE												
BOD REMOVAL												
		Capacity in mld										
		50	***60***	***70***	***80***	***90***	***100***	***110***	***120***	***130***	***140***	***150***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Predicted value (as per exponential cost function)		93.89	103.14	113.31	124.48	136.74	150.22	165.03	181.29	199.16	218.79	240.35
Value of R^2							0.97					
Absolute percentage error		9.99	4.45	0.80	5.33	5.47	7.07	3.65	1.49	0.96	4.67	8.59
Mean absolute percentage error (MAPE)							4.77					
Predicted value (as per linear cost function)		87.60	101.30	115.01	128.71	142.41	156.12	169.82	183.52	197.22	210.93	224.63
Value of R^2							0.9962					
Absolute percentage error		2.62	2.59	2.31	2.11	1.55	3.42	0.85	0.28	0.02	0.91	1.49
Mean absolute percentage error (MAPE)							1.65					
Predicted value (as per logarithmic cost function)		75.58	98.60	118.07	134.93	149.80	163.10	175.14	186.13	196.23	205.59	214.30
Value of R^2							0.99					
Absolute percentage error		11.46	0.15	5.03	2.62	3.56	0.90	2.25	1.13	0.52	1.65	3.18
Mean absolute percentage error (MAPE)							2.95					

Summary of data obtained for large group WWTPs with MBBR (continued)

REGRESSION ANALYSIS AND DETERMINATION OF MAPE (continued)

BOD REMOVAL

		Capacity in mld										
		50	***60***	***70***	***80***	***90***	***100***	***110***	***120***	***130***	***140***	***150***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Predicted value (as per polynomial cost function)		83.86	99.84	115.32	130.30	144.77	158.75	172.23	185.20	197.68	209.66	221.13
Value of R^2							1.00					
Absolute percentage error		1.76	1.11	2.58	0.90	0.08	1.79	0.55	0.63	0.21	0.30	0.09
Mean absolute percentage error (MAPE)							0.91					
Predicted value (as per power cost function)		85.33	100.17	114.71	129.01	143.09	156.98	170.70	184.28	197.71	211.03	224.23
Value of R^2							1.00					
Absolute percentage error		0.04	1.44	2.05	1.88	1.08	2.89	0.34	0.13	0.23	0.95	
Mean absolute percentage error (MAPE)							1.10					

Summary of data obtained for large group WWTPs with MBBR (continued)

95 % CONFIDENCE INTERVAL FOR MEAN OF ABSOLUTE PERCENTAGE ERROR AS PER SELECTED COST FUNCTION
BOD REMOVAL

		Capacity in mld										
		50	**60**	**70**	**80**	**90**	**100**	**110**	**120**	**130**	**140**	**150**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
		(as per linear cost function)										
Absolute percentage error	%	2.62	2.59	2.31	2.11	1.55	3.42	0.85	0.28	0.02	0.91	1.49
MAPE	%	1.65										
Standard deviation	%	1.07										
Alpha value for 95% confidence level		0.05										
Confidence		0.63										
Upper limit of MAPE	%	2.28										
Lower limit of MAPE	%	1.02										

Appendix- VII

Summary of data obtained for small group WWTPs with SBR

DESIGN SUMMARY FOR SEQUENTIAL BATCH REACTOR BASED SYSTEM – SMALL GROUP BOD REMOVAL											
		Capacity in mld									
		0.5	***1***	***1.5***	***2***	***2.5***	***3***	***3.5***	***4***	***4.5***	***5***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Influent flow rate	m^3/d	578.00	1156.00	1734.00	2312.00	2890.00	3468.00	4046.00	4624.00	5202.00	5780.00
Average BOD load	kg/d	163.64	327.28	490.92	654.56	818.20	981.84	1145.48	1309.12	1472.76	1636.40
Number of reaction basins	number	2	2	2	2	2	2	2	2	2	2
Fill time	h	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Reaction time	h	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Design time selected for aeration	h	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Settlement time	h	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Decantation time	h	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Total cycle time	h	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
Solids residence time - design value	d	16.10	16.10	16.10	16.10	16.10	16.10	16.10	16.10	16.10	16.10
Total volume of each reaction basin	m^3	289.00	578.00	867.00	1156.00	1445.00	1734.00	2023.00	2312.00	2601.00	2890.00
Fill volume per cycle per reaction basin	m^3	72.25	144.50	216.75	289.00	361.25	433.50	505.75	578.00	650.25	722.50
Selected value for (fill volume/total volume of reaction basin)	ratio	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Decant depth	m	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02
Total liquid depth when full	m	4.07	4.07	4.07	4.07	4.07	4.07	4.07	4.07	4.07	4.07
Mixed liquor suspended solids (X_{MLSS})	g.m^3	4000.00	4000.00	4000.00	4000.00	4000.00	4000.00	4000.00	4000.00	4000.00	4000.00
Mixed liquor volatile suspended solids (X_{MLVSS})	g.m^3	1690.64	1690.64	1690.64	1690.64	1690.64	1690.64	1690.64	1690.64	1690.64	1690.64

Summary of data obtained for small group WWTPs with SBR (continued)

DESIGN SUMMARY FOR SEQUENTIAL BATCH REACTOR BASED SYSTEM – SMALL GROUP (continued)											
BOD REMOVAL											
		Capacity in mld									
		0.5	***1***	***1.5***	***2***	***2.5***	***3***	***3.5***	***4***	***4.5***	***5***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
F/M	(g BOD/d)/g VSS	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Volumetric BOD loading	(kg BOD/d)/m^3	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57
Decant pumping rate	m^3/min	2.41	4.82	7.23	9.63	12.04	14.45	16.86	19.27	21.68	24.08
Total TSS purged per day	kg MLSS/d	143.59	287.17	430.76	574.34	717.93	861.52	1005.10	1148.69	1292.27	1435.86
Observed yield based on VSS	g VSS/g BOD	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
Observed yield based on TSS	g TSS/g BOD	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88
Oxygen demand per reaction basin	kg oxygen/d	93.12	186.25	279.37	372.50	465.62	558.75	651.87	744.99	838.12	931.24
Total aeration time per day per reaction basin	h	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Average oxygen transfer rate per reaction basin	kg oxygen/h	11.64	23.28	34.92	46.56	58.20	69.84	81.48	93.12	104.76	116.41
Concentration of BOD in effluent	g/m^3	9.66	9.66	9.66	9.66	9.66	9.66	9.66	9.66	9.66	9.66
Concentration of TSS in effluent	g/m^3	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00

Summary of data obtained for small group WWTPs with SBR (continued)

EQUIPMENT SUMMARY FOR SEQUENTIAL BATCH REACTOR BASED SYSTEM – SMALL GROUP BOD REMOVAL											
		Capacity in mld									
		0.5	***1***	***1.5***	***2***	***2.5***	***3***	***3.5***	***4***	***4.5***	***5***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Number of batteries		1	1	1	1	1	1	1	1	1	1
REACTION BASINS & ACCESSORIES											
Number of reaction basins		2	2	2	2	2	2	2	2	2	2
Length of each reaction basin	m	7.76	15.52	23.28	31.05	38.81	46.57	54.33	62.09	69.85	77.62
Width of each reaction basin	m	9.14	9.14	9.14	9.14	9.14	9.14	9.14	9.14	9.14	9.14
Depth of each reaction basin	m	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57
Number of swing arm headers of each reaction basin		2	3	5	6	8	9	11	12	14	15
REACTOR BASIN WASTE TRANSFER PUMPS AND PUMP-HOUSE											
Total number of pumps required		2	2	2	2	2	2	2	2	2	2
Capacity of each pump	m^3/h	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
Area required for pump-house	m ^2	60.00	60.00	60.00	60.00	60.00	60.00	60.00	60.00	60.00	60.00
BLOWERS AND BLOWER BUILDING											
Total number of blowers required		2	2	2	2	2	2	2	2	2	2
Capacity of each blower	scfm	360.00	720.00	1080.00	1440.00	1800.00	2160.00	2519.00	2879.00	3239.00	3599.00
Area required for blower building	m ^2	54.00	65.00	72.00	77.00	82.00	85.00	89.00	92.00	95.00	97.00

Summary of data obtained for small group WWTPs with SBR (continued)

ESTIMATED COST SUMMARY FOR SEQUENTIAL BATCH REACTOR BASED SYSTEM – SMALL GROUP BOD REMOVAL

		Capacity in mld									
		0.5	***1***	***1.5***	***2***	***2.5***	***3***	***3.5***	***4***	***4.5***	***5***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
REACTION BASINS & ACCESSORIES											
Total bare construction cost (CAPEX)	Crore ₹	0.50	0.79	1.08	1.39	1.71	2.03	2.35	2.66	2.99	3.30
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of reaction basins and accessories (OPEX)	Crore ₹	1.03	1.71	2.37	3.02	3.66	4.29	4.91	5.53	6.15	6.77
Overall cost inclusive of CAPEX & OPEX	Crore ₹	1.53	2.50	3.45	4.41	5.37	6.31	7.26	8.20	9.14	10.08
REACTOR BASIN WASTE TRANSFER PUMPS AND PUMP-HOUSE											
Total bare construction cost (CAPEX)	Crore ₹	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of pumps and pump-house (OPEX)	Crore ₹	0.16	0.18	0.19	0.20	0.21	0.22	0.23	0.24	0.24	0.25
Overall cost inclusive of CAPEX & OPEX	Crore ₹	0.81	0.82	0.84	0.85	0.86	0.87	0.88	0.88	0.89	0.90
BLOWERS AND BLOWER BUILDING											
Total bare construction cost (CAPEX)	Crore ₹	1.10	1.53	1.86	2.15	2.41	2.64	2.86	3.07	3.26	3.45

Summary of data obtained for small group WWTPs with SBR (continued)

ESTIMATED COST SUMMARY FOR SEQUENTIAL BATCH REACTOR BASED SYSTEM – SMALL GROUP (continued)

BOD REMOVAL

		Capacity in mld									
		0.5	***1***	***1.5***	***2***	***2.5***	***3***	***3.5***	***4***	***4.5***	***5***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
ESTIMATED CONSOLIDATED COSTS											
Total bare construction cost (CAPEX)	Crore ₹	2.25	2.96	3.60	4.19	4.77	5.32	5.86	6.38	6.90	7.40
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of STP	Crore ₹	1.19	1.89	2.56	3.22	3.87	4.50	5.14	5.77	6.40	7.03
Overall cost inclusive of CAPEX & OPEX	Crore ₹	3.45	4.85	6.15	7.41	8.64	9.82	11.00	12.15	13.30	14.42
COST OF LAND											
Cost of land	Crore ₹	0.77	1.08	1.39	1.70	2.00	2.31	2.61	2.91	3.22	3.52
OVERALL COST											
Overall cost inclusive of CAPEX & OPEX	Crore ₹	4.21	5.93	7.54	9.11	10.64	12.13	13.61	15.06	16.51	17.94
Overall cost inclusive of CAPEX & OPEX	Million $	0.53	0.74	0.94	1.14	1.33	1.52	1.70	1.88	2.06	2.24

Summary of data obtained for small group WWTPs with SBR (continued)

REGRESSION ANALYSIS AND DETERMINATION OF MAPE – SMALL GROUP BOD REMOVAL											
		Capacity in mld									
		0.5	***1***	***1.5***	***2***	***2.5***	***3***	***3.5***	***4***	***4.5***	***5***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Predicted value (as per exponential cost function)	Crore ₹	5.21	6.06	7.05	8.21	9.55	11.11	12.93	15.05	17.51	20.38
Value of R^2		0.9487									
Absolute percentage error	%	23.65	2.19	6.49	9.87	10.24	8.38	4.98	0.08	6.04	13.56
MAPE	%	8.55									
Predicted value (as per linear cost function)	Crore ₹	4.44	5.96	7.48	8.99	10.51	12.03	13.54	15.06	16.58	18.09
Value of R^2		0.9993									
Absolute percentage error	%	5.48	0.48	0.88	1.24	1.22	0.85	0.49	0.01	0.38	0.83
MAPE	%	1.19									
Predicted value (as per logarithmic cost function)	Crore ₹	2.19	6.36	8.79	10.52	11.86	12.96	13.89	14.69	15.40	16.03
Value of R^2		0.9202									
Absolute percentage error	%	48.02	7.16	16.58	15.56	11.51	6.84	2.03	2.46	6.76	10.66
MAPE	%	12.76									

Summary of data obtained for small group WWTPs with SBR (continued)

REGRESSION ANALYSIS AND DETERMINATION OF MAPE – SMALL GROUP (continued)

BOD REMOVAL

		Capacity in mld									
		0.5	***1***	***1.5***	***2***	***2.5***	***3***	***3.5***	***4***	***4.5***	***5***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Predicted value (as per polynomial cost function)	Crore ₹	4.26	5.90	7.51	9.09	10.63	12.15	13.63	15.09	16.52	17.91
Value of R^2		1									
Absolute percentage error	%	1.18	0.53	0.46	0.23	0.07	0.15	0.18	0.20	0.02	0.18
MAPE	%	0.32									
Predicted value (as per power cost function)	Crore ₹	3.92	6.10	7.91	9.51	10.97	12.33	13.61	14.83	15.99	17.10
Value of R^2		0.9924									
Absolute percentage error	%	7.02	2.92	4.92	4.48	3.15	1.68	0.02	1.55	3.18	4.68
MAPE	%	3.36									

Summary of data obtained for small group WWTPs with SBR (continued)

95 % CONFIDENCE INTERVAL FOR MEAN OF ABSOLUTE PERCENTAGE ERROR AS PER SELECTED COST FUNCTION

BOD REMOVAL

		Capacity in mld									
		0.5	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
(as per linear cost function)											
Absolute percentage error	%	5.48	0.48	0.88	1.24	1.22	0.85	0.49	0.01	0.38	0.83
MAPE	%	1.19									
Standard deviation	%	1.56									
Alpha value for 95% confidence level		0.05									
Confidence		0.96									
Upper limit of MAPE	%	2.15									
Lower limit of MAPE	%	0.22									

Appendix- VIII

Summary of data obtained for medium group WWTPs with SBR

DESIGN SUMMARY FOR SEQUENTIAL BATCH REACTOR BASED SYSTEM – MEDIUM GROUP
BOD REMOVAL

		Capacity in mld									
		5	***10***	***15***	***20***	***25***	***30***	***35***	***40***	***45***	***50***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Influent flow rate	m^3/d	5780.00	11560.00	17340.00	23120.00	28900.00	34680.00	40460.00	46240.00	52020.00	57800.00
Average BOD load	kg/d	1636.40	3272.80	4909.20	6545.60	8182.00	9818.40	11454.80	13091.20	14727.60	16364.00
Number of reaction basins	number	2	3	4	6	7	8	9	11	12	13
Fill time	h	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Reaction time	h	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Design time selected for aeration	h	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Settlement time	h	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Decantation time	h	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Total cycle time	h	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
Solids residence time - design value	d	16.10	16.10	16.10	16.10	16.10	16.10	16.10	16.10	16.10	16.10
Total volume of each reaction basin	m^3	2890.00	3853.33	4335.00	3853.33	4128.57	4335.00	4495.56	4203.64	4335.00	4446.15
Fill volume per cycle per reaction basin	m^3	722.50	963.33	1083.75	963.33	1032.14	1083.75	1123.89	1050.91	1083.75	1111.54
Selected value for (fill volume/total volume of reaction basin)	ratio	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Decant depth	m	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02
Total liquid depth when full	m	4.07	4.07	4.07	4.07	4.07	4.07	4.07	4.07	4.07	4.07
Mixed liquor suspended solids (X_{MLSS})	g.m^3	4000.00	4000.00	4000.00	4000.00	4000.00	4000.00	4000.00	4000.00	4000.00	4000.00
Mixed liquor volatile suspended solids (X_{MLVSS})	g.m^3	1690.64	1690.64	1690.64	1690.64	1690.64	1690.64	1690.64	1690.64	1690.64	1690.64

Summary of data obtained for medium group WWTPs with SBR (continued)

DESIGN SUMMARY FOR SEQUENTIAL BATCH REACTOR BASED SYSTEM – MEDIUM GROUP (continued)

BOD REMOVAL

		Capacity in mld									
		5	***10***	***15***	***20***	***25***	***30***	***35***	***40***	***45***	***50***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
F/M	(g BOD/d)/g VSS	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Volumetric BOD loading	(kg BOD/d)/m^3	0.57	0.85	1.13	1.70	1.98	2.26	2.55	3.11	3.40	3.68
Decant pumping rate	m^3/min	24.08	32.11	36.13	32.11	34.40	36.13	37.46	35.03	36.13	37.05
Total TSS purged per day	kg MLSS/d	1435.86	2871.72	4307.58	5743.44	7179.29	8615.15	10051.01	11486.87	12922.73	14358.59
Observed yield based on VSS	g VSS/g BOD	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
Observed yield based on TSS	g TSS/g BOD	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88
Oxygen demand per reaction basin	kg oxygen/d	931.24	1241.66	1396.86	1241.66	1330.35	1396.86	1448.60	1354.53	1396.86	1432.68
Total aeration time per day per reaction basin	h	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Average oxygen transfer rate per reaction basin	kg oxygen/h	116.41	155.21	174.61	155.21	166.29	174.61	181.07	169.32	174.61	179.08
Concentration of BOD in effluent	g/m^3	9.66	9.66	9.66	9.66	9.66	9.66	9.66	9.66	9.66	9.66
Concentration of TSS in effluent	g/m^3	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00

Summary of data obtained for medium group WWTPs with SBR (continued)

EQUIPMENT SUMMARY FOR SEQUENTIAL BATCH REACTOR BASED SYSTEM – MEDIUM GROUP

BOD REMOVAL

		Capacity in mld									
		5	***10***	***15***	***20***	***25***	***30***	***35***	***40***	***45***	***50***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Number of batteries		1	1	1	1	1	1	1	1	1	1
REACTION BASINS & ACCESSORIES											
Number of reaction basins		2	3	4	6	7	8	9	11	12	13
Length of each reaction basin	m	77.62	103.49	116.42	103.49	110.88	116.42	120.74	112.90	116.42	119.41
Width of each reaction basin	m	9.14	9.14	9.14	9.14	9.14	9.14	9.14	9.14	9.14	9.14
Depth of each reaction basin	m	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57
Number of swing arm headers of each reaction basin		15	20	45	40	65	68	70	88	90	116
REACTOR BASIN WASTE TRANSFER PUMPS AND PUMP-HOUSE											
Total number of pumps required		2	2	2	2	2	2	2	2	2	2
Capacity of each pump	m^3/h	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
Area required for pump-house	m ^2	60.00	60.00	61.00	61.00	61.00	61.00	61.00	62.00	62.00	62.00
BLOWERS AND BLOWER BUILDING											
Total number of blowers required		2	2	3	3	4	4	4	4	4	5
Capacity of each blower	scfm	3599.00	4798.00	5398.00	4798.00	5141.00	5398.00	5598.00	6979.00	7197.00	6921.00
Area required for blower building	m ^2	97.00	105.00	129.00	125.00	141.00	143.00	144.00	152.00	154.00	164.00

Summary of data obtained for medium group WWTPs with SBR (continued)

ESTIMATED COST SUMMARY FOR SEQUENTIAL BATCH REACTOR BASED SYSTEM – MEDIUM GROUP BOD REMOVAL											
		Capacity in mld									
		5	*10*	*15*	*20*	*25*	*30*	*35*	*40*	*45*	*50*
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
REACTION BASINS & ACCESSORIES											
Total bare construction cost (CAPEX)	Crore ₹	3.30	5.99	10.69	13.12	17.64	20.65	23.61	28.78	31.95	38.02
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of reaction basins and accessories (OPEX)	Crore ₹	6.77	9.12	19.00	17.58	26.95	28.50	29.79	36.66	38.02	47.82
Overall cost inclusive of CAPEX & OPEX	Crore ₹	10.08	15.11	29.69	30.70	44.58	49.15	53.40	65.43	69.97	85.84
REACTOR BASIN WASTE TRANSFER PUMPS AND PUMP-HOUSE											
Total bare construction cost (CAPEX)	Crore ₹	0.65	0.65	0.65	0.65	0.66	0.66	0.66	0.66	0.66	0.67
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of pumps and pump-house (OPEX)	Crore ₹	0.25	0.28	0.39	0.37	0.47	0.48	0.49	0.56	0.57	0.68
Overall cost inclusive of CAPEX & OPEX	Crore ₹	0.90	0.93	1.04	1.02	1.13	1.14	1.15	1.23	1.24	1.34
BLOWERS AND BLOWER BUILDING											
Total bare construction cost (CAPEX)	Crore ₹	3.45	4.01	6.11	5.73	7.68	7.89	8.06	9.12	9.28	11.11

Summary of data obtained for medium group WWTPs with SBR (continued)

ESTIMATED COST SUMMARY FOR SEQUENTIAL BATCH REACTOR BASED SYSTEM – MEDIUM GROUP (continued)											
BOD REMOVAL											
		Capacity in mld									
		5	***10***	***15***	***20***	***25***	***30***	***35***	***40***	***45***	***50***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
ESTIMATED CONSOLIDATED COSTS											
Total bare construction cost (CAPEX)	Crore ₹	7.40	10.65	17.46	19.51	25.98	29.20	32.33	38.56	41.89	49.79
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of STP	Crore ₹	7.03	9.39	19.39	17.94	27.42	28.99	30.28	37.22	38.59	48.49
Overall cost inclusive of CAPEX & OPEX	Crore ₹	14.42	20.05	36.84	37.45	53.39	58.18	62.61	75.78	80.49	98.29
COST OF LAND											
Cost of land	Crore ₹	3.52	6.24	9.80	12.25	14.92	17.54	20.14	22.70	25.30	27.91
OVERALL COST											
Overall cost inclusive of CAPEX & OPEX	Crore ₹	17.94	26.29	46.65	49.70	68.31	75.72	82.74	98.48	105.78	126.19
Overall cost inclusive of CAPEX & OPEX	Million $	2.24	3.29	5.83	6.21	8.54	9.47	10.34	12.31	13.22	15.77

Summary of data obtained for medium group WWTPs with SBR (continued)

REGRESSION ANALYSIS AND DETERMINATION OF MAPE – MEDIUM GROUP
BOD REMOVAL

		Capacity in mld									
		5	***10***	***15***	***20***	***25***	***30***	***35***	***40***	***45***	***50***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Predicted value (as per exponential cost function)	Crore ₹	24.66	30.06	36.64	44.66	54.44	66.36	80.89	98.60	120.19	146.51
Value of R^2		0.916									
Absolute percentage error	%	37.42	14.33	21.46	10.13	20.31	12.36	2.24	0.13	13.62	16.10
MAPE	%	14.81									
Predicted value (as per linear cost function)	Crore ₹	11.87	24.34	36.81	49.28	61.75	74.22	86.69	99.17	111.64	124.11
Value of R^2		0.9741									
Absolute percentage error	%	33.87	7.43	21.09	0.84	9.60	1.98	4.77	0.70	5.53	1.65
MAPE	%	8.75									
Predicted value (as per logarithmic cost function)	Crore ₹	1.45	32.81	51.15	64.16	74.26	82.51	89.48	95.52	100.85	105.62
Value of R^2		0.8977									
Absolute percentage error	%	91.93	24.79	9.65	29.11	8.71	8.96	8.14	3.00	4.66	16.31
MAPE	%	20.53									

Summary of data obtained for medium group WWTPs with SBR (continued)

REGRESSION ANALYSIS AND DETERMINATION OF MAPE – MEDIUM GROUP (continued)

BOD REMOVAL

		Capacity in mld									
		5	***10***	***15***	***20***	***25***	***30***	***35***	***40***	***45***	***50***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Predicted value (as per polynomial cost function)	Crore ₹	18.53	29.71	40.97	52.31	63.73	75.23	86.81	98.47	110.21	122.03
Value of R^2		0.9886									
Absolute percentage error	%	3.29	13.02	12.16	5.26	6.70	0.65	4.91	0.01	4.18	3.30
MAPE	%	5.35									
Predicted value (as per power cost function)	Crore ₹	16.68	30.04	42.38	54.09	65.37	76.30	86.97	97.40	107.64	117.70
Value of R^2		0.9861									
Absolute percentage error	%	7.02	14.27	9.16	8.84	4.31	0.77	5.10	1.09	1.75	6.73
MAPE	%	5.90									

Summary of data obtained for medium group WWTPs with SBR (continued)

95 % CONFIDENCE INTERVAL FOR MEAN OF ABSOLUTE PERCENTAGE ERROR AS PER SELECTED COST FUNCTION

BOD REMOVAL

		Capacity in mld									
		5	***10***	***15***	***20***	***25***	***30***	***35***	***40***	***45***	***50***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
						(as per linear cost function)					
Absolute percentage error	%	33.87	7.43	21.09	0.84	9.60	1.98	4.77	0.70	5.53	1.65
MAPE	%	8.75									
Standard deviation	%	10.73									
Alpha value for 95% confidence level		0.05									
Confidence		6.65									
Upper limit of MAPE	%	15.39									
Lower limit of MAPE	%	2.10									

Appendix- IX

Summary of data obtained for large group WWTPs with SBR

DESIGN SUMMARY FOR SEQUENTIAL BATCH REACTOR BASED SYSTEM – LARGE GROUP BOD REMOVAL

		Capacity in mld										
		50	***60***	***70***	***80***	***90***	***100***	***110***	***120***	***130***	***140***	***150***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Influent flow rate	m^3/d	57800.0	69360.0	80920.0	92480.0	104040.0	115600.0	127160.0	138720.0	150280.0	161840.0	173400.0
Average BOD load	kg/d	16364.00	19636.80	22909.60	26182.40	29455.20	32728.00	36000.80	39273.60	42546.40	45819.20	49092.00
Number of reaction basins	number	13	16	18	21	23	26	29	31	34	36	39
Fill time	h	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Reaction time	h	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Design time selected for aeration	h	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Settlement time	h	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Decantation time	h	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Total cycle time	h	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
Solids residence time - design value	d	16.10	16.10	16.10	16.10	16.10	16.10	16.10	16.10	16.10	16.10	16.10
Total volume of each reaction basin	m^3	4446.15	4335.00	4495.56	4403.81	4523.48	4446.15	4384.83	4474.84	4420.00	4495.56	4446.15
Fill volume per cycle per reaction basin	m^3	1111.54	1083.75	1123.89	1100.95	1130.87	1111.54	1096.21	1118.71	1105.00	1123.89	1111.54
Selected value for (fill volume/total volume of reaction basin)	ratio	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Decant depth	m	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02
Total liquid depth when full	m	4.07	4.07	4.07	4.07	4.07	4.07	4.07	4.07	4.07	4.07	4.07
Mixed liquor suspended solids (XMLSS)	g.m^3	4000.00	4000.00	4000.00	4000.00	4000.00	4000.00	4000.00	4000.00	4000.00	4000.00	4000.00

Summary of data obtained for large group WWTPs with SBR (continued)

DESIGN SUMMARY FOR SEQUENTIAL BATCH REACTOR BASED SYSTEM – LARGE GROUP (continued)
BOD REMOVAL

		Capacity in mld										
		50	***60***	***70***	***80***	***90***	***100***	***110***	***120***	***130***	***140***	***150***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Mixed liquor volatile suspended solids (X_{MLVSS})	g.m^3	1690.64	1690.64	1690.64	1690.64	1690.64	1690.64	1690.64	1690.64	1690.64	1690.64	1690.64
F/M	(g BOD/d)/g VSS	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Volumetric BOD loading	(kg BOD/d)/m^3	3.68	4.53	5.10	5.95	6.51	7.36	8.21	8.78	9.63	10.19	11.04
Decant pumping rate	m^3/min	37.05	36.13	37.46	36.70	37.70	37.05	36.54	37.29	36.83	37.46	37.05
Total TSS purged per day	kg MLSS/d	14358.59	17230.31	20102.02	22973.74	25845.46	28717.18	31588.89	34460.61	37332.33	40204.05	43075.76
Observed yield based on VSS	g VSS/g BOD	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
Observed yield based on TSS	g TSS/g BOD	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88
Oxygen demand per reaction basin	kg oxygen/d	1432.68	1396.86	1448.60	1419.04	1457.60	1432.68	1412.92	1441.92	1424.25	1448.60	1432.68
Total aeration time per day per reaction basin	h	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Average oxygen transfer rate per reaction basin	kg oxygen/h	179.08	174.61	181.07	177.38	182.20	179.08	176.61	180.24	178.03	181.07	179.08
Concentration of BOD in effluent	g/m^3	9.66	9.66	9.66	9.66	9.66	9.66	9.66	9.66	9.66	9.66	9.66
Concentration of TSS in effluent	g/m^3	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00

Summary of data obtained for large group WWTPs with SBR (continued)

EQUIPMENT SUMMARY FOR SEQUENTIAL BATCH REACTOR BASED SYSTEM – LARGE GROUP BOD REMOVAL

		Capacity in mld										
		50	***60***	***70***	***80***	***90***	***100***	***110***	***120***	***130***	***140***	***150***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Number of batteries		1	1	1	1	1	1	1	1	1	1	1
REACTION BASINS & ACCESSORIES												
Number of reaction basins		13	16	18	21	23	26	29	31	34	36	39
Length of each reaction basin	m	119.41	116.42	120.74	118.27	121.49	119.41	117.76	120.18	118.71	120.74	119.41
Width of each reaction basin	m	9.14	9.14	9.14	9.14	9.14	9.14	9.14	9.14	9.14	9.14	9.14
Depth of each reaction basin	m	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57
Number of swing arm headers of each reaction basin		116	135	140	160	188	208	228	256	276	280	300
REACTOR BASIN WASTE TRANSFER PUMPS AND PUMP-HOUSE												
Total number of pumps required		2	2	2	2	2	2	2	2	2	2	2
Capacity of each pump	m^3/h	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
Area required for pump-house	m ^2	62.00	62.00	62.00	63.00	63.00	64.00	64.00	64.00	65.00	65.00	65.00
BLOWERS AND BLOWER BUILDING												
Total number of blowers required		5	3	3	4	4	4	5	5	5	5	5
Capacity of each blower	scfm	6921.00	16194.00	16793.00	12795.00	15020.00	16609.00	13650.00	15323.00	16511.00	16793.00	17993.00
Area required for blower building	m ^2	164.00	170.00	172.00	178.00	185.00	190.00	195.00	200.00	204.00	205.00	209.00

Summary of data obtained for large group WWTPs with SBR (continued)

ESTIMATED COST SUMMARY FOR SEQUENTIAL BATCH REACTOR BASED SYSTEM – LARGE GROUP BOD REMOVAL

		Capacity in mld										
		50	***60***	***70***	***80***	***90***	***100***	***110***	***120***	***130***	***140***	***150***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
REACTION BASINS & ACCESSORIES												
Total bare construction cost (CAPEX)	Crore ₹	38.02	47.95	55.28	66.67	79.14	92.42	106.64	121.91	138.03	148.05	165.55
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of reaction basins and accessories (OPEX)	Crore ₹	47.82	56.01	58.61	67.03	78.28	86.79	95.39	106.86	115.56	118.17	127.03
Overall cost inclusive of CAPEX & OPEX	Crore ₹	85.84	103.96	113.89	133.70	157.42	179.22	202.03	228.77	253.59	266.22	292.59
REACTOR BASIN WASTE TRANSFER PUMPS AND PUMP-HOUSE												
Total bare construction cost (CAPEX)	Crore ₹	0.67	0.67	0.67	0.67	0.68	0.68	0.68	0.69	0.69	0.69	0.70
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of pumps and pump-house (OPEX)	Crore ₹	0.68	0.75	0.77	0.85	0.96	1.04	1.12	1.22	1.30	1.32	1.40
Overall cost inclusive of CAPEX & OPEX	Crore ₹	1.34	1.42	1.44	1.53	1.64	1.72	1.80	1.91	1.99	2.01	2.09
BLOWERS AND BLOWER BUILDING												
Total bare construction cost	Crore ₹	11.11	13.25	13.51	15.18	16.60	17.57	19.39	20.70	21.59	21.80	22.66

Summary of data obtained for large group WWTPs with SBR (continued)

ESTIMATED COST SUMMARY FOR SEQUENTIAL BATCH REACTOR BASED SYSTEM – LARGE GROUP (continued)
BOD REMOVAL

		Capacity in mld										
		50	***60***	***70***	***80***	***90***	***100***	***110***	***120***	***130***	***140***	***150***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
ESTIMATED CONSOLIDATED COSTS												
Total bare construction cost (CAPEX)	Crore ₹	49.79	61.86	69.47	82.52	96.42	110.67	126.72	143.30	160.31	170.54	188.91
Levelized cost based on energy requirement, operation and maintenance for 25 years of life of STP	Crore ₹	48.49	56.76	59.38	67.89	79.24	87.83	96.51	108.08	116.86	119.49	128.43
Overall cost inclusive of CAPEX & OPEX	Crore ₹	98.29	118.63	128.85	150.41	175.66	198.50	223.23	251.38	277.18	290.03	317.34
COST OF LAND												
Cost of land	Crore ₹	27.91	33.11	38.29	43.53	48.73	54.01	59.30	64.53	69.86	75.10	80.47
OVERALL COST												
Overall cost inclusive of CAPEX, OPEX & Land	Crore ₹	126.19	151.73	167.14	193.94	224.39	252.51	282.53	315.91	347.04	365.13	397.81
Overall cost inclusive of CAPEX, OPEX & Land	Million $	15.77	18.97	20.89	24.24	28.05	31.56	35.32	39.49	43.38	45.64	49.73

Summary of data obtained for large group WWTPs with SBR (continued)

REGRESSION ANALYSIS AND DETERMINATION OF MAPE – LARGE GROUP BOD REMOVAL

		Capacity in mld										
		50	***60***	***70***	***80***	***90***	***100***	***110***	***120***	***130***	***140***	***150***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Predicted value (as per exponential cost function)	Crore ₹	135.51	152.03	170.56	191.34	214.66	240.82	270.17	303.10	340.04	381.48	427.98
Value of R^2							0.9856					
Absolute percentage error	%	7.38	0.19	2.05	1.34	4.34	4.63	4.37	4.05	2.02	4.48	7.58
MAPE	%						3.86					
Predicted value (as per linear cost function)	Crore ₹	117.96	145.72	173.48	201.24	229.00	256.76	284.52	312.28	340.03	367.79	395.55
Value of R^2							0.9963					
Absolute percentage error	%	6.52	3.96	3.79	3.76	2.05	1.68	0.70	1.15	2.02	0.73	0.57
MAPE	%						2.45					
Predicted value (as per logarithmic cost function)	Crore ₹	95.80	141.79	180.68	214.37	244.08	270.66	294.71	316.66	336.85	355.55	372.95
Value of R^2							0.9612					
Absolute percentage error	%	24.09	6.55	8.10	10.53	8.77	7.19	4.31	0.24	2.94	2.62	6.25
MAPE	%						7.42					

Summary of data obtained for large group WWTPs with SBR (continued)

REGRESSION ANALYSIS AND DETERMINATION OF MAPE – LARGE GROUP (continued)

BOD REMOVAL

		Capacity in mld	**Capacity in mld**	**Capacity in mld**	**Capacity in mld**	**Capacity in mld**	**Capacity in mld**	**Capacity in mld**	**Capacity in mld**	**Capacity in mld**	**Capacity in mld**	**Capacity in mld**
		50	***60***	***70***	***80***	***90***	***100***	***110***	***120***	***130***	***140***	***150***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Predicted value (as per polynomial cost function)	Crore ₹	123.21	147.81	173.12	199.12	225.82	253.22	281.32	310.13	339.63	369.83	400.73
Value of R^2							0.9975					
Absolute percentage error	%	2.36	2.58	3.58	2.67	0.64	0.28	0.43	1.83	2.14	1.29	0.73
MAPE	%						1.68					
Predicted value (as per power cost function)	Crore ₹	121.76	147.97	174.50	201.29	228.31	255.55	282.97	310.57	338.34	366.25	394.29
Value of R^2							0.9955					
Absolute percentage error	%	3.52	2.48	4.40	3.79	1.75	1.20	0.16	1.69	2.51	0.31	0.88
MAPE	%						2.06					

Summary of data obtained for large group WWTPs with SBR (continued)

95 % CONFIDENCE INTERVAL FOR MEAN OF ABSOLUTE PERCENTAGE ERROR AS PER SELECTED COST FUNCTION

BOD REMOVAL

		Capacity in mld										
		50	**60**	**70**	**80**	**90**	**100**	**110**	**120**	**130**	**140**	**150**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
							(as per linear cost function)					
Absolute percentage error	%	6.52	3.96	3.79	3.76	2.05	1.68	0.70	1.15	2.02	0.73	0.57
MAPE	%						2.45					
Standard deviation	%						1.86					
Alpha value for 95% confidence level							0.05					
Confidence							1.1					
Upper limit of MAPE	%						3.55					
Lower limit of MAPE	%						1.35					

Appendix- X

Summary of cost response study for 5 mld capacity of WWTP with MBR

DESIGN SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM - 5 MLD BOD REMOVAL							
		BOD in mg/l	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Average wastewater flow rate	m^3/d	5000.00	5000.00	5000.00	5000.00	5000.00	5000.00
Influent flow rate to reactor basins	m^3/d	5780.00	5780.00	5780.00	5780.00	5780.00	5780.00
Average BOD load	kg/d	886.40	1036.40	1186.40	1336.40	1486.40	1636.40
Number of reactor basins	number	2	2	2	2	2	2
Aerobic solids residence time - design value	d	5.00	5.00	5.00	5.00	5.00	5.00
Total volume of each reactor basin	m^3	271.22	318.57	365.92	413.27	460.62	507.97
Hydraulic detention time of each reactor basin	h	2.25	2.65	3.04	3.43	3.83	4.22
MLSS (X_{MLSS})	g TSS/m^3	8000.00	8000.00	8000.00	8000.00	8000.00	8000.00
MLVSS (X_{MLVSS})	g VSS/m^3	3439.71	3427.09	3417.74	3410.53	3404.80	3400.14
F/M	(g BOD/d)/g bVSS	0.48	0.47	0.47	0.47	0.47	0.47
Volumetric BOD loading	(kg BOD/d)/m^3	1.63	1.63	1.62	1.62	1.61	1.61
Total sludge (TSS) purged per day	kg TSS/d	867.91	1019.43	1170.94	1322.46	1473.97	1625.49
Observed yield based on VSS	g b VSS/g bCOD	0.29	0.29	0.29	0.29	0.29	0.29
	g b VSS/g BOD	0.46	0.46	0.47	0.47	0.47	0.47
Observed yield based on TSS	g TSS/g bCOD	0.62	0.62	0.62	0.62	0.62	0.62
	g TSS/g BOD	0.99	0.99	0.99	0.99	1.00	1.00
Overall oxygen demand	kg oxygen/h	36.65	42.89	49.13	55.37	61.62	67.86
Air flow rate at average wastewater flow rate	m^3/min	31.24	36.56	41.88	47.20	52.52	57.84
RAS recycle ratio	-	1.96	1.96	1.95	1.94	1.94	1.93
Concentration of BOD of effluent	g/m^3	9.66	9.66	9.66	9.66	9.66	9.66
Concentration of TSS of effluent	g/m^3	10.00	10.00	10.00	10.00	10.00	10.00

Summary of cost response study for 5 mld capacity of WWTP with MBR (continued)

EQUIPMENT SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM - 5 MLD BOD REMOVAL							
		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
AEROBIC REACTOR BASINS & ACCESSORIES							
Number of reactor basins		2	2	2	2	2	2
Length of each reactor basin	m	7.28	8.56	9.83	11.10	12.37	13.64
Width of each reactor basin	m	9.14	9.14	9.14	9.14	9.14	9.14
Depth of each reactor basin	m	4.57	4.57	4.57	4.57	4.57	4.57
Number of swing arm headers of each reactor basin		3	3	4	4	4	5
MEMBRANE CHAMBERS & ACCESSORIES							
Number of membrane chambers		2	2	2	2	8	2
Length of each membrane chamber	m	8.29	8.29	8.29	8.29	8.29	8.29
Width of each membrane chamber	m	3.26	3.26	3.26	3.26	3.26	3.26
Depth of each membrane chamber	m	4.57	4.57	4.57	4.57	4.57	4.57
Number of membrane modules provided for membrane chambers		528	528	528	528	528	528
MIXED LIQUOR RECIRCULATION PUMPS AND PUMP-HOUSE							
Total number of pumps required		2	2	2	2	2	2
Capacity of each pump	m^3/h	480.00	480.00	480.00	480.00	480.00	480.00
Area required for pump house	m ^2	66.00	66.00	66.00	66.00	65.00	65.00
BLOWERS AND BLOWER BUILDING							
Total number of blowers required		2	2	2	2	2	2
Capacity of each blower	scfm	1382.00	1575.00	1768.00	1961.00	2154.00	2347.00
Area required for blower building	m ^2	76.00	79.00	81.00	83.00	85.00	87.00

Summary of cost response study for 5 mld capacity of WWTP with MBR (continued)

ESTIMATED COST SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM - 5 MLD

BOD REMOVAL

		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
AEROBIC REACTOR BASINS & ACCESSORIES							
Total bare construction cost	₹	11,00,93,718.71	11,06,01,348.05	11,12,11,170.83	11,17,26,614.07	11,22,45,370.05	11,28,65,200.61
Levelized cost for 25 years of life of reactor basins	₹	5,44,34,034.97	5,75,88,528.04	6,07,54,671.39	6,38,74,720.81	6,69,82,223.98	7,01,10,017.95
Overall cost	₹	16,45,27,753.69	16,81,89,876.08	17,19,65,842.22	17,56,01,334.88	17,92,27,594.03	18,29,75,218.56
MEMBRANE CHAMBERS & ACCESSORIES							
Total bare construction cost	₹	10,86,32,693.69	10,86,32,693.69	10,86,32,693.69	10,86,32,693.69	10,86,32,693.69	10,86,32,693.69
Levelized cost for 25 years of life of membrane chambers	₹	4,25,82,519.65	4,25,82,519.65	4,25,82,519.65	4,25,82,519.65	4,25,82,519.65	4,25,82,519.65
Overall cost	₹	15,12,15,213.34	15,12,15,213.34	15,12,15,213.34	15,12,15,213.34	15,12,15,213.34	15,12,15,213.34
MIXED LIQUOR RECIRCULATION PUMPS AND PUMP-HOUSE							
Total bare construction cost	₹	1,14,40,988.56	1,14,40,988.56	1,14,40,988.56	1,14,40,988.56	1,14,32,067.31	1,14,32,067.31
Levelized cost for 25 years of life of pumps and pump-house	₹	1,49,48,677.39	1,49,21,773.48	1,48,94,868.11	1,48,67,961.25	1,48,40,439.51	1,48,13,529.69
Overall cost	₹	2,63,89,665.95	2,63,62,762.04	2,63,35,856.66	2,63,08,949.81	2,62,72,506.82	2,62,45,597.00
BLOWERS AND BLOWER BUILDING							
Total bare construction cost	₹	2,10,68,902.67	2,25,01,298.69	2,38,61,877.68	2,51,50,495.25	2,63,90,112.69	2,75,77,364.59
Levelized cost for 25 years of life of blowers and blower building	₹	0.00	0.00	0.00	0.00	0.00	0.00
Overall cost	₹	2,10,68,902.67	2,25,01,298.69	2,38,61,877.68	2,51,50,495.25	2,63,90,112.69	2,75,77,364.59
ESTIMATED CONSOLIDATED COSTS							
Total bare construction cost	₹	25,12,36,303.63	25,31,76,328.99	25,51,46,730.76	25,69,50,791.57	25,87,00,243.75	26,05,07,326.20
Levelized cost for 25 years of life	₹	11,19,65,232.02	11,50,92,821.17	11,82,32,059.15	12,13,25,201.71	12,44,05,183.14	12,75,06,067.29
Consolidated cost	₹	36,32,01,535.65	36,82,69,150.16	37,33,78,789.91	37,82,75,993.28	38,31,05,426.88	38,80,13,393.49
COST OF LAND							
Cost of land	₹	1,09,91,766.17	1,15,21,889.53	1,20,49,012.90	1,25,71,636.26	1,30,91,259.63	1,36,09,382.99
OVERALL COST							
Overall cost	Crore ₹	37.42	37.98	38.54	39.08	39.62	40.16
Overall cost	Million USD	4.68	4.75	4.82	4.89	4.95	5.02

Summary of cost response study for 5 mld capacity of WWTP with MBR (continued)

REGRESSION ANALYSIS AND DETERMINATION OF MAPE
BOD REMOVAL

		BOD in mg/l	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Predicted value (as per exponential cost function)	Crore ₹	37.55	38.12	38.70	39.28	39.87	40.48
Value of R^2				0.9996			
Absolute percentage error		0.36	0.37	0.40	0.50	0.64	0.78
Mean absolute percentage error (MAPE)				0.51			
Predicted value (as per linear cost function)	Crore ₹	37.43	37.97	38.52	39.07	39.61	40.16
Value of R^2				0.9999			
Absolute percentage error		0.02	0.02	0.06	0.05	0.02	0.01
Mean absolute percentage error (MAPE)				0.03			
Predicted value (as per logarithmic cost function)	Crore ₹	37.27	38.05	38.67	39.19	39.62	40.00
Value of R^2				0.9848			
Absolute percentage error		0.39	0.20	0.34	0.26	0.01	0.40
Mean absolute percentage error (MAPE)				0.26			
Predicted value (as per polynomial cost function)	Crore ₹	37.42	37.99	38.54	39.09	39.63	40.17
Value of R^2				1.0000			
Absolute percentage error		0.01	0.02	0.00	0.02	0.03	0.01
Mean absolute percentage error (MAPE)				0.02			
Predicted value (as per power cost function)	Crore ₹	37.28	38.04	38.65	39.17	39.61	40.00
Value of R^2				0.9872			
Absolute percentage error		0.37	0.17	0.29	0.22	0.02	0.39
Mean absolute percentage error (MAPE)				0.24			

Summary of cost response study for 5 mld capacity of WWTP with MBR (continued)

95 % CONFIDENCE INTERVAL FOR MEAN OF ABSOLUTE PERCENTAGE ERROR AS PER SELECTED COST FUNCTION

BOD REMOVAL

		BOD in mg/l	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
		(as per linear cost function)					
Absolute percentage error	%	0.02	0.02	0.06	0.05	0.02	0.01
MAPE	%	0.03					
Standard deviation	%	0.02					
Alpha value for 95% confidence level		0.05					
Confidence		0.02					
Upper limit of MAPE	%	0.05					
Lower limit of MAPE	%	0.01					

Appendix- XI

Summary of cost response study for 50 mld capacity of WWTP with MBR

DESIGN SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM - 50 MLD
BOD REMOVAL

		BOD in mg/l	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Average wastewater flow rate	m^3/d	50000.00	50000.00	50000.00	50000.00	50000.00	50000.00
Influent flow rate to reactor basins	m^3/d	57800.00	57800.00	57800.00	57800.00	57800.00	57800.00
Average BOD load	kg/d	8864.00	10364.00	11864.00	13364.00	14864.00	16364.00
Number of reactor basins	number	6	6	6	6	6	6
Aerobic solids residence time - design value	d	5.00	5.00	5.00	5.00	5.00	5.00
Total volume of each reactor basin	m^3	904.07	1061.90	1219.73	1377.56	1535.39	1693.22
Hydraulic detention time of each reactor basin	h	2.25	2.65	3.04	3.43	3.83	4.22
MLSS (X_{MLSS})	g TSS/m^3	8000.00	8000.00	8000.00	8000.00	8000.00	8000.00
MLVSS (X_{MLVSS})	g VSS/m^3	3439.71	3427.09	3417.74	3410.53	3404.80	3400.14
F/M	(g BOD/d)/g bVSS	0.48	0.47	0.47	0.47	0.47	0.47
Volumetric BOD loading	(kg BOD/d)/m^3	1.63	1.63	1.62	1.62	1.61	1.61
Total sludge (TSS) purged per day	kg TSS/d	8679.11	10194.27	11709.42	13224.58	14739.73	16254.88
Observed yield based on VSS	g b VSS/g bCOD	0.29	0.29	0.29	0.29	0.29	0.29
	g b VSS/g BOD	0.46	0.46	0.47	0.47	0.47	0.47
Observed yield based on TSS	g TSS/g bCOD	0.62	0.62	0.62	0.62	0.62	0.62
	g TSS/g BOD	0.99	0.99	0.99	0.99	1.00	1.00
Overall oxygen demand	kg oxygen/h	366.53	428.93	491.34	553.74	616.15	678.56
Air flow rate at average wastewater flow rate	m^3/min	312.42	365.62	418.81	472.01	525.20	578.40
RAS recycle ratio	-	1.96	1.96	1.95	1.94	1.94	1.93
Concentration of BOD of effluent	g/m^3	9.66	9.66	9.66	9.66	9.66	9.66
Concentration of TSS of effluent	g/m^3	10.00	10.00	10.00	10.00	10.00	10.00

Summary of cost response study for 50 mld capacity of WWTP with MBR (continued)

EQUIPMENT SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM - 50 MLD
BOD REMOVAL

		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
AEROBIC REACTOR BASINS & ACCESSORIES							
Number of reactor basins		6	6	6	6	6	6
Length of each reactor basin	m	24.28	28.52	32.76	37.00	41.24	45.47
Width of each reactor basin	m	9.14	9.14	9.14	9.14	9.14	9.14
Depth of each reactor basin	m	4.57	4.57	4.57	4.57	4.57	4.57
Number of swing arm headers of each reactor basin		8	10	11	12	14	15
MEMBRANE CHAMBERS & ACCESSORIES							
Number of membrane chambers		6	6	6	6	6	6
Length of each membrane chamber	m	16.97	16.97	16.97	16.97	16.97	16.97
Width of each membrane chamber	m	3.26	3.26	3.26	3.26	3.26	3.26
Depth of each membrane chamber	m	4.57	4.57	4.57	4.57	4.57	4.57
Number of membrane modules provided for membrane chambers		3312	3312	3312	3312	3312	3312
MIXED LIQUOR RECIRCULATION PUMPS AND PUMP-HOUSE							
Total number of pumps required		2	2	2	2	2	2
Capacity of each pump	m^3/h	4760.00	4750.00	4740.00	4730.00	4720.00	4710.00
Area required for pump house	m ^2	115.00	115.00	115.00	115.00	115.00	115.00
BLOWERS AND BLOWER BUILDING							
Total number of blowers required		3	3	4	4	4	5
Capacity of each blower	scfm	6446.00	7410.00	5583.00	6226.00	6869.00	5635.00
Area required for blower building	m ^2	135.00	140.00	144.00	148.00	152.00	155.00

Summary of cost response study for 50 mld capacity of WWTP with MBR (continued)

ESTIMATED COST SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM - 50 MLD
BOD REMOVAL

		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
AEROBIC REACTOR BASINS & ACCESSORIES							
Total bare construction cost	₹	69,93,70,739.42	70,46,13,708.58	70,95,01,146.09	71,43,52,722.95	71,94,59,765.32	72,42,38,581.99
Levelized cost for 25 years of life of reactor basins	₹	29,33,53,342.86	32,27,35,081.13	35,19,90,677.71	38,11,87,024.65	41,03,82,929.48	43,94,84,140.75
Overall cost	₹	99,27,24,082.28	1,02,73,48,789.71	1,06,14,91,823.80	1,09,55,39,747.60	1,12,98,42,694.80	1,16,37,22,722.74
MEMBRANE CHAMBERS & ACCESSORIES							
Total bare construction cost	₹	67,33,94,493.63	67,33,94,493.63	67,33,94,493.63	67,33,94,493.63	67,33,94,493.63	67,33,94,493.63
Levelized cost for 25 years of life of membrane chambers	₹	16,07,57,872.36	16,07,57,872.36	16,07,57,872.36	16,07,57,872.36	16,07,57,872.36	16,07,57,872.36
Overall cost	₹	83,41,52,366.00	83,41,52,366.00	83,41,52,366.00	83,41,52,366.00	83,41,52,366.00	83,41,52,366.00
MIXED LIQUOR RECIRCULATION PUMPS AND PUMP-HOUSE							
Total bare construction cost	₹	5,11,44,013.07	5,10,37,321.55	5,09,30,662.96	5,08,15,116.11	5,07,08,523.54	5,06,01,964.08
Levelized cost for 25 years of life of pumps and pump-house	₹	12,54,22,377.10	12,51,48,041.69	12,48,73,703.95	12,49,67,430.22	12,46,96,397.48	12,44,25,361.06
Overall cost	₹	17,65,66,390.17	17,61,85,363.25	17,58,04,366.91	17,57,82,546.32	17,54,04,921.02	17,50,27,325.14
BLOWERS AND BLOWER BUILDING							
Total bare construction cost	₹	6,74,07,496.05	7,28,20,770.71	8,04,34,090.70	8,55,00,716.04	9,03,51,303.16	9,88,27,037.38
Levelized cost for 25 years of life of blowers and blower building	₹	0.00	0.00	0.00	0.00	0.00	0.00
Overall cost	₹	6,74,07,496.05	7,28,20,770.71	8,04,34,090.70	8,55,00,716.04	9,03,51,303.16	9,88,27,037.38

Summary of cost response study for 50 mld capacity of WWTP with MBR (continued)

ESTIMATED COST SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM - 50 MLD (continued)
BOD REMOVAL

		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
ESTIMATED CONSOLIDATED COSTS							
Total bare construction cost	₹	1,49,13,16,742.18	1,50,18,66,294.47	1,51,42,60,393.38	1,52,40,63,048.73	1,53,39,14,085.66	1,54,70,62,077.09
Levelized cost for 25 years of life	₹	57,95,33,592.32	60,86,40,995.19	63,76,22,254.03	66,69,12,327.24	69,58,37,199.33	72,46,67,374.17
Consolidated cost	₹	2,07,08,50,334.50	2,11,05,07,289.67	2,15,18,82,647.41	2,19,09,75,375.97	2,22,97,51,284.98	2,27,17,29,451.26
COST OF LAND							
Cost of land	₹	5,14,03,618.08	5,60,49,952.14	6,06,87,286.20	6,53,18,620.26	6,99,45,454.32	7,45,69,288.38
OVERALL COST							
Overall cost	₹	2,12,22,53,952.59	2,16,65,57,241.81	2,21,25,69,933.61	2,25,62,93,996.23	2,29,96,96,739.30	2,34,62,98,739.64
Overall cost	Crore ₹	212.23	216.66	221.26	225.63	229.97	234.63
Overall cost	Million USD	26.53	27.08	27.66	28.20	28.75	29.33

Summary of cost response study for 50 mld capacity of WWTP with MBR (continued)

REGRESSION ANALYSIS AND DETERMINATION OF MAPE
BOD REMOVAL

		BOD in mg/l	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Predicted value (as per exponential cost function)	Crore ₹	213.08	217.60	222.21	226.93	231.75	236.66
Value of R^2				0.9997			
Absolute percentage error		0.40	0.43	0.43	0.58	0.77	0.87
Mean absolute percentage error (MAPE)				0.58			
Predicted value (as per linear cost function)	Crore ₹	212.24	216.71	221.17	225.64	230.11	234.58
Value of R^2				0.9999			
Absolute percentage error		0.01	0.02	0.04	0.01	0.06	0.02
Mean absolute percentage error (MAPE)				0.03			
Predicted value (as per logarithmic cost function)	Crore ₹	210.95	217.31	222.35	226.52	230.07	233.17
Value of R^2				0.9823			
Absolute percentage error		0.60	0.30	0.49	0.39	0.04	0.62
Mean absolute percentage error (MAPE)				0.41			
Predicted value (as per polynomial cost function)	Crore ₹	212.20	216.63	221.06	225.49	229.91	234.33
Value of R^2				0.9999			
Absolute percentage error		0.01	0.01	0.09	0.06	0.03	0.13
Mean absolute percentage error (MAPE)				0.06			
Predicted value (as per power cost function)	Crore ₹	211.17	217.29	222.26	226.46	230.11	233.33
Value of R^2				0.9860			
Absolute percentage error		0.50	0.29	0.45	0.37	0.06	0.55
Mean absolute percentage error (MAPE)				0.37			

Summary of cost response study for 50 mld capacity of WWTP with MBR (continued)

95 % CONFIDENCE INTERVAL FOR MEAN OF ABSOLUTE PERCENTAGE ERROR AS PER SELECTED COST FUNCTION
BOD REMOVAL

		BOD in mg/l	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
		(as per linear cost function)					
Absolute percentage error	%	0.01	0.02	0.04	0.01	0.06	0.02
MAPE	%			0.03			
Standard deviation	%			0.02			
Alpha value for 95% confidence level				0.05			
Confidence				0.02			
Upper limit of MAPE	%			0.04			
Lower limit of MAPE	%			0.01			

Appendix- XII

Summary of cost response study for 150 mld capacity of WWTP with MBR

DESIGN SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM - 150 MLD

BOD REMOVAL

		BOD (mg/l)	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**
		100.00	**130.00**	**160.00**	**190.00**	**220.00**	**250.00**
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Average flow rate for wastewater	m^3/d	150000.00	150000.00	150000.00	150000.00	150000.00	150000.00
Flow rate to MBRs	m^3/d	173400.00	173400.00	173400.00	173400.00	173400.00	173400.00
Average BOD load	kg/d	26592.00	31092.00	35592.00	40092.00	44592.00	49092.00
Average TKN load	kg/d	4930.37	5932.16	6933.95	7935.97	8937.76	9939.55
Number of MBRs	number	12	12	12	12	12	12
Aerobic solids residence time - design value	d	5.00	5.00	5.00	5.00	5.00	5.00
Total volume of each MBR	m^3	1356.11	1592.85	1829.60	2066.34	2303.08	2539.83
Hydraulic detention time of each MBR	h	2.25	2.65	3.04	3.43	3.83	4.22
MLVSS (X_{MLVSS})	g VSS/m^3	3439.71	3427.09	3417.74	3410.53	3404.80	3400.14
Food to mass ratio	(g BOD/d)/g bVSS	0.48	0.47	0.47	0.47	0.47	0.47
Volumetric BOD loading	(kg BOD/d)/m^3	1.63	1.63	1.62	1.62	1.61	1.61
TSS purged per day	kg TSS/d	26037.34	30582.80	35128.27	39673.73	44219.19	48764.65
Observed yield (based on VSS)	g b VSS/g bCOD	0.29	0.29	0.29	0.29	0.29	0.29
	g b VSS/g BOD	0.46	0.46	0.47	0.47	0.47	0.47
Observed yield (based on TSS)	g TSS/g bCOD	0.62	0.62	0.62	0.62	0.62	0.62
	g TSS/g BOD	0.99	0.99	0.99	0.99	1.00	1.00
Overall oxygen demand	kg oxygen/h	1099.58	1286.80	1474.02	1661.23	1848.45	2035.67
Flow rate of air	m^3/min	937.27	1096.85	1256.44	1416.02	1575.61	1735.19
BOD	g/m^3	9.66	9.66	9.66	9.66	9.66	9.66
TSS	g/m^3	10.00	10.00	10.00	10.00	10.00	10.00

Summary of cost response study for 150 mld capacity of WWTP with MBR (continued)

EQUIPMENT SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM - 150 MLD **BOD REMOVAL**							
		BOD (mg/l)	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**
		100.00	**130.00**	**160.00**	**190.00**	**220.00**	**250.00**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
MBRs AND ACCESSORIES							
Number		12	12	12	12	12	12
Length (each)	m	36.42	42.78	49.14	55.49	61.85	68.21
Width (each)	m	9.14	9.14	9.14	9.14	9.14	9.14
Depth (each)	m	4.57	4.57	4.57	4.57	4.57	4.57
Number of swing arm headers (each MBR)		12	14	16	18	20	22
MEMBRANE CHAMBERS & ACCESSORIES							
Number		12	12	12	12	12	12
Length (each)	m	25.65	25.65	25.03	25.03	25.03	25.03
Width (each)	m	3.26	3.26	3.26	3.26	3.26	3.26
Depth (each)	m	4.57	4.57	4.57	4.57	4.57	4.57
Number of membrane modules (each MBR)		10080	10080	9792	9792	9792	9792
MIXED LIQUOR RECIRCULATION PUMPS AND PUMP-HOUSE							
Number of pumps required		2	2	2	2	2	2
Capacity (for each pump)	m^3/h	14270.00	14240.00	14210.00	14180.00	14150.00	14120.00
Area required for pump house	m ^2	226.00	225.00	225.00	225.00	224.00	224.00
BLOWERS AND BLOWER BUILDING							
Number of blowers required		4	4	4	5	5	5
Capacity (for each pump)	scfm	12913.00	14842.00	16726.00	13992.00	15439.00	16886.00
Area required for blower building	m ^2	178.00	185.00	190.00	196.00	201.00	205.00

Summary of cost response study for 150 mld capacity of WWTP with MBR (continued)

ESTIMATED COST SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM - 150 MLD

BOD REMOVAL

		BOD (mg/l)	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**
		100.00	**130.00**	**160.00**	**190.00**	**220.00**	**250.00**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
MBRs AND ACCESSORIES							
Capital Expenditure (CAPEX)	₹	2,11,01,74,723.08	2,12,35,23,038.33	2,07,91,89,133.19	2,09,23,01,110.56	2,10,53,19,012.44	2,11,82,71,723.00
Operation expenditure for 25 years (OPEX)	₹	77,81,44,593.05	86,41,19,909.41	94,25,00,245.17	1,02,82,31,329.85	1,11,38,69,503.35	1,19,94,30,190.80
Overall cost inclusive of CAPEX & OPEX	₹	2,88,83,19,316.13	2,98,76,42,947.74	3,02,16,89,378.36	3,12,05,32,440.41	3,21,91,88,515.79	3,31,77,01,913.80
MEMBRANE CHAMBERS & ACCESSORIES							
Capital Expenditure (CAPEX)	₹	2,04,38,57,037.83	2,04,38,57,037.83	1,98,56,87,435.91	1,98,56,87,435.91	1,98,56,87,435.91	1,98,56,87,435.91
Operation expenditure for 25 years (OPEX)	₹	39,46,09,805.70	39,46,09,805.70	38,35,90,358.73	38,35,90,358.73	38,35,90,358.73	38,35,90,358.73
Overall cost inclusive of CAPEX & OPEX	₹	2,43,84,66,843.53	2,43,84,66,843.53	2,36,92,77,794.64	2,36,92,77,794.64	2,36,92,77,794.64	2,36,92,77,794.64
MIXED LIQUOR RECIRCULATION PUMPS AND PUMP-HOUSE							
Capital Expenditure (CAPEX)	₹	16,50,29,871.27	16,46,44,548.18	16,42,59,342.92	16,38,74,255.71	16,34,89,286.75	16,31,04,436.26
Operation expenditure for 25 years (OPEX)	₹	37,37,01,111.07	37,28,75,821.63	37,20,50,534.39	37,12,25,249.35	37,03,99,966.51	36,95,74,685.88
Overall cost inclusive of CAPEX & OPEX	₹	53,87,30,982.34	53,75,20,369.81	53,63,09,877.31	53,50,99,505.06	53,38,89,253.27	53,26,79,122.14
BLOWERS AND BLOWER BUILDING							
Capital Expenditure (CAPEX)	₹	15,26,11,901.39	16,49,44,606.07	17,63,56,933.80	19,66,75,539.38	20,78,79,371.40	21,86,54,512.47
Operation expenditure for 25 years (OPEX)	₹	0.00	0.00	0.00	0.00	0.00	0.00
Overall cost inclusive of CAPEX & OPEX	₹	15,26,11,901.39	16,49,44,606.07	17,63,56,933.80	19,66,75,539.38	20,78,79,371.40	21,86,54,512.47

Summary of cost response study for 150 mld capacity of WWTP with MBR (continued)

ESTIMATED COST SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM - 150 MLD (continued) **BOD REMOVAL**							
		BOD (mg/l)	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**
		100.00	**130.00**	**160.00**	**190.00**	**220.00**	**250.00**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
ESTIMATED CONSOLIDATED COSTS							
Capital Expenditure (CAPEX)	₹	4,47,16,73,533.58	4,49,69,69,230.41	4,40,54,92,845.82	4,43,85,38,341.56	4,46,23,75,106.50	4,48,57,18,107.64
Operation expenditure for 25 years (OPEX)	₹	1,54,64,55,509.82	1,63,16,05,536.74	1,69,81,41,138.28	1,78,30,46,937.93	1,86,78,59,828.59	1,95,25,95,235.41
Overall cost inclusive of CAPEX & OPEX	₹	6,01,81,29,043.40	6,12,85,74,767.15	6,10,36,33,984.10	6,22,15,85,279.48	6,33,02,34,935.09	6,43,83,13,343.05
COST OF LAND							
Cost of land	₹	13,01,14,303.55	14,29,78,106.94	15,52,92,867.67	16,81,40,171.07	18,09,79,974.47	19,38,15,277.87
OVERALL COST							
Overall cost	₹	6,14,82,43,346.95	6,27,15,52,874.09	6,25,89,26,851.77	6,38,97,25,450.55	6,51,12,14,909.56	6,63,21,28,620.92
Overall cost	Crore ₹	614.82	627.16	625.89	638.97	651.12	663.21
Overall cost	Million USD	76.85	78.39	78.24	79.87	81.39	82.90

Summary of cost response study for 150 mld capacity of WWTP with MBR (continued)

REGRESSION ANALYSIS AND DETERMINATION OF MAPE BOD REMOVAL							
		BOD (mg/l)	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**
		100.00	**130.00**	**160.00**	**190.00**	**220.00**	**250.00**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Overall cost (as per exponential cost function)	Crore ₹	614.55	623.84	633.27	642.84	652.55	662.42
R^2		0.9547					
Absolute percentage error		0.04	0.53	1.18	0.61	0.22	0.12
Mean absolute percentage error (MAPE)		0.45					
Overall cost (as per linear cost function)	Crore ₹	613.51	622.85	632.19	641.53	650.87	660.21
R^2		0.9528					
Absolute percentage error		0.21	0.69	1.01	0.40	0.04	0.45
Mean absolute percentage error (MAPE)		0.47					
Overall cost (as per logarithmic cost function)	Crore ₹	611.30	624.37	634.71	643.27	650.57	656.94
R^2		0.9026					
Absolute percentage error		0.57	0.44	1.41	0.67	0.08	0.95
Mean absolute percentage error (MAPE)		0.69					

Summary of cost response study for 150 mld capacity of WWTP with MBR (continued)

REGRESSION ANALYSIS AND DETERMINATION OF MAPE (continued)

BOD REMOVAL

		BOD (mg/l)	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**
		100.00	**130.00**	**160.00**	**190.00**	**220.00**	**250.00**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Overall cost (as per polynomial cost function)	Crore ₹	616.22	621.53	628.65	637.56	648.27	660.79
R^2		0.9733					
Absolute percentage error		0.23	0.90	0.44	0.22	0.44	0.37
Mean absolute percentage error (MAPE)		0.43					
Overall cost (as per power cost function)	Crore ₹	611.58	624.24	634.45	643.02	650.43	656.95
R^2		0.9070					
Absolute percentage error		0.53	0.46	1.37	0.63	0.11	0.94
Mean absolute percentage error (MAPE)		0.67					

Summary of cost response study for 150 mld capacity of WWTP with MBR (continued)

95 % CONFIDENCE INTERVAL FOR MEAN OF ABSOLUTE PERCENTAGE ERROR AS PER SELECTED COST FUNCTION

BOD REMOVAL

		BOD in mg/l	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
		(as per linear cost function)					
Absolute percentage error	%	0.21	0.69	1.01	0.40	0.04	0.45
MAPE	%	0.47					
Standard deviation	%	0.35					
Alpha value for 95% confidence level		0.05					
Confidence		0.28					
Upper limit of MAPE	%	0.74					
Lower limit of MAPE	%	0.19					

Appendix- XIII

Summary of cost response study for 5 mld capacity of WWTP with MBBR

DESIGN SUMMARY FOR MOVING BED BIOFILM REACTOR BASINS – 5 MLD BOD REMOVAL

		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Average wastewater flow rate	m^3/d	5000.00	5000.00	5000.00	5000.00	5000.00	5000.00
Influent flow rate to reactor basins	m^3/d	5757.50	5750.75	5744.00	5737.25	5730.50	5723.75
Average BOD load	kg/d	711.40	808.90	906.40	1003.90	1101.40	1198.90
MLSS (X_{MLSS})	g TSS/m^3	5000.00	5000.00	5000.00	5000.00	5000.00	5000.00
MLVSS (X_{MLVSS})	g VSS/m^3	2670.83	2718.60	2756.24	2786.64	2811.67	2832.63
F/M	(g BOD/d)/g VSS	1.35	1.33	1.31	1.30	1.28	1.27
Volumetric BOD loading	(kg BOD/d)/m^3	3.61	3.61	3.61	3.61	3.61	3.61
Total sludge (TSS) purged per day	kg TSS/d	685.53	777.64	869.68	961.66	1053.57	1145.43
Observed yield based on VSS	g bVSS/g bCOD	0.33	0.33	0.34	0.34	0.34	0.34
	g bVSS/g BOD	0.52	0.53	0.54	0.54	0.55	0.55
Observed yield based on TSS	g TSS/g bCOD	0.61	0.61	0.61	0.61	0.61	0.61
	g TSS/g BOD	0.98	0.98	0.97	0.97	0.97	0.97
Overall oxygen demand	kg oxygen/h	27.31	30.98	34.64	38.31	41.98	45.65
Air flow rate at average wastewater flow rate	m^3/min	23.28	26.40	29.53	32.66	35.79	38.92
RAS recycle ratio	number	0.70	0.69	0.69	0.69	0.69	0.69
Internal recycle ratio	number	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
Concentration of BOD of effluent	g/m^3	10.05	10.03	10.02	10.01	10.00	9.99
Concentration of TSS of effluent	g/m^3	10.00	10.00	10.00	10.00	10.00	10.00

Summary of cost response study for 5 mld capacity of WWTP with MBBR (continued)

EQUIPMENT SUMMARY FOR MOVING BED BIOLOGICAL REACTOR BASED SYSTEM – 5 MLD
BOD REMOVAL

		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
PRIMARY CLARIFIERS							
Number of primary clarifiers	number	2	2	2	2	2	2
Diameter of each primary clarifier	m	10.00	10.00	10.00	10.00	10.00	10.00
Side water depth of each primary clarifier	m	4.00	4.00	4.00	4.00	4.00	4.00
PRIMARY CLARIFIER SLUDGE SUMP							
Number of sludge sumps	number	1	1	1	1	1	1
Length of each sludge sump	m	6.10	6.10	6.10	6.10	6.10	6.10
Width of each sludge sump	m	6.10	6.10	6.10	6.10	6.10	6.10
Depth of each sludge sump	m	3.10	3.10	3.10	3.10	3.10	3.10
PRIMARY CLARIFIER SLUDGE TRANSFER PUMPS & PUMP-HOUSE							
Nunber of pump-houses	number	1	1	1	1	1	1
Total number of pumps provided in each pump-house	number	2	2	2	2	2	2
Design capacity for each pump	m^3/h	10.00	10.00	10.00	10.00	10.00	10.00
Head to be developed by each pump	mlc	20.00	20.00	20.00	20.00	20.00	20.00
STAGE - 1 OF DOUBLE STAGE BOD REMOVAL REACTION BASINS & ACCESSORIES							
Number of reactor basins	number	2	2		2	2	2
Length of each reactor basin	m	4.20	4.50	4.80	5.00	5.30	5.50
Width of each reactor basin	m	3.50	3.80	4.00	4.20	4.50	4.60
Depth of each reactor basin	m	4.57	4.57	4.57	4.57	4.57	4.57

Summary of cost response study for 5 mld capacity of WWTP with MBBR (continued)

EQUIPMENT SUMMARY FOR MOVING BED BIOLOGICAL REACTOR BASED SYSTEM – 5 MLD (continued) *BOD REMOVAL*							
		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
STAGE - 2 OF DOUBLE STAGE BOD REMOVAL REACTION BASINS & ACCESSORIES							
Number of reactor basins	number	2	2	2	2	2	2
Length of each reactor basin	m	4.10	4.30	4.60	4.80	5.00	5.30
Width of each reactor basin	m	3.50	3.80	4.00	4.20	4.50	4.60
Depth of each reactor basin	m	4.57	4.57	4.57	4.57	4.57	4.57
SECONDARY CLARIFIERS							
Number of secondary clarifiers	number	2	2	2	2	2	2
Diameter of each secondary clarifier	m	21.00	21.00	21.00	20.90	20.90	20.90
Side water depth of each secondary clarifier	m	4.50	4.50	4.50	4.50	4.50	4.50
SECONDARY CLARIFIER SLUDGE SUMP							
Number of sludge sumps	number	1	1	1	1	1	1
Length of each sludge sump	m	11.13	11.10	11.08	11.05	11.02	10.99
Width of each sludge sump	m	6.10	6.10	6.10	6.10	6.10	6.10
Depth of each sludge sump	m	3.10	3.10	3.10	3.10	3.10	3.10
SECONDARY CLARIFIER SLUDGE TRANSFER PUMPS & PUMP-HOUSE							
Number of pump-houses	number	1	1	1	1	1	1
Total number of pumps provided in each pump-house	number	2	2	2	2	2	2
Design capacity for each pump	m^3/h	170.00	170.00	170.00	170.00	170.00	170.00
Head to be developed by each pump	mlc	20.00	20.00	20.00	20.00	20.00	20.00

Summary of cost response study for 5 mld capacity of WWTP with MBBR (continued)

ESTIMATED COST SUMMARY FOR MOVING BED BIOLOGICAL REACTOR BASED SYSTEM – 5 MLD
BOD REMOVAL

		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
PRIMARY CLARIFIERS							
Total bare construction cost	₹	1,04,99,042.47	1,04,99,042.47	1,04,99,042.47	1,04,99,042.47	1,04,99,042.47	1,04,99,042.47
Levelized cost for 25 years of life of primary clarifiers	₹	30,59,649.07	30,59,649.07	30,59,649.07	30,59,649.07	30,59,649.07	30,59,649.07
Overall cost	₹	1,35,58,691.54	1,35,58,691.54	1,35,58,691.54	1,35,58,691.54	1,35,58,691.54	1,35,58,691.54
PRIMARY CLARIFIER SLUDGE SUMP							
Total bare construction cost	₹	5,33,974.40	5,33,974.40	5,33,974.40	5,33,974.40	5,33,974.40	5,33,974.40
Levelized cost for 25 years of life of primary clarifiers	₹	14,03,054.76	14,03,054.76	14,03,054.76	14,03,054.76	14,03,054.76	14,03,054.76
Overall cost	₹	19,37,029.16	19,37,029.16	19,37,029.16	19,37,029.16	19,37,029.16	19,37,029.16
PRIMARY CLARIFIER SLUDGE TRANSFER PUMPS & PUMP-HOUSE							
Total bare construction cost	₹	66,72,066.57	66,72,066.57	66,72,066.57	66,72,066.57	66,72,066.57	66,72,066.57
Levelized cost for 25 years of life of primary clarifiers	₹	20,56,860.23	20,56,860.23	20,56,860.23	20,56,860.23	20,56,860.23	20,56,860.23
Overall cost	₹	87,28,926.80	87,28,926.80	87,28,926.80	87,28,926.80	87,28,926.80	87,28,926.80
STAGE - 1 OF DOUBLE STAGE BOD REMOVAL REACTION BASINS & ACCESSORIES							
Total bare construction cost	₹	36,82,519.43	38,88,518.49	42,43,725.14	45,21,636.01	48,29,572.63	50,98,539.12
Levelized cost for 25 years of life of primary clarifiers	₹	1,64,74,366.50	1,83,29,390.79	2,02,19,919.49	2,20,76,556.12	2,39,34,471.12	2,57,73,049.43
Overall cost	₹	2,01,56,885.93	2,22,17,909.28	2,44,63,644.63	2,65,98,192.13	2,87,64,043.75	3,08,71,588.55

Summary of cost response study for 5 mld capacity of WWTP with MBBR (continued)

ESTIMATED COST SUMMARY FOR MOVING BED BIOLOGICAL REACTOR BASED SYSTEM – 5 MLD (continued)
BOD REMOVAL

		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
STAGE - 2 OF DOUBLE STAGE BOD REMOVAL REACTION BASINS & ACCESSORIES							
Total bare construction cost	₹	24,57,026.42	26,03,747.50	27,57,905.06	28,96,787.21	30,47,090.44	31,93,920.82
Levelized cost for 25 years of life of primary clarifiers	₹	7,72,530.74	8,18,912.25	8,67,661.91	9,11,634.36	9,59,229.37	10,05,760.22
Overall cost	₹	32,29,557.16	34,22,659.75	36,25,566.97	38,08,421.57	40,06,319.82	41,99,681.04
BLOWERS AND BLOWER-BUILDING							
Total bare construction cost	₹	1,65,31,715.68	1,75,71,901.07	1,85,66,161.61	1,95,18,322.06	2,04,27,148.05	2,13,00,975.25
Levelized cost for 25 years of life of blowers and blower-building	₹	0.00	0.00	0.00	0.00	0.00	0.00
Overall cost	₹	1,65,31,715.68	1,75,71,901.07	1,85,66,161.61	1,95,18,322.06	2,04,27,148.05	2,13,00,975.25
SECONDARY CLARIFIERS							
Total bare construction cost	₹	2,22,23,578.32	2,22,23,578.32	2,22,23,578.32	2,21,13,094.51	2,21,13,094.51	2,21,13,094.51
Levelized cost for 25 years of life of secondary clarifiers	₹	60,13,927.88	60,13,927.88	60,13,927.88	59,83,385.55	59,83,385.55	59,83,385.55
Overall cost	₹	2,82,37,506.21	2,82,37,506.21	2,82,37,506.21	2,80,96,480.06	2,80,96,480.06	2,80,96,480.06
SECONDARY CLARIFIER SLUDGE SUMP							
Total bare construction cost	₹	7,79,196.38	7,77,824.72	7,76,453.60	7,75,082.98	7,73,712.84	7,72,343.17
Levelized cost for 25 years of life of secondary clarifier sludge sump	₹	14,27,141.88	14,27,007.15	14,26,872.47	14,26,737.84	14,26,603.26	14,26,468.72
Overall cost	₹	22,06,338.26	22,04,831.87	22,03,326.06	22,01,820.81	22,00,316.09	21,98,811.88

Summary of cost response study for 5 mld capacity of WWTP with MBBR (continued)

ESTIMATED COST SUMMARY FOR MOVING BED BIOLOGICAL REACTOR BASED SYSTEM – 5 MLD (continued) ***BOD REMOVAL***							
		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
SECONDARY CLARIFIER SLUDGE TRANSFER PUMPS & PUMP-HOUSE							
Total bare construction cost	₹	91,95,516.62	91,95,516.62	91,95,516.62	91,95,516.62	91,95,516.62	91,95,516.62
Levelized cost for 25 years of life of secondary clarifier sludge transfer pumps & pump-house	₹	68,72,289.48	68,72,289.48	68,72,289.48	68,72,289.48	68,72,289.48	68,72,289.48
Overall cost	₹	1,60,67,806.10	1,60,67,806.10	1,60,67,806.10	1,60,67,806.10	1,60,67,806.10	1,60,67,806.10
ESTIMATED CONSOLIDATED COSTS							
Total bare construction cost	₹	7,25,74,636.30	7,39,66,170.16	7,54,68,423.78	7,67,25,522.83	7,80,91,218.53	7,93,79,472.93
Levelized cost for 25 years of life of WWTP	₹	3,80,79,820.54	3,99,81,091.61	4,19,20,235.29	4,37,90,167.41	4,56,95,542.83	4,75,80,517.45
Overall cost	₹	11,06,54,456.84	11,39,47,261.77	11,73,88,659.07	12,05,15,690.24	12,37,86,761.36	12,69,59,990.38
COST OF LAND							
Cost of land	₹	3,55,41,187.20	3,59,01,362.51	3,62,13,242.80	3,63,53,204.31	3,67,33,218.49	3,69,53,715.71
OVERALL COST							
Overall cost	₹	14,61,95,644.04	14,98,48,624.28	15,36,01,901.88	15,68,68,894.55	16,05,19,979.85	16,39,13,706.09
Overall cost	Crore ₹	14.62	14.98	15.36	15.69	16.05	16.39
Overall cost	Million USD	1.83	1.87	1.92	1.96	2.01	2.05

Summary of cost response study for 5 mld capacity of WWTP with MBBR (continued)

REGRESSION ANALYSIS AND DETERMINATION OF MAPE

BOD REMOVAL

		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Predicted value (as per exponential cost function)	Crore ₹	14.70	15.06	15.42	15.80	16.18	16.57
Value of R^2		0.9990					
Absolute percentage error		0.55	0.48	0.41	0.71	0.81	1.12
Mean absolute percentage error (MAPE)		0.68					
Predicted value (as per linear cost function)	Crore ₹	14.63	14.98	15.34	15.69	16.05	16.40
Value of R^2		0.9997					
Absolute percentage error		0.07	0.01	0.14	0.03	0.04	0.05
Mean absolute percentage error (MAPE)		0.06					
Predicted value (as per logarithmic cost function)	Crore ₹	14.53	15.03	15.43	15.76	16.05	16.29
Value of R^2		0.9855					
Absolute percentage error		0.63	0.32	0.47	0.49	0.04	0.61
Mean absolute percentage error (MAPE)		0.43					
Predicted value (as per polynomial cost function)	Crore ₹	14.63	15.00	15.36	15.72	16.07	16.42
Value of R^2		0.9998					
Absolute percentage error		0.05	0.08	0.00	0.20	0.12	0.17
Mean absolute percentage error (MAPE)		0.10					
Predicted value (as per power cost function)	Crore ₹	14.54	15.03	15.42	15.75	16.04	16.30
Value of R^2		0.9892					
Absolute percentage error		0.53	0.27	0.38	0.42	0.06	0.56
Mean absolute percentage error (MAPE)		0.37					

Summary of cost response study for 5 mld capacity of WWTP with MBBR (continued)

95 % CONFIDENCE INTERVAL FOR MEAN OF ABSOLUTE PERCENTAGE ERROR AS PER SELECTED COST FUNCTION

BOD REMOVAL

		BOD in mg/l	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
		(as per linear cost function)					
Absolute percentage error	%	0.07	0.01	0.14	0.03	0.04	0.05
MAPE	%				0.06		
Standard deviation	%				0.05		
Alpha value for 95% confidence level					0.05		
Confidence					0.04		
Upper limit of MAPE	%				0.09		
Lower limit of MAPE	%				0.02		

Appendix- XIV

Summary of cost response study for 50 mld capacity of WWTP with MBBR

DESIGN SUMMARY FOR MOVING BED BIOFILM REACTOR BASINS – 50 MLD
BOD REMOVAL

		BOD (mg/l)	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**
		100.00	**130.00**	**160.00**	**190.00**	**220.00**	**250.00**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Average flow rate for wastewater	m^3/d	50000.00	50000.00	50000.00	50000.00	50000.00	50000.00
Flow rate to MBBRs	m^3/d	57575.00	57507.50	57440.00	57372.50	57305.00	57237.50
Average BOD load	kg/d	7114.00	8089.00	9064.00	10039.00	11014.00	11989.00
Number of tanks in stage – 1	number	6	6	6	6	6	6
Volume of each tank in stage – 1	m^3	197.61	224.69	251.78	278.86	305.94	333.03
Effluent BOD (stage – 1)	mg/l	27.80	31.65	35.50	39.37	43.24	47.13
Number of tanks in stage – 2	number	6	6	6	6	6	6
Volume of each tank in stage – 2	m^3	193.32	219.81	246.30	272.80	299.29	325.79
Effluent BOD (stage – 2)	mg/l	1.76	2.00	2.25	2.49	2.74	2.98
MLVSS (X_{MLVSS})	g VSS/m^3	2670.83	2718.60	2756.24	2786.64	2811.67	2832.63
Food to mass ratio	(g BOD/d)/g VSS	1.35	1.33	1.31	1.30	1.28	1.27
Volumetric BOD loading	(kg BOD/d)/m^3	3.61	3.61	3.61	3.61	3.61	3.61
TSS purged per day	kg TSS/d	6855.34	7776.42	8696.82	9616.58	10535.73	11454.30
Observed yield (based on VSS)	g bVSS/g bCOD	0.33	0.33	0.34	0.34	0.34	0.34
	g bVSS/g BOD	0.52	0.53	0.54	0.54	0.55	0.55
Observed yield (based on TSS)	g TSS/g bCOD	0.61	0.61	0.61	0.61	0.61	0.61
	g TSS/g BOD	0.98	0.98	0.97	0.97	0.97	0.97
Overall oxygen demand	kg oxygen/h	273.06	309.75	346.44	383.14	419.84	456.55
Flow rate of air	m^3/min	232.76	264.03	295.31	326.59	357.87	389.16
BOD	mg/l	10.05	10.03	10.02	10.01	10.00	9.99
TSS	mg/l	10.00	10.00	10.00	10.00	10.00	10.00

Summary of cost response study for 50 mld capacity of WWTP with MBBR (continued)

EQUIPMENT SUMMARY FOR MOVING BED BIOFILM REACTOR BASINS – 50 MLD

BOD REMOVAL

		BOD (mg/l)	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**
		100.00	**130.00**	**160.00**	**190.00**	**220.00**	**250.00**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
PRIMARY CLARIFIERS							
Number	number	4	4	4	4	4	4
Diameter (each)	m	21.40	21.40	21.40	21.40	21.40	21.40
Liquid depth (each)	m	4.00	4.00	4.00	4.00	4.00	4.00
PRIMARY CLARIFIER SLUDGE SUMP							
Number	number	1	1	1	1	1	1
Length (each)	m	6.10	6.10	6.10	6.10	6.10	6.10
Width (each)	m	6.10	6.10	6.10	6.10	6.10	6.10
Depth (each)	m	3.10	3.10	3.10	3.10	3.10	3.10
PRIMARY CLARIFIER SLUDGE TRANSFER PUMPS AND PUMP-HOUSE							
Number of pump-houses	number	1	1	1	1	1	1
Total number of pumps provided (in each pump-house)	number	2	2	2	2	2	2
Design capacity (for each pump)	m^3/h	10.00	20.00	20.00	20.00	30.00	30.00
Head to be developed (for each pump)	mlc	20.00	20.00	20.00	20.00	20.00	20.00
STAGE - 1 OF DOUBLE STAGE BOD REMOVAL REACTION BASINS & ACCESSORIES							
Number of reactor basins	number	6	6		6	6	6
Length (each)	m	7.70	8.20	8.70	9.10	9.50	10.00
Width (each)	m	6.50	6.90	7.30	7.60	8.00	8.40
Depth (each)	m	4.57	4.57	4.57	4.57	4.57	4.57
STAGE - 2 OF DOUBLE STAGE BOD REMOVAL REACTION BASINS & ACCESSORIES							
Number of reactor basins	number	6	6	6	6	6	6
Length (each)	m	7.40	7.90	8.30	8.90	9.20	9.60
Width (each)	m	6.50	6.90	7.30	7.60	8.00	8.40
Depth (each)	m	4.57	4.57	4.57	4.57	4.57	4.57
SECONDARY CLARIFIERS							
Number	number	4	4	4	4	4	4
Diameter (each)	m	44.60	44.60	44.50	44.50	44.50	44.50
Liquid depth (each)	m	4.50	4.50	4.50	4.50	4.50	4.50

Summary of cost response study for 50 mld capacity of WWTP with MBBR (continued)

EQUIPMENT SUMMARY FOR MOVING BED BIOFILM REACTOR BASINS – 50 MLD (continued)

BOD REMOVAL

		BOD (mg/l)	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**
		100.00	**130.00**	**160.00**	**190.00**	**220.00**	**250.00**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
SECONDARY CLARIFIER SLUDGE SUMP							
Number	number	2	2	2	2	2	2
Length (each)	m	55.66	55.52	55.38	55.24	55.10	54.96
Width (each)	m	6.10	6.10	6.10	6.10	6.10	6.10
Depth (each)	m	3.10	3.10	3.10	3.10	3.10	3.10
CLARIFIER SLUDGE TRANSFER PUMPS AND PUMP-HOUSE							
Number of pump-houses	number	1	1	1	1	1	1
Total number of pumps provided (in each pump-house)	number	2	2	2	2	2	2
Design capacity (for each pump)	m^3/h	1700.00	1700.00	1690.00	1690.00	1680.00	1680.00
Head to be developed (for each pump)	mlc	20.00	20.00	20.00	20.00	20.00	20.00

Summary of cost response study for 50 mld capacity of WWTP with MBBR (continued)

ESTIMATED COST SUMMARY FOR MOVING BED BIOFILM REACTOR BASINS – 50 MLD

BOD REMOVAL

		BOD (mg/l)	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**
		100.00	**130.00**	**160.00**	**190.00**	**220.00**	**250.00**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
PRIMARY CLARIFIERS							
Capital Expenditure (CAPEX)	₹	4,44,17,444.72	4,44,17,444.72	4,44,17,444.72	4,44,17,444.72	4,44,17,444.72	4,44,17,444.72
Operation expenditure for 25 years (OPEX)	₹	1,00,81,523.56	1,00,81,523.56	1,00,81,523.56	1,00,81,523.56	1,00,81,523.56	1,00,81,523.56
Overall cost inclusive of CAPEX & OPEX	₹	5,44,98,968.28	5,44,98,968.28	5,44,98,968.28	5,44,98,968.28	5,44,98,968.28	5,44,98,968.28
PRIMARY CLARIFIER SLUDGE SUMP							
CAPEX	₹	5,33,974.40	5,33,974.40	5,33,974.40	5,33,974.40	5,33,974.40	5,33,974.40
OPEX	₹	14,03,054.76	14,03,054.76	14,03,054.76	14,03,054.76	14,03,054.76	14,03,054.76
Overall cost inclusive of CAPEX & OPEX	₹	19,37,029.16	19,37,029.16	19,37,029.16	19,37,029.16	19,37,029.16	19,37,029.16
PRIMARY CLARIFIER SLUDGE TRANSFER PUMPS AND PUMP-HOUSE							
CAPEX	₹	66,72,066.57	70,18,201.15	70,18,201.15	70,18,201.15	72,77,725.70	72,77,725.70
OPEX	₹	20,56,860.23	24,65,890.39	24,65,890.39	24,65,890.39	28,19,150.94	28,19,150.94
Overall cost inclusive of CAPEX & OPEX	₹	87,28,926.80	94,84,091.54	94,84,091.54	94,84,091.54	1,00,96,876.64	1,00,96,876.64
STAGE - 1 OF DOUBLE STAGE BOD REMOVAL REACTION BASINS & ACCESSORIES							
CAPEX	₹	2,83,29,660.29	3,16,83,836.99	3,47,84,726.95	3,75,96,009.53	4,04,45,018.79	4,30,48,125.47
OPEX	₹	13,47,75,537.15	15,21,86,791.07	16,95,21,967.30	18,67,79,333.06	20,40,19,075.67	22,11,95,069.16
Overall cost inclusive of CAPEX & OPEX	₹	16,31,05,197.44	18,38,70,628.06	20,43,06,694.25	22,43,75,342.59	24,44,64,094.45	26,42,43,194.63
STAGE - 2 OF DOUBLE STAGE BOD REMOVAL REACTION BASINS & ACCESSORIES							
CAPEX	₹	1,47,49,123.40	1,60,43,634.12	1,72,96,814.77	1,86,20,267.05	1,98,38,542.17	2,11,21,122.17
OPEX	₹	25,47,253.41	27,71,668.29	29,89,078.74	32,18,770.40	34,30,416.70	36,53,316.50
Overall cost inclusive of CAPEX & OPEX	₹	1,72,96,376.81	1,88,15,302.41	2,02,85,893.51	2,18,39,037.46	2,32,68,958.87	2,47,74,438.67
BLOWERS AND BLOWER-BUILDING							
CAPEX	₹	5,34,45,647.86	5,72,43,859.72	6,08,63,712.64	6,43,32,776.12	6,76,65,368.38	7,08,72,442.05
OPEX	₹	0.00	0.00	0.00	0.00	0.00	0.00
Overall cost inclusive of CAPEX & OPEX	₹	5,34,45,647.86	5,72,43,859.72	6,08,63,712.64	6,43,32,776.12	6,76,65,368.38	7,08,72,442.05

Summary of cost response study for 50 mld capacity of WWTP with MBBR (continued)

ESTIMATED COST SUMMARY FOR MOVING BED BIOFILM REACTOR BASINS – 50 MLD (continued)

BOD REMOVAL

		BOD (mg/l)	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**	**BOD (mg/l)**
		100.00	**130.00**	**160.00**	**190.00**	**220.00**	**250.00**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
SECONDARY CLARIFIERS							
CAPEX	₹	10,52,45,523.14	10,52,45,523.14	10,49,45,835.20	10,49,45,835.20	10,49,45,835.20	10,49,45,835.20
OPEX	₹	2,41,40,177.57	2,41,40,177.57	2,40,73,466.11	2,40,73,466.11	2,40,73,466.11	2,40,73,466.11
Overall cost inclusive of CAPEX & OPEX	₹	12,93,85,700.72	12,93,85,700.72	12,90,19,301.31	12,90,19,301.31	12,90,19,301.31	12,90,19,301.31
SECONDARY CLARIFIER SLUDGE SUMP							
CAPEX	₹	52,45,373.36	52,33,204.41	52,21,040.25	52,08,880.58	51,96,725.17	51,84,573.89
OPEX	₹	37,38,162.46	37,32,032.14	37,25,899.29	37,19,763.73	37,13,625.36	37,07,484.07
Overall cost inclusive of CAPEX & OPEX	₹	89,83,535.82	89,65,236.56	89,46,939.54	89,28,644.31	89,10,350.53	88,92,057.96
SECONDARY CLARIFIER SLUDGE TRANSFER PUMPS AND PUMP-HOUSE							
CAPEX	₹	1,97,63,998.76	1,97,63,998.76	1,96,72,182.23	1,96,72,182.23	1,95,80,444.14	1,95,80,444.14
OPEX	₹	4,66,35,930.35	4,66,35,930.35	4,63,75,525.06	4,63,75,525.06	4,61,15,098.77	4,61,15,098.77
Overall cost inclusive of CAPEX & OPEX	₹	6,63,99,929.11	6,63,99,929.11	6,60,47,707.29	6,60,47,707.29	6,56,95,542.91	6,56,95,542.91
ESTIMATED CONSOLIDATED COSTS							
CAPEX	₹	27,84,02,812.51	28,71,83,677.43	29,47,53,932.31	30,23,45,570.99	30,99,01,078.67	31,69,81,687.74
OPEX	₹	22,53,78,499.51	24,34,17,068.14	26,06,36,405.22	27,81,17,327.07	29,56,55,411.86	31,30,48,163.86
Overall cost inclusive of CAPEX & OPEX	₹	50,37,81,312.02	53,06,00,745.57	55,53,90,337.53	58,04,62,898.06	60,55,56,490.53	63,00,29,851.61
COST OF LAND							
Cost of land	₹	21,38,68,124.48	21,59,40,798.71	21,74,90,241.87	21,93,75,140.43	22,13,62,745.57	22,36,01,084.19
OVERALL COST							
Overall cost inclusive of CAPEX, OPEX & land	₹	71,76,49,436.49	74,65,41,544.28	77,28,80,579.40	79,98,38,038.49	82,69,19,236.11	85,36,30,935.79
Overall cost inclusive of CAPEX, OPEX & land	Crore ₹	71.76	74.65	77.29	79.98	82.69	85.36
Overall cost inclusive of CAPEX, OPEX & land	Million USD	8.97	9.33	9.66	10.00	10.34	10.67

Summary of cost response study for 50 mld capacity of WWTP with MBBR (continued)

REGRESSION ANALYSIS AND DETERMINATION OF MAPE – 50 MLD

BOD REMOVAL

Design parameter	**Unit**	**BOD (mg/l) 100.00 Value**	**BOD (mg/l) 130.00 Value**	**BOD (mg/l) 160.00 Value**	**BOD (mg/l) 190.00 Value**	**BOD (mg/l) 220.00 Value**	**BOD (mg/l) 250.00 Value**
Overall cost (as per exponential cost function)	Crore ₹	72.35	75.00	77.75	80.60	83.55	86.62
R^2		0.9988					
Absolute percentage error		0.81	0.46	0.60	0.77	1.04	1.47
Mean absolute percentage error (MAPE)		0.86					
Overall cost (as per linear cost function)	Crore ₹	71.85	74.56	77.27	79.98	82.69	85.40
R^2		0.9999					
Absolute percentage error		0.12	0.13	0.03	0.01	0.01	0.04
Mean absolute percentage error (MAPE)		0.05					
Overall cost (as per logarithmic cost function)	Crore ₹	71.07	74.93	77.99	80.52	82.68	84.56
R^2		0.9845					
Absolute percentage error		0.97	0.37	0.91	0.67	0.02	0.94
Mean absolute percentage error (MAPE)		0.65					
Overall cost (as per polynomial cost function)	Crore ₹	71.76	74.50	77.20	79.86	82.49	85.08
R^2		0.9999					
Absolute percentage error		0.00	0.21	0.11	0.15	0.24	0.33
Mean absolute percentage error (MAPE)		0.17					
Overall cost (as per power cost function)	Crore ₹	71.26	74.87	77.86	80.42	82.67	84.69
R^2		0.9902					
Absolute percentage error		0.70	0.29	0.74	0.55	0.02	0.79
Mean absolute percentage error (MAPE)		0.52					

Summary of cost response study for 50 mld capacity of WWTP with MBBR (continued)

95 % CONFIDENCE INTERVAL FOR MEAN OF ABSOLUTE PERCENTAGE ERROR AS PER SELECTED COST FUNCTION

BOD REMOVAL

		BOD in mg/l	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
		(as per linear cost function)					
Absolute percentage error	%	0.12	0.13	0.03	0.01	0.01	0.04
MAPE	%	0.05					
Standard deviation	%	0.05					
Alpha value for 95% confidence level		0.05					
Confidence		0.04					
Upper limit of MAPE	%	0.10					
Lower limit of MAPE	%	0.01					

Appendix- XV

Summary of cost response study for 150 mld capacity of WWTP with MBBR

DESIGN SUMMARY FOR MOVING BED BIOFILM REACTOR BASINS - 150 MLD
BOD REMOVAL

		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Average wastewater flow rate	m^3/d	150000.00	150000.00	150000.00	150000.00	150000.00	150000.00
Influent flow rate to reactor basins	m^3/d	172725.00	172522.50	172320.00	172117.50	171915.00	171712.50
Average BOD load	kg/d	21342.00	24267.00	27192.00	30117.00	33042.00	35967.00
Number of tanks for stage - 1 (for preliminary BOD removal)	number	12	12	12	12	12	12
Volume of each tank for stage - 1 (for preliminary BOD removal)	m^3	296.42	337.04	377.67	418.29	458.92	499.54
Concentration of BOD in effluent from stage - 1	g/m^3	27.80	31.65	35.50	39.37	43.24	47.13
Number of tanks for stage - 2 (for final BOD removal)	number	12	12	12	12	12	12
Volume of each tank for stage - 2 (for final BOD removal)	m^3	289.97	329.71	369.46	409.20	448.94	488.68
Concentration of BOD in effluent from stage - 2	g/m^3	1.76	2.00	2.25	2.49	2.74	2.98
MLSS (X_{MLSS})	g TSS/m^3	5000.00	5000.00	5000.00	5000.00	5000.00	5000.00
MLVSS (X_{MLVSS})	g VSS/m^3	2670.83	2718.60	2756.24	2786.64	2811.67	2832.63
F/M	(g BOD/d)/g VSS	1.35	1.33	1.31	1.30	1.28	1.27
Volumetric BOD loading	(kg BOD/d)/m^3	3.61	3.61	3.61	3.61	3.61	3.61
Total sludge (TSS) purged per day	kg TSS/d	20566.01	23329.25	26090.45	28849.74	31607.20	34362.91
Observed yield based on VSS	g bVSS/g bCOD	0.33	0.33	0.34	0.34	0.34	0.34
	g bVSS/g BOD	0.52	0.53	0.54	0.54	0.55	0.55
Observed yield based on TSS	g TSS/g bCOD	0.61	0.61	0.61	0.61	0.61	0.61
	g TSS/g BOD	0.98	0.98	0.97	0.97	0.97	0.97
Overall oxygen demand	kg oxygen/h	819.19	929.25	1039.33	1149.43	1259.53	1369.65
Air flow rate at average wastewater flow rate	m^3/min	698.27	792.09	885.92	979.76	1073.61	1167.48
RAS recycle ratio	number	0.70	0.69	0.69	0.69	0.69	0.69
Concentration of BOD of effluent	g/m^3	10.05	10.03	10.02	10.01	10.00	9.99
Concentration of TSS of effluent	g/m^3	10.00	10.00	10.00	10.00	10.00	10.00

Summary of cost response study for 150 mld capacity of WWTP with MBBR (continued)

EQUIPMENT SUMMARY FOR MOVING BED BIOLOGICAL REACTOR BASED SYSTEM - 150 MLD BOD REMOVAL

		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
PRIMARY CLARIFIERS							
Number of primary clarifiers	number	8	8	8	8	8	8
Diameter of each primary clarifier	m	26.20	26.20	26.20	26.20	26.20	26.20
Side water depth of each primary clarifier	m	4.00	4.00	4.00	4.00	4.00	4.00
PRIMARY CLARIFIER SLUDGE SUMP							
Number of sludge sumps	number	1	1	1	1	1	1
Length of each sludge sump	m	6.10	6.10	6.10	6.10	6.10	6.10
Width of each sludge sump	m	6.10	6.10	6.10	6.10	6.10	6.10
Depth of each sludge sump	m	3.10	3.10	3.10	3.10	3.10	3.10
PRIMARY CLARIFIER SLUDGE TRANSFER PUMPS & PUMP-HOUSE							
Number of pump-houses	number	1	1	1	1	1	1
Total number of pumps provided in each pump-house	number	2	2	2	2	2	2
Design capacity for each pump	m^3/h	30.00	40.00	50.00	60.00	70.00	80.00
Head to be developed by each pump	mlc	20.00	20.00	20.00	20.00	20.00	20.00
STAGE - 1 OF DOUBLE STAGE BOD REMOVAL REACTION BASINS & ACCESSORIES							
Number of reactor basins	number	12	12	12	12	12	12
Length of each reactor basin	m	9.40	10.00	10.60	11.20	11.70	12.20
Width of each reactor basin	m	7.90	8.40	8.90	9.40	9.80	10.20
Depth of each reactor basin	m	4.57	4.57	4.57	4.57	4.57	4.57
STAGE - 2 OF DOUBLE STAGE BOD REMOVAL REACTION BASINS & ACCESSORIES							
Number of reactor basins	number	12	12	12	12	12	12
Length of each reactor basin	m	9.10	9.70	10.20	10.70	11.30	11.80
Width of each reactor basin	m	7.90	8.40	8.90	9.40	9.80	10.20
Depth of each reactor basin	m	4.57	4.57	4.57	4.57	4.57	4.57

Summary of cost response study for 150 mld capacity of WWTP with MBBR (continued)

EQUIPMENT SUMMARY FOR MOVING BED BIOLOGICAL REACTOR BASED SYSTEM - 150 MLD (continued)
BOD REMOVAL

		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
SECONDARY CLARIFIERS							
Number of secondary clarifiers	number	8	8	8	8	8	8
Diameter of each secondary clarifier	m	51.70	51.70	51.60	51.60	51.60	51.50
Side water depth of each secondary clarifier	m	4.50	4.50	4.50	4.50	4.50	4.50
SECONDARY CLARIFIER SLUDGE SUMP							
Number of sludge sumps	number	5	5	5	5	5	5
Length of each sludge sump	m	66.79	66.62	66.45	66.29	66.12	65.95
Width of each sludge sump	m	6.10	6.10	6.10	6.10	6.10	6.10
Depth of each sludge sump	m	3.10	3.10	3.10	3.10	3.10	3.10
SECONDARY CLARIFIER SLUDGE TRANSFER PUMPS & PUMP-HOUSE							
Number of pump-houses	number	1	1	1	1	1	1
Total number of pumps provided in each pump-house	number	3	3	3	3	3	3
Design capacity for each pump	m^3/h	2550.00	2540.00	2540.00	2530.00	2520.00	2520.00
Head to be developed by each pump	mlc	20.00	20.00	20.00	20.00	20.00	20.00

Summary of cost response study for 150 mld capacity of WWTP with MBBR (continued)

ESTIMATED COST SUMMARY FOR MOVING BED BIOLOGICAL REACTOR BASED SYSTEM - 150 MLD (continued)
BOD REMOVAL

		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
	Unit	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
PRIMARY CLARIFIERS							
Total bare construction cost	₹	11,02,97,041.24	11,02,97,041.24	11,02,97,041.24	11,02,97,041.24	11,02,97,041.24	11,02,97,041.24
Levelized cost for 25 years of life of primary clarifiers	₹	2,18,73,563.87	2,18,73,563.87	2,18,73,563.87	2,18,73,563.87	2,18,73,563.87	2,18,73,563.87
Overall cost	₹	13,21,70,605.12	13,21,70,605.12	13,21,70,605.12	13,21,70,605.12	13,21,70,605.12	13,21,70,605.12
PRIMARY CLARIFIER SLUDGE SUMP							
Total bare construction cost	₹	5,33,974.40	5,33,974.40	5,33,974.40	5,33,974.40	5,33,974.40	5,33,974.40
Levelized cost for 25 years of life of primary clarifiers	₹	14,03,054.76	14,03,054.76	14,03,054.76	14,03,054.76	14,03,054.76	14,03,054.76
Overall cost	₹	19,37,029.16	19,37,029.16	19,37,029.16	19,37,029.16	19,37,029.16	19,37,029.16
PRIMARY CLARIFIER SLUDGE TRANSFER PUMPS & PUMP-HOUSE							
Total bare construction cost	₹	72,77,725.70	75,02,556.82	76,91,097.54	78,60,463.10	80,15,459.34	81,68,106.37
Levelized cost for 25 years of life of primary clarifiers	₹	28,19,150.94	31,48,187.61	34,62,207.43	37,66,709.00	40,64,401.14	43,57,566.78
Overall cost	₹	1,00,96,876.64	1,06,50,744.43	1,11,53,304.97	1,16,27,172.10	1,20,79,860.48	1,25,25,673.15
STAGE - 1 OF DOUBLE STAGE BOD REMOVAL REACTION BASINS & ACCESSORIES							
Total bare construction cost	₹	7,43,62,388.93	8,20,64,148.50	9,03,26,458.03	9,79,63,028.53	10,53,64,757.95	11,27,45,927.41
Levelized cost for 25 years of life of primary clarifiers	₹	38,77,88,319.08	43,84,77,360.00	48,91,84,428.24	53,97,62,824.96	59,02,69,199.69	64,07,36,242.01
Overall cost	₹	46,21,50,708.01	52,05,41,508.50	57,95,10,886.27	63,77,25,853.49	69,56,33,957.65	75,34,82,169.43
STAGE - 2 OF DOUBLE STAGE BOD REMOVAL REACTION BASINS & ACCESSORIES							
Total bare construction cost	₹	3,83,18,232.56	4,20,53,002.11	4,57,18,411.20	4,94,14,324.32	5,31,28,515.15	5,67,58,033.42
Levelized cost for 25 years of life of primary clarifiers	₹	49,72,381.72	54,58,691.60	59,36,293.98	64,18,152.10	69,02,681.76	73,76,505.97
Overall cost	₹	4,32,90,614.28	4,75,11,693.71	5,16,54,705.18	5,58,32,476.42	6,00,31,196.91	6,41,34,539.39

Summary of cost response study for 150 mld capacity of WWTP with MBBR (continued)

ESTIMATED COST SUMMARY FOR MOVING BED BIOLOGICAL REACTOR BASED SYSTEM - 150 MLD (continued)

BOD REMOVAL

		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
	Unit	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
BLOWERS AND BLOWER-BUILDING							
Total bare construction cost	₹	10,55,79,934.64	11,34,30,777.40	13,18,64,285.01	13,94,40,605.56	15,30,42,206.93	16,03,76,580.52
Levelized cost for 25 years of life of blowers and blower-building	₹	0.00	0.00	0.00	0.00	0.00	0.00
Overall cost	₹	10,55,79,934.64	11,34,30,777.40	13,18,64,285.01	13,94,40,605.56	15,30,42,206.93	16,03,76,580.52
SECONDARY CLARIFIERS							
Total bare construction cost	₹	25,51,92,137.41	25,51,92,137.41	25,45,33,054.58	25,45,33,054.58	25,45,33,054.58	25,38,74,847.55
Levelized cost for 25 years of life of secondary clarifiers	₹	5,01,03,771.63	5,01,03,771.63	4,99,80,695.26	4,99,80,695.26	4,99,80,695.26	4,98,57,728.10
Overall cost	₹	30,52,95,909.04	30,52,95,909.04	30,45,13,749.84	30,45,13,749.84	30,45,13,749.84	30,37,32,575.65
SECONDARY CLARIFIER SLUDGE SUMP							
Total bare construction cost	₹	1,43,61,130.14	1,43,27,406.99	1,42,93,697.09	1,42,59,999.63	1,42,26,314.01	1,41,92,639.79
Levelized cost for 25 years of life of secondary clarifier sludge sump	₹	76,73,904.75	76,61,001.58	76,48,093.87	76,35,181.28	76,22,263.56	76,09,340.51
Overall cost	₹	2,20,35,034.89	2,19,88,408.57	2,19,41,790.97	2,18,95,180.91	2,18,48,577.56	2,18,01,980.31
SECONDARY CLARIFIER SLUDGE TRANSFER PUMPS & PUMP-HOUSE							
Total bare construction cost	₹	4,05,81,174.47	4,04,30,634.08	4,04,30,634.08	4,02,71,256.01	4,01,20,883.03	4,01,20,883.03
Levelized cost for 25 years of life of secondary clarifier sludge transfer pumps & pump-house	₹	13,34,12,823.04	13,28,95,230.12	13,28,95,230.12	13,23,77,014.21	13,18,59,402.08	13,18,59,402.08
Overall cost	₹	17,39,93,997.51	17,33,25,864.20	17,33,25,864.20	17,26,48,270.22	17,19,80,285.12	17,19,80,285.12

Summary of cost response study for 150 mld capacity of WWTP with MBBR (continued)

ESTIMATED COST SUMMARY FOR MOVING BED BIOLOGICAL REACTOR BASED SYSTEM - 150 MLD (continued)

BOD REMOVAL

		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
	Unit	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
ESTIMATED CONSOLIDATED COSTS							
Total bare construction cost	₹	64,65,03,739.49	66,58,31,678.96	69,56,88,653.19	71,45,73,747.39	73,92,62,206.65	75,70,68,033.75
Levelized cost for 25 years of life of WWTP	₹	61,00,46,969.80	66,10,20,861.18	71,23,83,567.53	76,32,17,195.43	81,39,75,262.12	86,50,73,404.08
Overall cost	₹	1,25,65,50,709.29	1,32,68,52,540.13	1,40,80,72,220.72	1,47,77,90,942.82	1,55,32,37,468.77	1,62,21,41,437.83
COST OF LAND							
Cost of land	₹	56,48,36,601.25	57,06,83,960.34	57,54,08,600.66	58,14,86,612.52	58,69,47,482.72	59,12,09,721.16
OVERALL COST							
Overall cost	₹	1,82,13,87,310.54	1,89,75,36,500.47	1,98,34,80,821.38	2,05,92,77,555.34	2,14,01,84,951.50	2,21,33,51,159.00
Overall cost	Crore ₹	182.14	189.75	198.35	205.93	214.02	221.34
Overall cost	Million USD	22.77	23.72	24.79	25.74	26.75	27.67

Summary of cost response study for 150 mld capacity of WWTP with MBBR (continued)

REGRESSION ANALYSIS AND DETERMINATION OF MAPE – 150 MLD
BOD REMOVAL

		BOD in g/m^3	BOD in g/m^3	BOD in g/m^3	BOD in g/m^3	BOD in g/m^3	BOD in g/m^3
		100.00	*130.00*	*160.00*	*190.00*	*220.00*	*250.00*
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Predicted value (as per exponential cost function)	Crore ₹	182.51	189.77	197.31	205.16	213.32	221.80
Value of R^2		0.9982					
Absolute percentage error		0.20	0.01	0.52	0.37	0.33	0.21
Mean absolute percentage error (MAPE)		0.27					
Predicted value (as per linear cost function)	Crore ₹	182.18	190.08	197.97	205.87	213.76	221.66
Value of R^2		0.9996					
Absolute percentage error		0.02	0.17	0.19	0.03	0.12	0.15
Mean absolute percentage error (MAPE)		0.11					
Predicted value (as per logarithmic cost function)	Crore ₹	179.89	191.15	200.07	207.45	213.74	219.23
Value of R^2		0.9846					
Absolute percentage error		1.23	0.74	0.87	0.74	0.13	0.95
Mean absolute percentage error (MAPE)		0.78					
Predicted value (as per polynomial cost function)	Crore ₹	181.96	190.10	198.12	206.01	213.77	221.41
Value of R^2		0.9997					
Absolute percentage error		0.10	0.18	0.12	0.04	0.12	0.03
Mean absolute percentage error (MAPE)		0.10					
Predicted value (as per power cost function)	Crore ₹	180.49	190.92	199.59	207.08	213.68	219.61
Value of R^2		0.9906					
Absolute percentage error		0.91	0.61	0.63	0.56	0.16	0.78
Mean absolute percentage error (MAPE)		0.61					

Summary of cost response study for 150 mld capacity of WWTP with MBBR (continued)

95 % CONFIDENCE INTERVAL FOR MEAN OF ABSOLUTE PERCENTAGE ERROR AS PER SELECTED COST FUNCTION

BOD REMOVAL

		BOD in mg/l	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
		(as per linear cost function)					
Absolute percentage error	%	0.02	0.17	0.19	0.03	0.12	0.15
MAPE	%	0.11					
Standard deviation	%	0.07					
Alpha value for 95% confidence level		0.05					
Confidence		0.06					
Upper limit of MAPE	%	0.17					
Lower limit of MAPE	%	0.06					

Appendix- XVI

Summary of cost response study for 5 mld capacity of WWTP with SBR

DESIGN SUMMARY FOR SEQUENTIAL BATCH REACTOR BASED SYSTEM – 5 MLD
BOD REMOVAL

		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Influent flow rate	m^3/d	5780.00	5780.00	5780.00	5780.00	5780.00	5780.00
Average BOD load	kg/d	886.40	1036.40	1186.40	1336.40	1486.40	1636.40
Number of reaction basins	number	2	2	2	2	2	2
Fill time	h	3.00	3.00	3.00	3.00	3.00	3.00
Reaction time	h	2.00	2.00	2.00	2.00	2.00	2.00
Design time selected for aeration	h	2.00	2.00	2.00	2.00	2.00	2.00
Settlement time	h	0.50	0.50	0.50	0.50	0.50	0.50
Decantation time	h	0.50	0.50	0.50	0.50	0.50	0.50
Total cycle time	h	6.00	6.00	6.00	6.00	6.00	6.00
Solids residence time - design value	d	33.73	27.86	23.65	20.49	18.04	16.10
Total volume of each reaction basin	m^3	2890.00	2890.00	2890.00	2890.00	2890.00	2890.00
Fill volume per cycle per reaction basin	m^3	722.50	722.50	722.50	722.50	722.50	722.50
Selected value for (fill volume/total volume of reaction basin)	ratio	0.25	0.25	0.25	0.25	0.25	0.25
Decant depth	m	1.02	1.02	1.02	1.02	1.02	1.02
Total liquid depth when full	m	4.07	4.07	4.07	4.07	4.07	4.07
Mixed liquor suspended solids (X_{MLSS})	g/m^3	4000.00	4000.00	4000.00	4000.00	4000.00	4000.00
Mixed liquor volatile suspended solids (X_{MLVSS})	g/m^3	1452.82	1521.77	1576.86	1621.83	1659.17	1690.64
F/M	(g BOD/d)/g VSS	0.11	0.12	0.13	0.14	0.15	0.17
Volumetric BOD loading	(kg BOD/d)/m^3	0.31	0.36	0.41	0.46	0.51	0.57
Decant pumping rate	m^3/min	24.08	24.08	24.08	24.08	24.08	24.08
Total TSS purged per day	kg MLSS/d	685.45	829.84	977.75	1128.41	1281.26	1435.86

Summary of cost response study for 5 mld capacity of WWTP with SBR (continued)

DESIGN SUMMARY FOR SEQUENTIAL BATCH REACTOR BASED SYSTEM – 5 MLD (continued)
BOD REMOVAL

		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Observed yield based on VSS	g VSS/g BOD	0.28	0.31	0.33	0.34	0.36	0.37
Observed yield based on TSS	g TSS/g BOD	0.77	0.80	0.83	0.85	0.86	0.88
Oxygen demand per reaction basin	kg oxygen/d	553.04	632.12	709.08	784.36	858.33	931.24
Total aeration time per day per reaction basin	h	8.00	8.00	8.00	8.00	8.00	8.00
Average oxygen transfer rate per reaction basin	kg oxygen/h	69.13	79.02	88.63	98.05	107.29	116.41
Concentration of BOD in effluent	g/m^3	9.66	9.66	9.66	9.66	9.66	9.66
Concentration of TSS in effluent	g/m^3	10.00	10.00	10.00	10.00	10.00	10.00

Summary of cost response study for 5 mld capacity of WWTP with SBR (continued)

EQUIPMENT SUMMARY FOR SEQUENTIAL BATCH REACTOR BASED SYSTEM BOD REMOVAL							
		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	***130.00***	***160.00***	**190**	**220**	**250**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
REACTION BASINS & ACCESSORIES							
Number of reaction basins		2	2	2	2	2	2
Length of each reaction basin	m	77.62	77.62	77.62	77.62	77.62	77.62
Width of each reaction basin	m	9.14	9.14	9.14	9.14	9.14	9.14
Depth of each reaction basin	m	4.57	4.57	4.57	4.57	4.57	4.57
Number of swing arm headers of each reaction basin		9	11	12	13	14	15
REACTION BASIN WASTE TRANSFER PUMPS AND PUMP-HOUSE							
Total number of pumps required		2	2	2	2	2	2
Capacity of each pump	m^3/h	6.00	6.00	6.00	6.00	6.00	6.00
Area required for pump-house	m ^2	60.00	60.00	60.00	60.00	60.00	60.00
BLOWERS AND BLOWER BUILDING							
Total number of blowers required		2	2	2	2	2	2
Capacity of each blower	scfm	2138.00	2443.00	2741.00	3031.00	3317.00	3599.00
Area required for blower building	m ^2	85.00	88.00	91.00	93.00	95.00	97.00

Summary of cost response study for 5 mld capacity of WWTP with SBR (continued)

ESTIMATED COST SUMMARY FOR SEQUENTIAL BATCH REACTOR BASED SYSTEM
BOD REMOVAL

		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	***130.00***	***160.00***	**190**	**220**	**250**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
REACTION BASINS & ACCESSORIES							
Total bare construction cost	₹	3,03,26,408.09	3,09,57,247.10	3,14,86,197.40	3,20,09,538.30	3,25,31,127.54	3,30,48,751.31
Levelized cost for 25 years of life of reaction basins	₹	4,47,82,543.86	4,96,04,153.63	5,42,50,947.13	5,87,90,964.30	6,33,01,524.00	6,77,38,245.87
Overall cost	₹	7,51,08,951.96	8,05,61,400.74	8,57,37,144.53	9,08,00,502.60	9,58,32,651.53	10,07,86,997.18
REACTOR BASIN WASTE TRANSFER PUMPS AND PUMP-HOUSE							
Total bare construction cost	₹	64,81,764.04	64,81,764.04	64,81,764.04	64,90,685.29	64,90,685.29	64,90,685.29
Levelized cost for 25 years of life of pumps and pump-house	₹	20,74,332.29	21,67,072.30	22,56,814.64	23,44,823.38	24,30,314.18	25,14,219.00
Overall cost	₹	85,56,096.33	86,48,836.34	87,38,578.68	88,35,508.67	89,20,999.47	90,04,904.29
BLOWERS AND BLOWER BUILDING							
Total bare construction cost	₹	2,62,87,296.55	2,81,47,990.72	2,98,82,654.88	3,14,85,219.67	3,30,02,624.70	3,44,50,894.04
ESTIMATED CONSOLIDATED COSTS							
Total bare construction cost	₹	6,30,95,468.68	6,55,87,001.86	6,78,50,616.33	6,99,85,443.25	7,20,24,437.52	7,39,90,330.64
Levelized cost for 25 years of life	₹	4,68,56,876.15	5,17,71,225.93	5,65,07,761.77	6,11,35,787.68	6,57,31,838.17	7,02,52,464.87
Consolidated cost	₹	10,99,52,344.83	11,73,58,227.80	12,43,58,378.09	13,11,21,230.93	13,77,56,275.70	14,42,42,795.51
COST OF LAND							
Cost of land	₹	3,49,90,940.98	3,50,37,440.98	3,50,80,940.98	3,51,19,940.98	3,51,54,440.98	3,51,87,440.98
OVERALL COST							
Overall cost	₹	14,49,43,285.82	15,23,95,668.78	15,94,39,319.08	16,62,41,171.91	17,29,10,716.68	17,94,30,236.49
Overall cost	Crore ₹	14.49	15.24	15.94	16.62	17.29	17.94
Overall cost	Million USD	1.81	1.90	1.99	2.08	2.16	2.24

Summary of cost response study for 5 mld capacity of WWTP with SBR (continued)

REGRESSION ANALYSIS AND DETERMINATION OF MAPE – 5 MLD
BOD REMOVAL

		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Predicted value (as per exponential cost function)	Crore ₹	14.55	15.18	15.83	16.51	17.22	17.95
Value of R^2		0.9970					
Absolute percentage error		0.41	0.41	0.72	0.70	0.44	0.06
Mean absolute percentage error (MAPE)		0.46					
Predicted value (as per linear cost function)	Crore ₹	14.53	15.22	15.91	16.59	17.28	17.97
Value of R^2		0.9994					
Absolute percentage error		0.27	0.13	0.23	0.18	0.06	0.14
Mean absolute percentage error (MAPE)		0.17					
Predicted value (as per logarithmic cost function)	Crore ₹	14.33	15.32	16.09	16.74	17.29	17.77
Value of R^2		0.9881					
Absolute percentage error		1.11	0.50	0.94	0.69	0.02	0.98
Mean absolute percentage error (MAPE)		0.71					
Predicted value (as per polynomial cost function)	Crore ₹	14.52	15.27	16.00	16.71	17.40	18.08
Value of R^2		1.0000					
Absolute percentage error		0.18	0.19	0.33	0.50	0.64	0.74
Mean absolute percentage error (MAPE)		0.43					
Predicted value (as per power cost function)	Crore ₹	14.39	15.30	16.05	16.71	17.29	17.81
Value of R^2		0.9939					
Absolute percentage error		0.70	0.38	0.70	0.51	0.01	0.74
Mean absolute percentage error (MAPE)		0.51					

Summary of cost response study for 5 mld capacity of WWTP with SBR (continued

95 % CONFIDENCE INTERVAL FOR MEAN OF ABSOLUTE PERCENTAGE ERROR AS PER SELECTED COST FUNCTION

BOD REMOVAL

		BOD in mg/l	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
		(as per linear cost function)					
Absolute percentage error	%	0.27	0.13	0.23	0.18	0.06	0.14
MAPE	%	0.17					
Standard deviation	%	0.08					
Alpha value for 95% confidence level		0.05					
Confidence		0.06					
Upper limit of MAPE	%	0.23					
Lower limit of MAPE	%	0.11					

Appendix- XVII

Summary of cost response study for 50 mld capacity of WWTP with SBR

DESIGN SUMMARY FOR SEQUENTIAL BATCH REACTOR BASED SYSTEM – 50 MLD
BOD REMOVAL

		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Influent flow rate	m^3/d	57800.00	57800.00	57800.00	57800.00	57800.00	57800.00
Average BOD load	kg/d	8864.00	10364.00	11864.00	13364.00	14864.00	16364.00
Average TKN load	kg/d	1672.47	2007.57	2342.13	2676.13	3009.91	3343.37
Number of reaction basins	number	14	14	14	14	14	14
Fill time	h	3.00	3.00	3.00	3.00	3.00	3.00
Reaction time	h	2.00	2.00	2.00	2.00	2.00	2.00
Design time selected for aeration	h	2.00	2.00	2.00	2.00	2.00	2.00
Settlement time	h	0.50	0.50	0.50	0.50	0.50	0.50
Decantation time	h	0.50	0.50	0.50	0.50	0.50	0.50
Total cycle time	h	6.00	6.00	6.00	6.00	6.00	6.00
Solids residence time - design value	d	33.73	27.86	23.65	20.49	18.04	16.10
Total volume of each reaction basin	m^3	4128.57	4128.57	4128.57	4128.57	4128.57	4128.57
Fill volume per cycle per reaction basin	m^3	1032.14	1032.14	1032.14	1032.14	1032.14	1032.14
Selected value for (fill volume/total volume of reaction basin)	ratio	0.25	0.25	0.25	0.25	0.25	0.25
Decant depth	m	1.02	1.02	1.02	1.02	1.02	1.02
Total liquid depth when full	m	4.07	4.07	4.07	4.07	4.07	4.07
Mixed liquor suspended solids (X_{MLSS})	g/m^3	4000.00	4000.00	4000.00	4000.00	4000.00	4000.00
Mixed liquor volatile suspended solids (X_{MLVSS})	g/m^3	1452.82	1521.77	1576.86	1621.83	1659.17	1690.64
F/M	(g BOD/d)/g VSS	0.11	0.12	0.13	0.14	0.15	0.17
Volumetric BOD loading	(kg BOD/d)/m^3	2.15	2.51	2.87	3.24	3.60	3.96
Decant pumping rate	m^3/min	34.40	34.40	34.40	34.40	34.40	34.40
Total TSS purged per day	kg MLSS/d	6854.48	8298.41	9777.48	11284.13	12812.62	14358.59

Summary of cost response study for 50 mld capacity of WWTP with SBR (continued)

DESIGN SUMMARY FOR SEQUENTIAL BATCH REACTOR BASED SYSTEM – 50 MLD (continued)
BOD REMOVAL

		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Observed yield based on VSS	g VSS/g BOD	0.28	0.31	0.33	0.34	0.36	0.37
Observed yield based on TSS	g TSS/g BOD	0.77	0.80	0.83	0.85	0.86	0.88
Oxygen demand per reaction basin	kg oxygen/d	790.06	903.03	1012.97	1120.52	1226.19	1330.35
Total aeration time per day per reaction basin	h	8.00	8.00	8.00	8.00	8.00	8.00
Average oxygen transfer rate per reaction basin	kg oxygen/h	98.76	112.88	126.62	140.06	153.27	166.29
Concentration of BOD in effluent	g/m^3	9.66	9.66	9.66	9.66	9.66	9.66
Concentration of TSS in effluent	g/m^3	10.00	10.00	10.00	10.00	10.00	10.00

Summary of cost response study for 50 mld capacity of WWTP with SBR (continued)

EQUIPMENT SUMMARY FOR SEQUENTIAL BATCH REACTOR BASED SYSTEM – 50 MLD ***BOD REMOVAL***							
		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	***130.00***	***160.00***	**190**	**220**	**250**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
REACTION BASINS & ACCESSORIES							
Number of reaction basins		14	14	14	14	14	14
Length of each reaction basin	m	110.88	110.88	110.88	110.88	110.88	110.88
Width of each reaction basin	m	9.14	9.14	9.14	9.14	9.14	9.14
Depth of each reaction basin	m	4.57	4.57	4.57	4.57	4.57	4.57
Number of swing arm headers of each reaction basin		64	73	82	91	99	108
REACTION BASIN WASTE TRANSFER PUMPS AND PUMP-HOUSE							
Total number of pumps required		2	2	2	2	2	2
Capacity of each pump	m^3/h	6.00	6.00	6.00	6.00	6.00	6.00
Area required for pump-house	m ^2	61.00	61.00	61.00	61.00	62.00	62.00
BLOWERS AND BLOWER BUILDING							
Total number of blowers required		4	4	4	4	5	5
Capacity of each blower	scfm	5089.00	5816.00	6524.00	7217.00	5923.00	6426.00
Area required for blower building	m ^2	141.00	145.00	150.00	154.00	157.00	161.00

Summary of cost response study for 50 mld capacity of WWTP with SBR (continued)

ESTIMATED COST SUMMARY FOR SEQUENTIAL BATCH REACTOR BASED SYSTEM – 50 MLD BOD REMOVAL							
		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	***130.00***	***160.00***	**190**	**220**	**250**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
REACTION BASINS & ACCESSORIES							
Total bare construction cost	₹	32,11,35,685.19	33,30,70,981.31	34,48,22,744.76	35,64,32,152.90	36,72,07,382.42	37,85,53,008.13
Levelized cost for 25 years of life of reaction basins	₹	28,61,00,296.14	32,02,39,081.52	35,34,31,377.59	38,58,80,972.55	41,76,16,975.69	44,89,94,376.10
Overall cost	₹	60,72,35,981.34	65,33,10,062.83	69,82,54,122.35	74,23,13,125.44	78,48,24,358.11	82,75,47,384.23
REACTOR BASIN WASTE TRANSFER PUMPS AND PUMP-HOUSE							
Total bare construction cost	₹	65,53,134.01	65,70,976.50	65,88,818.99	66,06,661.48	66,24,503.97	66,51,267.71
Levelized cost for 25 years of life of pumps and pump-house	₹	41,48,044.02	45,99,602.84	50,55,090.66	55,13,654.09	59,74,578.51	64,37,910.26
Overall cost	₹	1,07,01,178.02	1,11,70,579.34	1,16,43,909.65	1,21,20,315.57	1,25,99,082.49	1,30,89,177.97
BLOWERS AND BLOWER BUILDING							
Total bare construction cost	₹	7,63,80,712.71	8,22,93,342.90	8,77,73,757.10	9,29,03,341.47	10,16,54,626.87	10,64,71,850.72
ESTIMATED CONSOLIDATED COSTS							
Total bare construction cost	₹	40,40,69,531.91	42,19,35,300.72	43,91,85,320.85	45,59,42,155.85	47,54,86,513.27	49,16,76,126.56
Levelized cost for 25 years of life	₹	29,02,48,340.16	32,48,38,684.37	35,84,86,468.25	39,13,94,626.63	42,35,91,554.20	45,54,32,286.35
Consolidated cost	₹	69,43,17,872.07	74,67,73,985.08	79,76,71,789.10	84,73,36,782.48	89,90,78,067.47	94,71,08,412.91
COST OF LAND							
Cost of land	₹	27,86,53,383.54	27,87,34,383.54	27,88,07,883.54	27,88,73,883.54	27,89,33,883.54	27,89,92,383.54
OVERALL COST							
Overall cost	₹	97,29,71,255.60	1,02,55,08,368.62	1,07,64,79,672.64	1,12,62,10,666.02	1,17,80,11,951.01	1,22,61,00,796.45
Overall cost	Crore ₹	97.30	102.55	107.65	112.62	117.80	122.61
Overall cost	Million USD	12.16	12.82	13.46	14.08	14.73	15.33

Summary of cost response study for 50 mld capacity of WWTP with SBR (continued)

REGRESSION ANALYSIS AND DETERMINATION OF MAPE – 50 MLD
BOD REMOVAL

		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Predicted value (as per exponential cost function)	Crore ₹	97.38	101.86	106.55	111.46	116.59	121.95
Value of R^2		0.9981					
Absolute percentage error		0.09	0.67	1.02	1.04	1.03	0.54
Mean absolute percentage error (MAPE)		0.73					
Predicted value (as per linear cost function)	Crore ₹	97.42	102.48	107.55	112.61	117.68	122.74
Value of R^2		0.9999					
Absolute percentage error		0.13	0.07	0.09	0.01	0.11	0.11
Mean absolute percentage error (MAPE)		0.08					
Predicted value (as per logarithmic cost function)	Crore ₹	95.96	103.18	108.90	113.64	117.67	121.19
Value of R^2		0.9848					
Absolute percentage error		1.38	0.62	1.16	0.90	0.11	1.15
Mean absolute percentage error (MAPE)		0.89					
Predicted value (as per polynomial cost function)	Crore ₹	97.29	102.47	107.59	112.63	117.59	122.49
Value of R^2		1.0000					
Absolute percentage error		0.01	0.08	0.06	0.00	0.18	0.10
Mean absolute percentage error (MAPE)		0.07					
Predicted value (as per power cost function)	Crore ₹	96.42	103.02	108.56	113.37	117.65	121.51
Value of R^2		0.9919					
Absolute percentage error		0.90	0.46	0.85	0.67	0.13	0.90
Mean absolute percentage error (MAPE)		0.65					

Summary of cost response study for 50 mld capacity of WWTP with SBR (continued)

95 % CONFIDENCE INTERVAL FOR MEAN OF ABSOLUTE PERCENTAGE ERROR AS PER SELECTED COST FUNCTION

BOD REMOVAL

		BOD in mg/l	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
		(as per linear cost function)					
Absolute percentage error	%	0.13	0.07	0.09	0.01	0.11	0.11
MAPE	%	0.08					
Standard deviation	%	0.04					
Alpha value for 95% confidence level		0.05					
Confidence		0.03					
Upper limit of MAPE	%	0.12					
Lower limit of MAPE	%	0.05					

Appendix- XVIII

Summary of cost response study for 150 mld capacity of WWTP with SBR

DESIGN SUMMARY FOR SEQUENTIAL BATCH REACTOR BASED SYSTEM – 150 MLD
BOD REMOVAL

		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	**130.00**	**160.00**	**190.00**	**220.00**	**250.00**
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Influent flow rate	m^3/d	173400.00	173400.00	173400.00	173400.00	173400.00	173400.00
Average BOD load	kg/d	26592.00	31092.00	35592.00	40092.00	44592.00	49092.00
Average TKN load	kg/d	5017.42	6022.72	7026.38	8028.40	9029.73	10030.11
Number of reaction basins	number	40	40	40	40	40	40
Fill time	h	3.00	3.00	3.00	3.00	3.00	3.00
Reaction time	h	2.00	2.00	2.00	2.00	2.00	2.00
Design time selected for aeration	h	2.00	2.00	2.00	2.00	2.00	2.00
Settlement time	h	0.50	0.50	0.50	0.50	0.50	0.50
Decantation time	h	0.50	0.50	0.50	0.50	0.50	0.50
Total cycle time	h	6.00	6.00	6.00	6.00	6.00	6.00
Solids residence time - design value	d	33.73	27.86	23.65	20.49	18.04	16.10
Total volume of each reaction basin	m^3	4335.00	4335.00	4335.00	4335.00	4335.00	4335.00
Fill volume per cycle per reaction basin	m^3	1083.75	1083.75	1083.75	1083.75	1083.75	1083.75
Selected value for (fill volume/total volume of reaction basin)	ratio	0.25	0.25	0.25	0.25	0.25	0.25
Decant depth	m	1.02	1.02	1.02	1.02	1.02	1.02
Total liquid depth when full	m	4.07	4.07	4.07	4.07	4.07	4.07
Mixed liquor suspended solids (X_{MLSS})	g/m^3	4000.00	4000.00	4000.00	4000.00	4000.00	4000.00
Mixed liquor volatile suspended solids (X_{MLVSS})	g/m^3	1452.82	1521.77	1576.86	1621.83	1659.17	1690.64
F/M	(g BOD/d)/g VSS	0.11	0.12	0.13	0.14	0.15	0.17

Summary of cost response study for 150 mld capacity of WWTP with SBR (continued)

DESIGN SUMMARY FOR SEQUENTIAL BATCH REACTOR BASED SYSTEM – 150 MLD (continued)
BOD REMOVAL

		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	**130.00**	**160.00**	**190.00**	**220.00**	**250.00**
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Volumetric BOD loading	(kg BOD/d)/m^3	6.13	7.17	8.21	9.25	10.29	11.32
Decant pumping rate	m^3/min	36.13	36.13	36.13	36.13	36.13	36.13
Total TSS purged per day	kg MLSS/d	20563.44	24895.23	29332.43	33852.38	38437.86	43075.76
Observed yield based on VSS	g VSS/g BOD	0.28	0.31	0.33	0.34	0.36	0.37
Observed yield based on TSS	g TSS/g BOD	0.77	0.80	0.83	0.85	0.86	0.88
Oxygen demand per reaction basin	kg oxygen/d	829.56	948.18	1063.61	1176.55	1287.50	1396.86
Total aeration time per day per reaction basin	h	8.00	8.00	8.00	8.00	8.00	8.00
Average oxygen transfer rate per reaction basin	kg oxygen/h	103.70	118.52	132.95	147.07	160.94	174.61
Concentration of BOD in effluent	g/m^3	9.66	9.66	9.66	9.66	9.66	9.66
Concentration of TSS in effluent	g/m^3	10.00	10.00	10.00	10.00	10.00	10.00

Summary of cost response study for 150 mld capacity of WWTP with SBR (continued)

EQUIPMENT SUMMARY FOR SEQUENTIAL BATCH REACTOR BASED SYSTEM – 150 MLD
BOD REMOVAL

		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	**130.00**	**160.00**	**190.00**	**220.00**	**250.00**
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
REACTION BASINS & ACCESSORIES							
Number of reaction basins		40	40	40	40	40	40
Length of each reaction basin	m	116.42	116.42	116.42	116.42	116.42	116.42
Width of each reaction basin	m	9.14	9.14	9.14	9.14	9.14	9.14
Depth of each reaction basin	m	4.57	4.57	4.57	4.57	4.57	4.57
Number of swing arm headers of each reaction basin		187	214	240	266	291	315
REACTION BASIN WASTE TRANSFER PUMPS AND PUMP-HOUSE							
Total number of pumps required		2	2	2	2	2	2
Capacity of each pump	m^3/h	6.00	6.00	6.00	6.00	6.00	6.00
Area required for pump-house	m ^2	63.00	63.00	64.00	64.00	65.00	65.00
BLOWERS AND BLOWER BUILDING							
Total number of blowers required		4	4	5	5	5	2
Capacity of each blower	scfm	14960.00	17099.00	14386.00	15913.00	17413.00	75569.00
Area required for blower building	m ^2	185.00	192.00	197.00	202.00	207.00	211.00

Summary of cost response study for 150 mld capacity of WWTP with SBR (continued)

ESTIMATED COST SUMMARY FOR SEQUENTIAL BATCH REACTOR BASED SYSTEM – 150 MLD
BOD REMOVAL

		BOD in g/m^3 100.00	**BOD in g/m^3 130.00**	**BOD in g/m^3 160.00**	**BOD in g/m^3 190**	**BOD in g/m^3 220**	**BOD in g/m^3 250**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
REACTION BASINS & ACCESSORIES							
Total bare construction cost	₹	1,30,55,77,625.54	1,39,47,95,842.13	1,48,09,89,124.20	1,56,62,85,285.12	1,64,89,35,321.83	1,72,90,83,504.07
Levelized cost for 25 years of life of reaction basins	₹	83,22,09,441.04	93,69,51,617.50	1,03,87,03,779.23	1,13,83,00,229.92	1,23,59,36,793.32	1,33,19,53,233.52
Overall cost	₹	2,13,77,87,066.58	2,33,17,47,459.64	2,51,96,92,903.43	2,70,45,85,515.03	2,88,48,72,115.15	3,06,10,36,737.59
REACTOR BASIN WASTE TRANSFER PUMPS AND PUMP-HOUSE							
Total bare construction cost	₹	67,22,637.68	67,76,165.15	68,29,692.63	68,83,220.10	69,36,747.58	69,90,275.05
Levelized cost for 25 years of life of pumps and pump-house	₹	81,50,686.36	93,91,190.86	1,06,53,327.43	1,19,32,399.08	1,32,24,764.01	1,45,27,625.04
Overall cost	₹	1,48,73,324.04	1,61,67,356.01	1,74,83,020.06	1,88,15,619.18	2,01,61,511.59	2,15,17,900.09
BLOWERS AND BLOWER BUILDING							
Total bare construction cost	₹	16,56,76,313.46	17,85,45,252.76	19,97,74,109.75	21,14,56,117.61	22,24,86,497.20	54,38,57,052.70
ESTIMATED CONSOLIDATED COSTS							
Total bare construction cost	₹	1,47,79,76,576.69	1,58,01,17,260.05	1,68,75,92,926.58	45,59,42,155.85	1,87,83,58,566.61	2,27,99,30,831.83
Levelized cost for 25 years of life	₹	84,03,60,127.40	94,63,42,808.36	1,04,93,57,106.66	39,13,94,626.63	1,24,91,61,557.33	1,34,64,80,858.56
Consolidated cost	₹	2,31,83,36,704.08	2,52,64,60,068.41	2,73,69,50,033.24	2,93,48,57,251.83	3,12,75,20,123.94	3,62,64,11,690.38
COST OF LAND							
Cost of land	₹	80,53,22,992.56	80,54,35,492.56	80,55,37,492.56	80,56,28,992.56	80,57,14,492.56	80,57,93,992.56
OVERALL COST							
Overall cost	Crore ₹	312.37	333.19	354.25	374.05	393.32	443.22
Overall cost	Million USD	39.05	41.65	44.28	46.76	49.17	55.40

Summary of cost response study for 150 mld capacity of WWTP with SBR (continued)

REGRESSION ANALYSIS AND DETERMINATION OF MAPE – 150 MLD
BOD REMOVAL

		BOD in g/m^3 100.00	BOD in g/m^3 130.00	BOD in g/m^3 160.00	BOD in g/m^3 190.00	BOD in g/m^3 220.00	BOD in g/m^3 250.00
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Predicted value (as per exponential cost function)	Crore ₹	310.77	331.97	354.62	378.82	404.66	432.27
Value of R^2		0.9790					
Absolute percentage error		0.51	0.36	0.11	1.28	2.88	2.47
Mean absolute percentage error (MAPE)		1.27					
Predicted value (as per linear cost function)	Crore ₹	307.37	331.78	356.20	380.61	405.03	429.44
Value of R^2		0.9630					
Absolute percentage error		1.60	0.42	0.55	1.75	2.98	3.11
Mean absolute percentage error (MAPE)		1.74					
Predicted value (as per logarithmic cost function)	Crore ₹	301.56	335.74	362.79	385.18	404.28	420.94
Value of R^2		0.9135					
Absolute percentage error		3.46	0.77	2.41	2.98	2.79	5.03
Mean absolute percentage error (MAPE)		2.90					
Predicted value (as per polynomial cost function)	Crore ₹	315.17	329.42	348.52	372.49	401.32	435.01
Value of R^2		0.9840					
Absolute percentage error		0.90	1.13	1.62	0.42	2.03	1.85
Mean absolute percentage error (MAPE)		1.32					

Summary of cost response study for 150 mld capacity of WWTP with SBR (continued)

REGRESSION ANALYSIS AND DETERMINATION OF MAPE – 150 MLD (continued)
BOD REMOVAL

		BOD in g/m^3	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**	**BOD in g/m^3**
		100.00	**130.00**	**160.00**	**190.00**	**220.00**	**250.00**
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Predicted value (as per power cost function)	Crore ₹	305.30	334.97	360.49	383.06	403.44	422.09
Value of R^2		0.9424					
Absolute percentage error		2.26	0.54	1.76	2.41	2.57	4.77
Mean absolute percentage error (MAPE)		2.38					

Summary of cost response study for 150 mld capacity of WWTP with SBR (continued)

95 % CONFIDENCE INTERVAL FOR MEAN OF ABSOLUTE PERCENTAGE ERROR AS PER SELECTED COST FUNCTION

BOD REMOVAL

		BOD in mg/l	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**	**BOD in mg/l**
		100.00	***130.00***	***160.00***	***190.00***	***220.00***	***250.00***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
		(as per linear cost function)					
Absolute percentage error	%	1.60	0.42	0.55	1.75	2.98	3.11
MAPE	%				1.74		
Standard deviation	%				1.15		
Alpha value for 95% confidence level					0.05		
Confidence					0.92		
Upper limit of MAPE	%				2.65		
Lower limit of MAPE	%				0.82		

Appendix- XIX

Sensibility analysis for WWTPs with MBR – small range: Co-efficients for item-wise unit costs

BOD removal: Co-efficients for item-wise unit costs											
		Capacity in mld									
		0.5	***1***	***1.5***	***2***	***2.5***	***3***	***3.5***	***4***	***4.5***	***5***
Items	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Total earthwork required	ft^3	28163.25	31872.51	34688.45	37802.17	41511.43	44327.37	47441.08	51150.35	53956.87	57070.58
Total quantity of RCC	ft^3	11500.51	13202.61	14399.65	15765.04	17467.14	18664.18	20029.57	21731.67	22928.71	24294.10
Total quantity of handrails	ft	345.44	402.40	439.02	482.42	539.38	576.00	619.40	676.36	712.97	756.37
Total area of house or building	ft^2	1347.78	1461.50	1540.78	1604.51	1659.35	1707.52	1750.13	1790.52	1825.29	1860.13
Blower		0.95	1.42	1.80	2.14	2.45	2.74	3.00	3.26	3.50	3.73
Installation man-hour	MH	55.56	55.56	111.11	111.11	166.67	166.67	222.22	222.22	222.22	277.78
Crane requirement for installation	hour	5.56	5.56	11.11	11.11	16.67	16.67	22.22	22.22	22.22	27.78
Pumps		1.48	2.01	2.41	2.67	2.96	3.22	3.41	3.62	3.83	4.02
Diffusers		22.00	44.00	66.00	85.56	107.56	129.56	151.56	171.11	193.11	215.11
Swing arm diffuser headers		2.44	2.44	4.89	4.89	7.33	7.33	9.78	9.78	9.78	12.22
Membrane modules		234.67	352.00	469.33	586.67	704.00	821.33	938.67	1056.00	1173.33	1290.67
Air piping		1400.20	1623.54	1780.03	1903.83	2061.83	2393.62	2729.21	3068.35	3410.86	3756.54
Operation and maintenance material costs	₹ (in lakh)	25.44	31.04	36.68	42.10	47.42	52.51	57.50	62.34	67.02	71.63
Requirement of energy for operation	kwhr/year	81639.72	157752.34	233839.88	309911.16	385970.37	462019.94	538061.52	614096.25	690125.00	766148.43
Requirement of operation & maintenance manpower	MH/year	1840.60	2230.53	2515.25	2747.52	2947.13	3123.98	3283.87	3430.53	3566.50	3693.64
Requirement of chemicals for maintenance											
Sodium hypochlorite	kg/year	1339.55	2115.24	2609.51	3197.58	3973.27	4467.53	5055.61	5831.30	6325.56	6913.64
Citric acid	kg/year	215.46	365.55	403.07	478.12	628.21	665.73	740.78	890.87	928.40	1003.44

Appendix- XX

Sensibility analysis for WWTPs with MBR – medium range: Co-efficients for item-wise unit costs

BOD removal: Co-efficients for item-wise unit costs											
		Capacity in mld									
		5	***10***	***15***	***20***	***25***	***30***	***35***	***40***	***45***	***50***
Items	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Total earthwork required	ft^3	57070.58	86696.64	131246.71	161221.74	191196.76	223585.26	245852.33	274329.13	303577.21	329740.17
Total quantity of RCC	ft^3	24294.10	38535.89	60360.03	73114.29	85868.56	99969.64	113094.01	125332.80	138016.13	148921.29
Total quantity of handrails	ft	756.37	1185.56	1759.65	2154.32	2548.99	2997.90	3282.18	3657.25	4050.41	4371.25
Total area of house or building	ft^2	1860.13	2121.76	2323.40	2495.03	2650.00	2792.68	2927.65	3054.84	3178.69	3296.99
Blower		3.73	5.63	7.19	8.38	9.61	10.77	12.28	13.33	14.35	16.02
Installation man-hour	MH	277.78	500.00	777.78	1000.00	1222.22	1555.56	1833.33	2000.00	2333.33	2500.00
Crane requirement for installation	hour	27.78	50.00	77.78	100.00	122.22	155.56	183.33	200.00	233.33	250.00
Pumps		4.02	5.42	7.62	10.62	13.74	16.97	20.28	23.67	27.12	20.62
Diffusers		215.11	429.00	645.33	855.56	1070.67	1285.78	1496.00	1716.00	1928.67	2141.33
Swing arm diffuser headers		12.22	22.00	34.22	44.00	53.78	68.44	80.67	88.00	102.67	110.00
Membrane modules		1290.67	1936.00	2581.33	3285.33	3989.33	4928.00	5632.00	6336.00	7392.00	8096.00
Air piping		3756.54	7295.75	11062.27	14992.59	18773.79	21635.20	24481.02	27311.34	30182.10	32902.48
Operation and maintenance material costs	₹ (in lakh)	71.63	90.24	109.21	129.01	147.85	173.62	190.64	207.14	233.69	248.12
Requirement of energy for operation	kwhr/year	766148.43	1501601.64	2236805.56	2974578.00	3712230.29	4460707.85	5198184.87	5935593.81	6689324.74	7426621.33
Requirement of operation & maintenance manpower	MH/year	3693.64	4688.95	5580.81	6371.35	7069.13	7728.79	8308.20	8848.28	9389.14	9868.25
Requirement of chemicals for maintenance											
Sodium hypochlorite	kg/year	6913.64	10370.45	13827.27	17543.32	21259.38	26526.81	30124.85	34216.14	39790.22	43037.23
Citric acid	kg/year	1003.44	1505.16	2006.89	2532.21	3057.53	3883.04	4361.16	5036.58	5824.57	6162.28

Appendix- XXI

Sensibility analysis for WWTPs with MBR – large range: Co-efficients for item-wise unit costs

BOD removal: Co-efficients for item-wise unit costs												
		Capacity in mld										
		50	***60***	***70***	***80***	***90***	***100***	***110***	***120***	***130***	***140***	***150***
Items	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Total earthwork required	ft^3	329740.17	385913.08	436827.83	489326.35	542752.30	593756.29	646452.37	699157.85	747453.75	800761.63	851540.99
Total quantity of RCC	ft^3	148921.29	172954.31	198471.00	220686.99	243455.36	268676.18	291196.45	313716.72	333596.12	359841.91	381301.92
Total quantity of handrails	ft	4371.25	5103.32	5761.16	6419.39	7100.23	7735.47	8405.45	9075.43	9636.93	10301.70	10926.78
Total area of house or building	ft^2	3296.99	3522.42	3740.13	3947.84	4149.93	4347.65	4539.74	4729.67	4916.27	5099.48	5280.52
Blower		16.02	17.91	21.77	24.69	26.49	28.18	29.83	33.11	34.69	36.28	37.78
Installation man-hour	MH	2500.00	3000.00	3555.56	4000.00	4444.44	5000.00	5555.56	5833.33	6388.89	7000.00	7333.33
Crane requirement for installation	hour	250.00	300.00	355.56	400.00	444.44	500.00	555.56	583.33	638.89	700.00	733.33
Pumps		20.62	25.45	30.42	35.50	40.68	38.28	42.70	47.33	51.87	56.62	54.82
Diffusers		2141.33	2566.67	2992.00	3422.22	3852.44	4277.78	4705.56	5133.33	5561.11	5984.00	6424.00
Swing arm diffuser headers		110.00	132.00	156.44	176.00	195.56	220.00	244.44	256.67	281.11	308.00	322.67
Membrane modules		8096.00	9504.00	11264.00	12672.00	14549.33	15840.00	17600.00	19360.00	20533.33	22528.00	23936.00
Air piping		32902.48	38211.74	43480.54	48523.93	53610.41	58426.31	63312.82	68132.09	72698.81	77478.29	82013.51
Operation and maintenance material costs	₹ (in lakh)	248.12	277.88	315.93	343.36	381.68	404.08	437.60	470.20	488.84	525.63	548.09
Requirement of energy for operation	kwhr/year	7426621.33	8901076.26	10391753.84	11865913.99	13361797.32	14830272.66	16320495.08	17810631.26	19273385.95	20774291.21	22247826.31
Requirement of operation & maintenance manpower	MH/year	9868.25	10730.43	11703.73	12595.73	13472.96	14279.72	15108.99	15908.26	16641.09	17428.02	18181.55
Requirement of chemicals												
Sodium hypochlorite	kg/year	43037.23	50938.38	60485.73	67917.84	77327.01	84897.30	94187.44	103477.57	108889.26	119518.95	127138.68
Citric acid	kg/year	6162.28	7400.54	8816.74	9867.39	11068.13	12334.23	13647.55	14960.86	15523.71	17052.47	18178.17

Appendix- XXII

Sensibility analysis for small range WWTPs with MBBR: Co-efficients for item-wise unit costs

BOD removal: Co-efficients for item-wise unit costs											
		Capacity in mld									
		0.5	***1***	***1.5***	***2***	***2.5***	***3***	***3.5***	***4***	***4.5***	***5***
Item	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Total earthwork required	ft^3	51251.70	68364.85	85091.27	102246.84	119063.98	121757.32	136768.02	151791.49	166846.54	182539.04
Total quantity of RCC	ft^3	20672.01	25096.98	28861.74	32357.63	35500.15	36346.11	39108.92	41767.39	44366.11	46960.39
Total quantity of handrails	ft	353.22	381.65	405.71	425.40	442.90	460.39	473.52	486.64	499.76	512.89
Total area of house or building	ft^2	2017.32	2118.63	2187.65	2239.93	2285.69	2323.59	2358.17	2389.41	2419.61	2445.23
Clarifier mechanism		1.33	1.78	2.12	2.40	2.64	2.65	2.82	2.99	3.14	3.28
Blower		0.66	1.01	1.30	1.55	1.78	1.99	2.19	2.38	2.56	2.73
Installation man-hour		224.06	293.35	346.89	448.12	487.49	489.06	574.54	602.89	628.08	653.28
Crane requirement for installation		22.41	29.34	34.69	44.81	48.75	48.91	57.45	60.29	62.81	65.33
Pumps		1.72	2.07	2.34	2.45	2.65	2.83	2.91	3.06	3.21	3.27
Diffusers		14.67	29.33	44.00	58.67	73.33	88.00	102.67	117.33	129.56	144.22
Swing arm diffuser headers		2.44	2.44	2.44	4.89	4.89	4.89	7.33	7.33	7.33	7.33
Carrier media		19.33	38.65	57.98	77.30	96.63	115.95	135.28	154.60	173.93	193.25
Air piping		755.14	901.33	999.63	1075.81	1138.88	1193.14	1241.03	1428.94	1633.07	1840.27
Operation and maintenance material costs	₹ (in lakh)	4.32	4.76	5.15	5.56	5.89	5.98	6.28	6.59	6.88	7.16
Requirement of energy for operation	kwhr/year	61912.42	104585.80	147712.42	186447.56	229355.99	271957.17	310525.88	353305.48	396057.88	434580.39
Requirement of operation & maintenance manpower	mh/year	3995.66	4371.09	4650.68	4894.30	5154.74	5279.58	5497.29	5708.54	5901.12	6081.64

Appendix- XXIII

Sensibility analysis for medium range WWTPs with MBBR: Co-efficients for item-wise unit costs

BOD removal: Co-efficients for item-wise unit costs											
		Capacity in mld									
		5	***10***	***15***	***20***	***25***	***30***	***35***	***40***	***45***	***50***
Item	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Total earthwork required	ft^3	182539.04	319628.60	500469.30	673606.16	858182.71	1049189.47	1131017.54	1302030.40	1482594.14	1670735.02
Total quantity of RCC	ft^3	46960.39	71262.17	103693.37	123636.36	143138.52	161863.79	201329.75	224711.58	243569.64	262558.58
Total quantity of handrails	ft	512.89	774.95	1027.71	1113.52	1199.32	1272.00	1579.81	1646.65	1713.50	1774.51
Total area of house or building	ft^2	2445.23	2646.60	2790.20	2908.30	3009.67	3099.93	3182.42	3259.35	3331.83	3401.05
Clarifier mechanism		3.28	4.23	5.04	5.68	6.25	6.75	9.51	11.37	11.96	12.51
Blower		2.73	4.18	5.37	6.42	7.36	8.06	8.86	9.63	10.35	11.05
Installation man-hour		653.28	988.45	1360.28	1594.23	1926.68	2135.43	2736.75	3188.45	3468.50	3742.26
Crane requirement for installation		65.33	98.85	136.03	159.42	192.67	213.54	273.67	318.85	346.85	374.23
Pumps		3.27	4.18	4.86	5.41	6.13	6.56	7.14	8.18	9.37	10.45
Diffusers		144.22	289.67	435.11	576.89	723.56	865.33	1012.00	1151.33	1298.00	1444.67
Swing arm diffuser headers		7.33	14.67	24.44	29.33	39.11	44.00	51.33	58.67	66.00	73.33
Carrier media		193.25	386.51	579.76	773.01	966.26	1159.52	1352.77	1546.02	1739.27	1932.53
Air piping		1840.27	4037.92	6394.30	8860.04	11410.45	14030.41	16709.68	18691.54	20558.99	22387.05
Operation and maintenance material costs	₹ (in lakh)	7.16	9.81	12.77	14.70	16.62	18.38	22.48	25.28	27.00	28.69
Requirement of energy for operation	kwhr/year	434580.39	849307.42	1264410.66	1679848.32	2095008.13	2509842.82	2924515.63	3339043.73	3753470.46	4167761.83
Requirement of operation & maintenance manpower	mh/year	6081.64	7393.21	8877.36	10077.34	11253.78	12284.83	13267.17	14206.20	15129.52	15979.52

Appendix- XXIV

Sensibility analysis for large range WWTPs with MBBR: Co-efficients for item-wise unit costs

BOD removal: Co-efficients for item-wise unit costs												
		Capacity in mld										
		50	***60***	***70***	***80***	***90***	***100***	***110***	***120***	***130***	***140***	***150***
Item	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Total earthwork required	ft^3	1670735.02	2050285.40	2461422.75	2569515.38	2939069.63	3295193.52	3322812.27	3678163.40	4039606.58	4415783.25	4779338.81
Total quantity of rcc	ft^3	262558.58	298571.61	344776.95	405199.64	442072.93	501116.76	512950.36	547702.33	582099.52	627738.67	660546.59
Total quantity of handrails	ft	1774.51	1890.71	2269.74	2377.18	2477.34	2863.66	2965.27	3049.39	3142.26	3534.41	3621.44
Total area of house or building	ft^2	3401.05	3529.35	3648.82	3761.63	3867.71	3970.52	4067.71	4162.68	4255.49	4346.01	4436.73
Clarifier mechanism		12.51	13.50	14.42	20.13	21.17	25.01	25.24	26.20	27.13	27.99	28.81
Blower		11.05	12.83	14.12	16.04	17.25	18.41	21.57	22.71	24.97	26.09	27.18
Installation man-hour		3742.26	4270.87	4897.99	6024.15	6673.32	7484.51	7800.09	8544.62	9005.07	9397.38	9894.49
Crane requirement for installation		374.23	427.09	489.80	602.41	667.33	748.45	780.01	854.46	900.51	939.74	989.45
Pumps		10.45	12.66	15.02	17.34	19.78	22.19	24.69	27.18	29.73	22.24	24.07
Diffusers		1444.67	1730.67	2014.22	2307.56	2591.11	2884.44	3165.56	3458.89	3740.00	4033.33	4326.67
Swing arm diffuser headers		73.33	88.00	107.56	117.33	136.89	146.67	158.89	183.33	195.56	205.33	220.00
Carrier media		1932.53	2319.03	2705.54	3092.04	3478.55	3865.05	4251.56	4638.06	5024.57	5411.07	5797.58
Air piping		22387.05	25942.68	29386.06	32736.16	36006.81	39208.44	42349.23	45435.74	48473.32	51466.43	54418.85
Operation and maintenance material costs	₹ (in lakh)	28.69	31.87	35.47	42.41	45.57	51.43	52.90	55.88	58.75	61.04	63.70
Requirement of energy for operation	kwhr/year	4167761.8	4996504.5	5825368.5	6653924.0	7482318.2	8310484.5	9135978.6	9963726.3	10791409.93	11618856.36	12450439.42
Requirement of operation & maintenance manpower	mh/year	15979.52	17560.62	19068.40	20463.93	21808.78	23074.02	23754.52	24896.02	26015.08	27067.49	27990.01

Appendix- XXV

Sensibility analysis for small range WWTPs with SBR: Co-efficients for item-wise unit costs

BOD removal: Co-efficients for item-wise unit costs											
		Capacity in mld									
		0.5	***1***	***1.5***	***2***	***2.5***	***3***	***3.5***	***4***	***4.5***	***5***
Item	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Total earthwork required	ft^3	31695.07	45700.54	59706.00	73720.87	87726.34	101731.80	115737.27	129752.14	143757.60	157763.07
Total quantity of RCC	ft^3	11151.75	17004.34	22856.93	28709.51	34562.10	40414.68	46267.27	52119.86	57972.44	63825.03
Total quantity of handrails	ft	308.10	477.86	647.62	817.39	987.15	1156.91	1326.68	1496.44	1666.20	1835.97
Total area of house or building	ft^2	1396.34	1520.78	1605.23	1670.85	1724.18	1770.85	1811.96	1849.80	1883.14	1914.25
Blower		1.17	1.80	2.31	2.76	3.17	3.55	3.90	4.24	4.55	4.86
Installation man-hour	MH	111.11	166.67	277.78	333.33	444.44	500.00	611.11	666.67	777.78	833.33
Crane requirement for installation	hour	11.11	16.67	27.78	33.33	44.44	50.00	61.11	66.67	77.78	83.33
Pumps		0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58
Diffusers		73.33	146.67	220.00	293.33	366.67	440.00	513.33	586.67	660.00	733.33
Swing arm diffuser headers		4.89	7.33	12.22	14.67	19.56	22.00	26.89	29.33	34.22	36.67
Decanters		353.22	706.44	1059.67	1412.89	1766.11	2119.33	2472.56	2825.78	3179.00	3532.22
Air piping		958.97	1144.61	1358.08	1881.77	2423.45	2979.90	3548.95	4129.00	4718.85	5317.55
Operation and maintenance material costs	₹ (in lakh)	3.38	4.28	5.19	6.11	7.02	7.86	8.70	9.48	10.28	11.02
Requirement of energy for operation	kwhr/year	87902.38	175801.56	263699.53	351596.72	439493.33	527389.48	615285.25	703180.68	791075.83	878970.72
Requirement of operation & maintenance manpower	mh/year	1393.07	1748.76	2004.50	2211.57	2388.73	2545.26	2686.51	2815.89	2958.28	3104.31

Appendix- XXVI

Sensibility analysis for medium range WWTPs with SBR: Co-efficients for item-wise unit costs

BOD removal: Co-efficients for item-wise unit costs

		Capacity in mld									
		5	***10***	***15***	***20***	***25***	***30***	***35***	***40***	***45***	***50***
Item	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Total earthwork required	ft^3	157763.07	280167.90	455655.41	561229.81	680183.58	797581.55	914025.86	1024985.76	1141046.83	1256802.41
Total quantity of RCC	ft^3	63825.03	114667.48	188592.26	233084.06	282604.49	331459.74	379882.23	426505.15	474712.01	522746.14
Total quantity of handrails	ft	1835.97	3224.68	5318.08	6343.68	7625.13	8879.64	10116.18	11216.08	12441.19	13658.39
Total area of house or building	ft^2	1914.25	2003.20	2296.86	2250.13	2448.24	2469.35	2486.08	2589.61	2604.05	2729.93
Blower		4.86	5.80	9.36	8.71	12.11	12.48	12.77	14.63	14.91	18.19
Installation man-hour	MH	833.33	1666.67	5000.00	6666.67	12638.89	15111.11	17500.00	26888.89	30000.00	41888.89
Crane requirement for installation	hour	83.33	166.67	500.00	666.67	1263.89	1511.11	1750.00	2688.89	3000.00	4188.89
Pumps		0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58
Diffusers		733.33	1466.67	4400.00	5866.67	11002.44	13200.00	15400.00	23460.56	26400.00	36655.67
Swing arm diffuser headers		36.67	73.33	220.00	293.33	556.11	664.89	770.00	1183.11	1320.00	1843.11
Decanters		3532.22	7064.44	10596.67	14128.89	17661.11	21193.33	24725.56	28257.78	31790.00	35322.22
Air piping		5317.55	7368.09	18025.69	16167.11	24050.83	25018.52	25765.07	30794.27	31570.00	38593.68
Operation and maintenance material costs	₹ (in lakh)	11.02	16.45	26.14	29.71	37.57	41.88	45.97	54.03	58.15	67.25
Requirement of energy for operation	kwhr/year	878970.72	1171952.15	2636836.53	2343861.89	3766874.31	3955213.00	4101698.48	5113776.53	5273577.82	6760953.49
Requirement of operation & maintenance manpower	mh/year	3104.31	3546.18	5217.29	4928.16	6211.37	6362.58	6477.88	7227.02	7338.73	8311.36

Appendix- XXVII

Sensibility analysis for large range WWTPs with SBR: Co-efficients for item-wise unit costs

BOD removal:Co-efficients for item-wise unit costs												
		Capacity in mld										
		50	***60***	***70***	***80***	***90***	***100***	***110***	***120***	***130***	***140***	***150***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Total earthwork required	ft^3	1256802.41	1486098.29	1717081.73	1948240.78	2179452.92	2412365.94	2646438.53	2878731.35	3114369.15	3347434.76	3584612.78
Total quantity of RCC	ft^3	522746.14	618349.05	714048.11	810200.40	905773.74	1002424.88	1099430.52	1195152.26	1292576.35	1388440.19	1486272.10
Total quantity of handrails	ft	13658.39	16002.75	18412.96	20764.92	23159.12	25516.73	27880.61	30263.19	32629.61	35006.53	37375.07
Total area of house or building	ft^2	2729.93	2814.64	2834.71	2909.35	3005.29	3066.60	3124.64	3200.52	3251.90	3263.07	3312.22
Blower		18.19	22.11	22.59	25.64	28.20	29.93	33.30	35.67	37.28	37.66	39.23
Installation man-hour	MH	41888.89	60000.00	70000.00	93333.33	120111.11	150222.22	183666.67	220444.44	260666.67	280000.00	325000.00
Crane requirement for installation	hour	4188.89	6000.00	7000.00	9333.33	12011.11	15022.22	18366.67	22044.44	26066.67	28000.00	32500.00
Pumps		0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58
Diffusers		36655.67	52780.44	61578.00	82107.67	105557.22	131973.11	161272.22	193536.44	228721.78	246312.00	285904.67
Swing arm diffuser headers		1843.11	2640.00	3080.00	4106.67	5284.89	6609.78	8081.33	9699.56	11469.33	12320.00	14300.00
Decanters		35322.22	42386.67	49451.11	56515.56	63580.00	70644.44	77708.89	84773.33	91837.78	98902.22	105966.67
Air piping		38593.68	43817.18	45124.68	50269.04	57227.03	62073.18	66837.79	73387.65	77955.25	79030.88	83564.56
Operation and maintenance material costs	₹ (in lakh)	67.25	80.79	89.43	104.09	119.77	136.02	153.05	170.99	189.56	199.41	218.98
Requirement of energy for operation	kwhr/year	6760953.4	7910283.2	8203248.9	9375109.1	11005517.0	12169530.3	13335162.4	14969750.2	16130475.0	16406202.4	17578042.5
Requirement of operation & maintenance manpower	mh/year	8311.36	8996.18	9163.22	9805.30	10639.82	11201.11	11738.91	12457.92	12946.77	13060.50	13534.35

JOURNAL PAPER

Publication in Scopus-indexed Journal

Journal	Details	Year	Title
Global NEST Journal	Vol 25, No 8, pp 146-155	2023	Development of cost functions for biological treatment by membrane bioreactor
Journal of The Institution of Engineers (India): Series A - a Springer Journal	https://doi.org/10.1007/s40030-023-00751-8	2023	Integrated Cost Functions for Biological Treatment by Moving Bed Biofilm Reactor in Wastewater Treatment Plant
JOURNAL of ENVIRONMENTAL ENGINEERING & LANDSCAPE MANAGEMENT	https://doi.org/10.3846/jeelm.2024.22305	2024	DEVELOPMENT OF COST FUNCTIONS FOR WASTEWATER TREATMENT BY SEQUENTIAL BATCH REACTOR

Publication in Scopus-indexed Journal

Global NEST Journal, Vol 25, No 8, pp 146-155
Copyright© 2023 Global NEST
Printed in Greece. All rights reserved

Development of cost functions for biological treatment by membrane bioreactor

Bhaskar Sengupta* and Somnath Mukherjee
Environmental Engineering Division, Department of Civil Engineering, Jadavpur University, Kolkata - 700032, India

Received: 29/10/2022, Accepted: 01/07/2023, Available online: 10/08/2023

*to whom all correspondence should be addressed: e-mail: senguptabhaskar1962@yahoo.co.in, senguptabhaskar1962@gmail.com

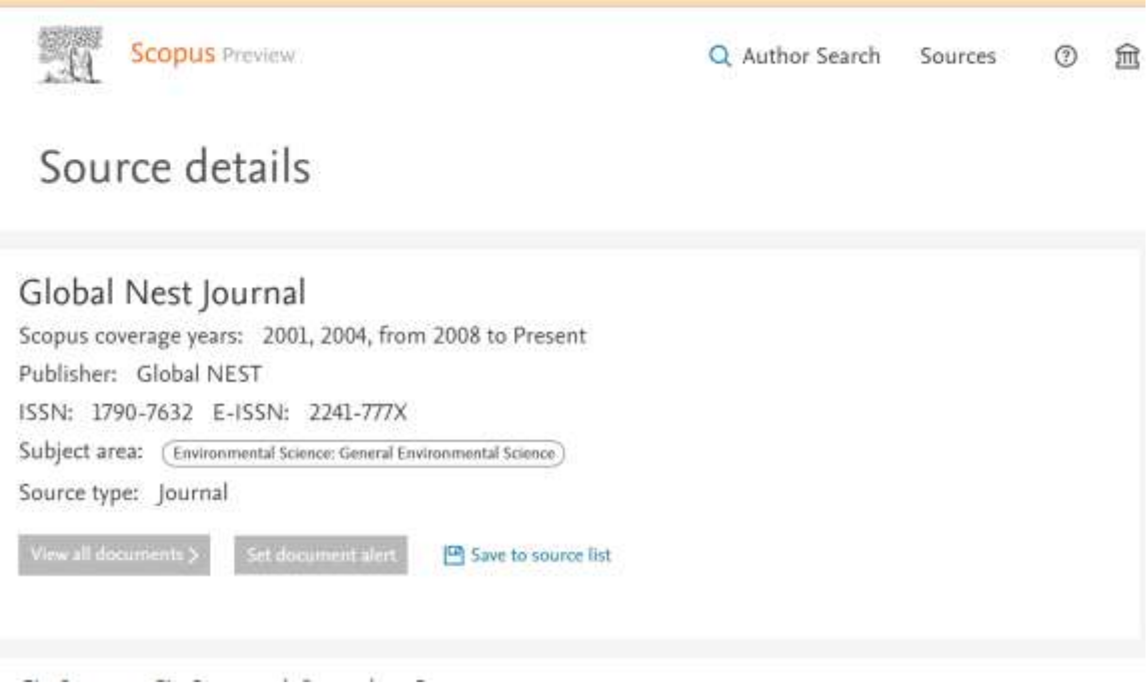
https://doi.org/10.30955/gnj.004537

Graphical abstract

1. Introduction

1.1. Background of the study

Growth of industries across the developing countries has



Source details

Global Nest Journal

Scopus coverage years: 2001, 2004, from 2008 to Present

Publisher: Global NEST

ISSN: 1790-7632 E-ISSN: 2241-777X

Subject area: Environmental Science: General Environmental Science

Source type: Journal

Publication in Scopus-indexed Journal

J. Inst. Eng. India Ser. A
https://doi.org/10.1007/s40030-023-00751-8

ORIGINAL CONTRIBUTION

Integrated Cost Functions for Biological Treatment by Moving Bed Biofilm Reactor in Wastewater Treatment Plant

Bhaskar Sengupta[1] · Somnath Mukherjee[1]

Received: 24 February 2023 / Accepted: 18 July 2023

Abstract This paper presents the methodology for the determination of integrated cost functions to estimate the forecast level cost for biological treatment of wastewater by use of Moving Bed Biofilm Reactor–one of the space-saving wastewater treatment options for improvement of local infrastructure. The cost functions developed are useful for inflows over a broad range and have been derived based on process design and cost estimation but not on collection of historic cost data. The same have been validated by

Keywords Cost function · Determination coefficient · Mean absolute percentage error · Moving bed biofilm reactor · Regression analysis

Introduction

Background of the study

Source details

Journal of the Institution of Engineers (India): Civil Engineering Division

Scopus coverage years: from 1970 to 1990, 1992, from 1994 to 2011

(coverage discontinued in Scopus)

Publisher: Institution of Engineers (India)

ISSN: 0373-1995

Subject area: Engineering: Civil and Structural Engineering · Engineering: Building and Construction

Source type: Journal

Publication in Scopus-indexed Journal

ISSN: 1648-6897 / eISSN: 1822-4199

VILNIUS TECH
Vilniaus Gedimino Technikos Universitetas

JOURNAL of
ENVIRONMENTAL ENGINEERING
& LANDSCAPE MANAGEMENT

2024
Volume 32
Issue 4
Pages 339–356
https://doi.org/10.3846/jeelm.2024.22305

DEVELOPMENT OF COST FUNCTIONS FOR WASTEWATER TREATMENT BY SEQUENTIAL BATCH REACTOR

Bhaskar SENGUPTA✉, Abhisek ROY, Somnath MUKHERJEE

Environmental Engineering Division, Department of Civil Engineering, Jadavpur University, Kolkata, India

Highlights:

- the cost functions for WWTPs with SBR for small, **medium and large capacities are best expressed by polynomial equations;**
- the determination coefficient in respect of cost functions developed for small, medium and large capacities are 1, 0.9886 and 0.9975 respectively;
- the values of Mean Absolute Percentage Error with reference to the cost functions for small, medium and large capacities are 0.32%, 5.35% and 1.68% respectively. In each case, the value of Mean Absolute Percentage Error is found to be within 10%;
- cost functions have been developed based on detail engineering design and cost estimations with due consideration of rates applicable in India. The cost functions are not derived from collected historic cost data-base;
- the approach as adopted and addressed may be followed to develop cost functions applicable for any location in any country across the world either based on use of design & estimation algorithms developed and region specific schedule of rates for precise forecast or adjustment of projected costs by use of applicable factor for conversion of currency.

Article History:

- received 09 January 2024
- accepted 17 June 2024

Abstract. Sequential batch reactor is widely used for industrial wastewater treatment. To consider sequential batch reactor for biological treatment of wastewater at a specific site, it is essential to ensure economy and sustainability. An approach for scrutiny of economic aspects may be based upon use of cost functions to compare sequential batch reactor and other technologies. Such approach will enable to conduct prudent analysis and select the most economic treatment scheme for a particular project. In most of published studies, the cost functions for conventional wastewater treatment systems are described with historic or some other data available to the investigators. No detailed engineering exercise related to cost functions for sequential batch reactor is cited in earlier research studies. In this document the novel and appropriate methodology has been presented to develop cost functions based on engineering, estimation and statistical approach to forecast cost for sequential batch reactor based wastewater treatment system.

Keywords: cost function, mean absolute percentage error, capacity in mld, SBR, regression analysis, wastewater treatment.

✉Corresponding author. E-mails: *senguptabhaskar1962@yahoo.co.in; senguptabhaskar1962@gmail.com*

Source details

Journal of Environmental Engineering and Landscape Management

Open Access

Years currently covered by Scopus: from 2004 to 2025

Publisher: Vilnius Gediminas Technical University

ISSN: 1648-6897 E-ISSN: 1822-4199

Subject area: Environmental Science: Nature and Landscape Conservation; Environmental Science: Environmental Engineering; Environmental Science: Management, Monitoring, Policy and Law

Source type: Journal

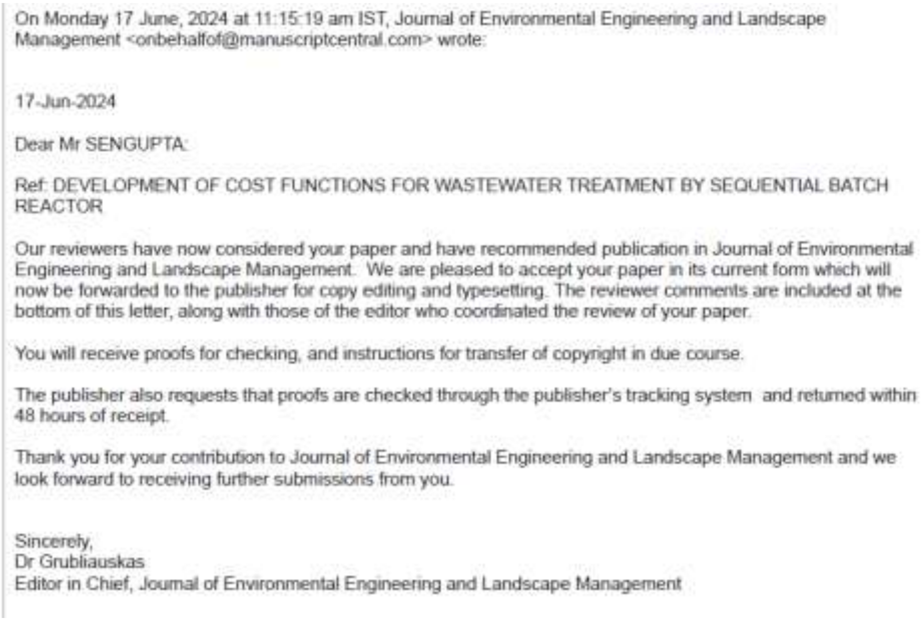
CiteScore 2023
1.9

SJR 2023
0.277

SNIP 2023
0.373

Publication Accepted and under progress in Scopus and WoS indexed Journal (SCI)

Journal	Details	Title	Remarks
Journal of Environmental Engineering and Landscape Management	Manuscript ID JEELM-2023-0012	Development of Cost Functions for Biological Treatment by Sequential Batch Reactor in Wastewater Treatment Plant	Paper accepted. Publication under progress.



On Monday 17 June, 2024 at 11:15:19 am IST, Journal of Environmental Engineering and Landscape Management <onbehalfof@manuscriptcentral.com> wrote:

17-Jun-2024

Dear Mr SENGUPTA:

Ref: DEVELOPMENT OF COST FUNCTIONS FOR WASTEWATER TREATMENT BY SEQUENTIAL BATCH REACTOR

Our reviewers have now considered your paper and have recommended publication in Journal of Environmental Engineering and Landscape Management. We are pleased to accept your paper in its current form which will now be forwarded to the publisher for copy editing and typesetting. The reviewer comments are included at the bottom of this letter, along with those of the editor who coordinated the review of your paper.

You will receive proofs for checking, and instructions for transfer of copyright in due course.

The publisher also requests that proofs are checked through the publisher's tracking system and returned within 48 hours of receipt.

Thank you for your contribution to Journal of Environmental Engineering and Landscape Management and we look forward to receiving further submissions from you.

Sincerely,
Dr Grubliauskas
Editor in Chief, Journal of Environmental Engineering and Landscape Management

Source details

Journal of Environmental Engineering and Landscape Management
Open Access
Scopus coverage years: from 2004 to Present
Publisher: Vilnius Gediminas Technical University
ISSN: 1648-6897 E-ISSN: 1822-4199
Subject area: Environmental Science: Nature and Landscape Conservation; Environmental Science: Environmental Engineering; Environmental Science: Management, Monitoring, Policy and Law
Source type: Journal

BOOK CHAPTER

Under progress for publication as a <u>BOOK CHAPTER</u> of Proceedings of the ***International Conference, ICPCCE-2023 by <u>Springer</u>***

INTERNATIONAL CONFERENCE
ON
POLLUTION CONTROL FOR CLEAN ENVIRONMENT
(ICPCCE-2023)

15 -16 December 2023
Indian Institute of Technology Bhubaneswar, Odisha, India

CERTIFICATE OF PARTICIPATION

Presented to

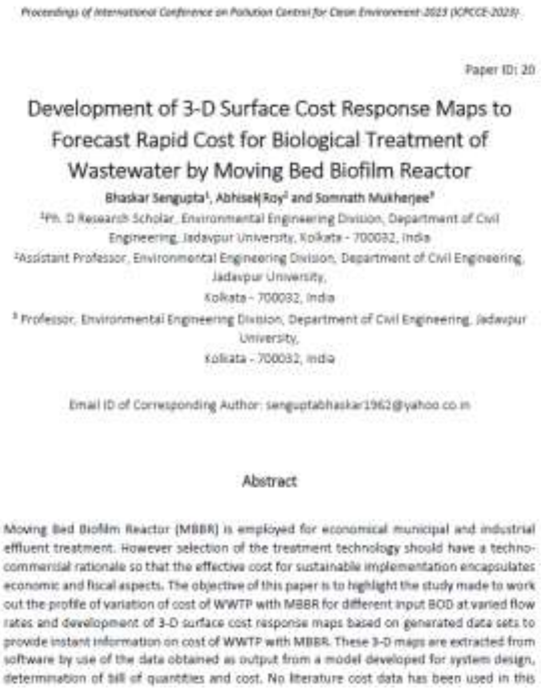
Bhaskar Sengupta

for her/his conference oral presentation entitled

"Development of 3-D Surface Cost Response Maps to Forecast Rapid Cost for Biological Treatment of Wastewater by Moving Bed Biofilm Reactor"

Dr. Manaswini Behera Co-Convener, ICPCCE 2023	Dr. Sankarsan Mohapatro Co-Convener, ICPCCE 2023	Prof. Rajesh Roshan Dash Convener, ICPCCE 2023

Springer



Proceedings of International Conference on Pollution Control for Clean Environment 2023 (ICPCCE-2023)

Paper ID: 20

Development of 3-D Surface Cost Response Maps to Forecast Rapid Cost for Biological Treatment of Wastewater by Moving Bed Biofilm Reactor

Bhaskar Sengupta[1], Abhisek Roy[2] and Somnath Mukherjee[3]

[1]Ph. D Research Scholar, Environmental Engineering Division, Department of Civil Engineering, Jadavpur University, Kolkata - 700032, India

[2]Assistant Professor, Environmental Engineering Division, Department of Civil Engineering, Jadavpur University,
Kolkata - 700032, India

[3] Professor, Environmental Engineering Division, Department of Civil Engineering, Jadavpur University,
Kolkata - 700032, India

Email ID of Corresponding Author: senguptabhaskar1962@yahoo.co.in

Abstract

Moving Bed Biofilm Reactor (MBBR) is employed for economical municipal and industrial effluent treatment. However selection of the treatment technology should have a techno-commercial rationale so that the effective cost for sustainable implementation encapsulates economic and fiscal aspects. The objective of this paper is to highlight the study made to work out the profile of variation of cost of WWTP with MBBR for different input BOD at varied flow rates and development of 3-D surface cost response maps based on generated data sets to provide instant information on cost of WWTP with MBBR. These 3-D maps are extracted from software by use of the data obtained as output from a model developed for system design, determination of bill of quantities and cost. No literature cost data has been used in this

Under progress for publication as a <u>BOOK CHAPTER</u> of Proceedings of the ***International Conference, SATEM - 2023 by <u>Springer</u>***

Indian Institute of Engineering Science and Technology, Shibpur

SATEM - 2023

Certificate of Paper Presentation

This is to certify that ***Bhaskar Sengupta*** of Jadavpur University has presented the paper titled ***Methodology for Development of Cost Response Maps for Wastewater Treatment by Membrane Bioreactor*** in the

"1ST INTERNATIONAL CONFERENCE ON SUSTAINABLE ADVANCED TECHNOLOGIES FOR ENVIRONMENTAL MANAGEMENT (SATEM – 2023)"

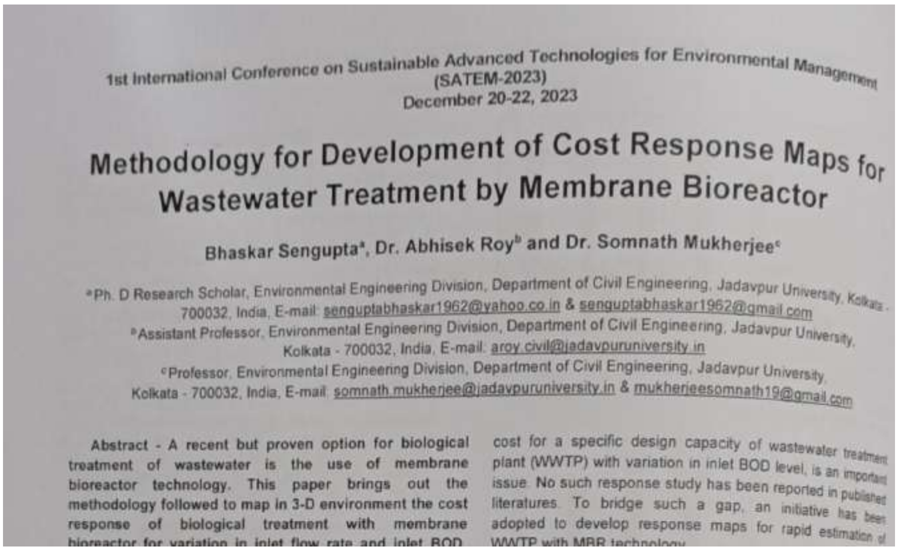
Organized by

Department of Civil Engineering

December 20-22, 2023

(Prof. D. Mazumder)
Executive Chairman, SATEM-2023

(Prof. S. Chattopadhyay)
Coordinator, CEP Cell, IIEST-S



1st International Conference on Sustainable Advanced Technologies for Environmental Management
(SATEM-2023)
December 20-22, 2023

Methodology for Development of Cost Response Maps for Wastewater Treatment by Membrane Bioreactor

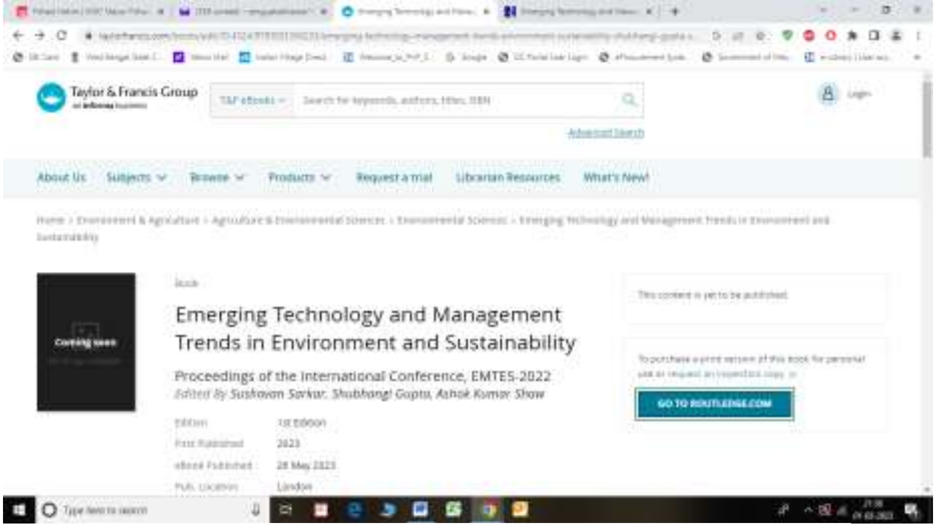
Bhaskar Sengupta[a], Dr. Abhisek Roy[b] and Dr. Somnath Mukherjee[c]

[a]Ph. D Research Scholar, Environmental Engineering Division, Department of Civil Engineering, Jadavpur University, Kolkata - 700032, India, E-mail: senguptabhaskar1962@yahoo.co.in & senguptabhaskar1962@gmail.com
[b]Assistant Professor, Environmental Engineering Division, Department of Civil Engineering, Jadavpur University, Kolkata - 700032, India, E-mail: aroy.civil@jadavpuruniversity.in
[c]Professor, Environmental Engineering Division, Department of Civil Engineering, Jadavpur University, Kolkata - 700032, India, E-mail: somnath.mukherjee@jadavpuruniversity.in & mukherjeesomnath19@gmail.com

Abstract - A recent but proven option for biological treatment of wastewater is the use of membrane bioreactor technology. This paper brings out the methodology followed to map in 3-D environment the cost response of biological treatment with membrane bioreactor for variation in inlet flow rate and inlet BOD cost for a specific design capacity of wastewater treatment plant (WWTP) with variation in inlet BOD level, is an important issue. No such response study has been reported in published literatures. To bridge such a gap, an initiative has been adopted to develop response maps for rapid estimation of WWTP with MBR technology.

CONFERENCE PAPER PRESENTED

Paper presentation in International Conferences & publication		
Conference	***Date***	***Title***
Emerging Technology and Management Trends in Environment and Sustainability (EMTES 2022)	***29 to 30 November 2022***	***Development of Cost Functions for Construction of Wastewater Treatment Plant with State-of-the-Art Technology*** ***[Published as a BOOK CHAPTER of Proceedings of the International Conference, EMTES 2022 by Environmental Science – CRC Press - Taylor & Francis Group]***
3rd International Conference on Advanced Technologies for Industrial Pollution Control (ATIPC 2022)	***21 to 23 December 2022***	***Importance of Cost Functions for Biological Treatment of Wastewater*** ***[Published as a BOOK CHAPTER of Proceedings of ATIPC 2022 by Springer in Earth and Environmental Sciences]***



Home › Environment & Agriculture › Agriculture & Environmental Sciences › Environmental Sciences › Emerging Technology and Management Trends in Environment and Sustainability

Book

Emerging Technology and Management Trends in Environment and Sustainability

Proceedings of the International Conference, EMTES-2022

Edited By Sushovan Sarkar, Shubhangi Gupta, Ashok Kumar Shaw

Edition: 1st Edition
First Published: 2023
eBook Published: 28 May 2023
Pub. Location: London

This content is yet to be published

To purchase a print version of this book for personal use or request an inspection copy >>

CHAPTER 2

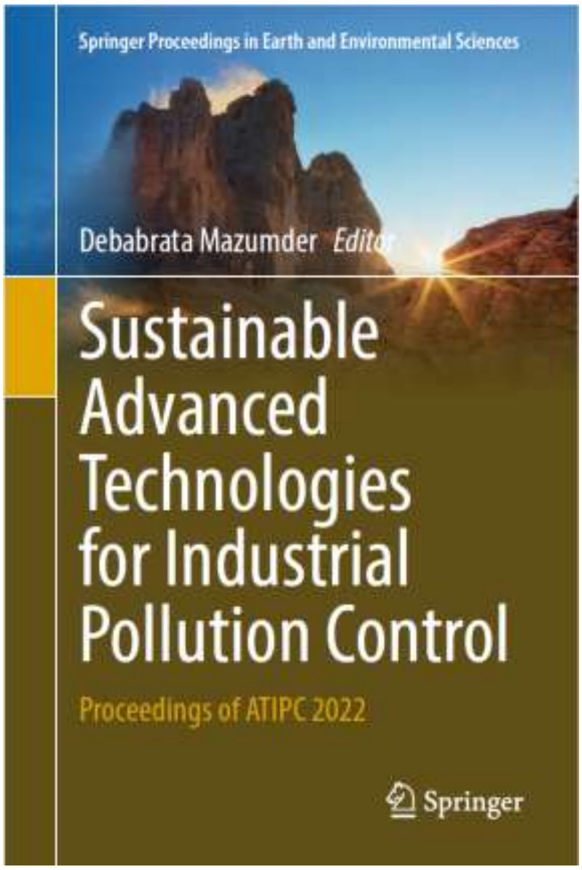
Development of Cost Functions for Construction of Wastewater Treatment Plant with State-of-the-Art Technology

Bhaskar Sengupta[1]
Ph. D Research Scholar, Environmental Engineering Division,
Department of Civil Engineering, Jadavpur University, Kolkata, India
Somnath Mukherjee[2]
Professor, Environmental Engineering Division, Department of Civil Engineering,
Jadavpur University, Kolkata, India

Abstract

The availability of many conventional and updated technological options for biological treatment of municipal and industrial wastewater often leads to the selection of inappropriate

BOOK CHAPTER of Proceedings of ATIPC 2022 by Springer



Importance of Cost Functions for Biological Treatment of Wastewater

Bhaskar Sengupta and Somnath Mukherjee

Abstract The availability of many technological alternatives for the biological treatment of wastewater, ranging from conventional treatment options to advanced technologies, introduces the requirement for scrutiny to select the most appropriate technology for the treatment of wastewater for any specific project. Use of cost function may be an approach to compare the costs of alternatives for the biological treatment of wastewater. It enables better engineering decisions and suitable selection of the appropriate treatment scheme based on parametric criteria, requirement of space, construction cost and annual cost of operation as well as maintenance. The literatures available in the context of selection of appropriate technology for biological treatment of wastewater on the basis of engineering economics and other issues are limited, and in most of the studies, the cost functions for wastewater treatment plants have been derived from region-specific historic cost data collected. The objective of this paper is to highlight the importance of initiatives to develop the cost functions and present a methodology for its development by the application of modelled algorithms for process design as well as cost estimation and the use of different statistical regression techniques. This research initiative is believed to be useful in the planning of new facilities by the stakeholders of assets.

Keywords Biological treatment · CAPEX · Cost function · Cost estimation · Methodology · OPEX · Regression · Space saving · Wastewater · WWTP

Abbreviations

ASP	Activated sludge process
BOD_5	Five-day biochemical oxygen demand
BOD_u	Ultimate biochemical oxygen demand

B. Sengupta (✉) · S. Mukherjee
Environmental Engineering Division, Department of Civil Engineering, Jadavpur University, Kolkata, India
e-mail: somnath.mukherjee@jadavpuruniversity.in

63

D. Mazumder (ed.), *Sustainable Advanced Technologies for Industrial Pollution Control*, Springer Proceedings in Earth and Environmental Sciences,
https://doi.org/10.1007/978-3-031-37596-5_6