Life cycle cost analysis of wastewater treatment technologies

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Abstract. With the ever-increasing population, volumes of wastewater treatment are a major concern in our country. The Activated Sludge Process (ASP), Biological Filtration and Oxygenated Reactor (BIOFOR), Upflow Anaerobic Sludge Blanket (UASB), and Moving Bed Bio Reactor (MBBR) are all monetarily investigated in the present study using the Life Cycle Cost Assessment (LCCA) tool. In this study, life cycle costing is done using the present value method, which involves discounting the costs for a 20-year economic life. The costs of treating wastewater per million litres per day (MLD) of wastewater treatment technology are obtained from the literature. Moreover, this study takes into account the capital, annual operation, energy, salvage, and replacement costs to compare the life cycle costs of ASP, UASB, BIOFOR, and MBBR to make the best guess of an economical technology. The LCCA demonstrates that the MBBR has the highest costs of treatment, resulting in the highest Life Cycle Cost (LCC). BIOFOR has the largest energy requirement making LCC the second-highest among the technologies. In India, ASP is one of the most widely used technologies, whose LCC is the third most advanced of the four technologies. Because of its lower energy and operating costs, UASB has the lowest LCC.

Keywords. Life Cycle Cost Assessment (LCCA), Life Cycle Cost (LCC), Wastewater Treatment Technology, Activated Sludge Process (ASP), Upflow Anaerobic Sludge Blanket (UASB), Moving Bed Bio Reactor (MBBR).

1. Introduction
Water supply and sanitation are vital commodities. The wastewater generation will increase with an increase in population. From a sustainability point of view, wastewater should be treated and reused to meet future water demands. Apparently, there is a need for proper infrastructure for wastewater treatment to meet the non-potable water quality standards. There are numerous technologies available...
and being used for the treatment of wastewater [1]. The wastewater treatment plant is a costly affair requiring skilled personnel, expensive units, etc.

The choice of method to treat wastewater is dependent on many factors like process dependability, land area requirement, influent standards, process complexity, required grade of treated wastewater, cost of treatment, environmental concerns, etc. All these aspects need to be assessed and weighed against cost considerations [2]. To evaluate the best option considering the economic aspects of wastewater treatment Life Cycle Cost Analysis is done in the present study.

Life Cycle Cost Assessment (LCCA) analyses the treatment methodologies throughout its life taking into account the costs. The LCCA tool is used to determine the optimum solution in terms of the lowest life-cycle cost, which encompasses project capital expenditures, operations, maintenance, repair, replacement, and disposal costs [3]. It is often utilized to choose the best system, guaranteeing that perhaps the alternative preferred has a reduced average ownership cost while still ensuring adequate quality and functionality.

The current study compares four technologies, ASP, UASB, BIOFOR, and MBBR, to determine which is the most cost-effective option to choose in given conditions. Among the most widely used technologies in sewage treatment plants are ASP, UASB, and MBBR [4]. BIOFOR is a relatively new technology that is being implemented in a few places such as Delhi, India [5][6]. This research will provide a comprehensive analysis of BIOFOR to the other three methods. All costs and other data for treating 1 MLD of wastewater are considered to compare on a single platform. The technologies are classified based on their effluent quality after treatment performance. A comparison of their energy costs and area requirements per MLD is performed so that a correct decision can be made in the field. With the guidance of the present study, a judgment on an optimal wastewater treatment process can be reached.

2. Wastewater Treatment Technologies
While there are several treatment technologies adopted for sewage treatment. The two commonly known conventional technologies ASP and UASB are taken for analysis whereas MBBR and BIOFOR are advanced technologies. Following is a brief description of the wastewater treatment processes assessed in this study.

2.1. Activated Sludge Process (ASP)
Activated Sludge Process is an aerobic treatment method invented in 1914 by Arden and Lockett [7]. It is a suspended growth process in which oxygen is introduced into raw wastewater to form a biological floc. The floc minimizes the organic mass in influent thus reducing biological oxygen demand (BOD) and total suspended particles from wastewater. It was named so because it involved the creation of an active mass of microorganisms capable of aerobically stabilizing organic matter in wastewater. The reason for its wide applicability is because its performance is not affected by variation in season and takes up less area. It usually requires a continuous energy supply for aeration and sludge recirculation [8]. The performance of ASP in terms of percentage removal of BOD, COD, TSS, and Fecal coliform is given in Table1. The advantage of this method is even due to regular fluctuations in wastewater properties, the performance of wastewater treatment technologies is unaffected. The drawback of ASP has been that it needs a steady supply of electricity, which has a considerable impact on efficiency [8].

2.2. Upflow Anaerobic Sludge Blanket (UASB)
Upflow Anaerobic Sludge Blanket reactor, a suspended anaerobic bioreactor processes wastewater by moving it upward from the reactor's bottom. Bacteria in the suspended sludge blanket, filter and purify wastewater by converting organic particles to biogas. There is no need for an aeration device in this process. On top of the unit, baffles are provided to keep the sludge layer from leaving the reactor. UASB alone cannot meet the effluent standards. Table 1 describes the effluent quality from UASB in terms of BOD, COD, and TSS removal percentages [2][7]. UASB has the benefit of ensuring minimal sludge
management and being able to bear hydraulic and organic shock loads. The process has the flaw of not being able to treat wastewater effectively on its own [8].

2.3. Biological Filtration and Oxygenated Reactor (BIOFOR)
Biological Filtration and Oxygenated Reactor is M/s Degremont Ltd.’s patented inventions. It is an aerobic attached growth process. BIOFOR uses a media known as Biolite to filter the unwanted particles. In this process, chemical dosing is needed in the form of coagulant and polyelectrolyte. Biolite is a layer of special clay granules on a bed of multiple media to filtrate the subsequent granules formed in flocculation. Diffusers induce air into the reactor thereby introducing an airy environment to oxidize the organic content in the raw influent. BIOFOR is a compact process requiring less space and more energy compared to ASP. Treatment efficiency (BOD, COD, and TSS % removal) of BIOFOR is stated in Table 1 [6][8]. Higher aeration efficiency thanks to a co-current diffused oxygenation device; less space required because secondary sedimentation is eliminated; and the capacity to endure volume flow and biological load fluctuations. The demerit is that it requires a high dosage of chemicals for treatment [8].

2.4. Moving Bed Biofilm Reactor (MBBR)
Moving Bed Biofilm Reactor is a hybrid of the activated sludge process (suspended growth) and the biofilter process (attached growth). The biofilm comprises plastic carriers that decompose organic waste thereby reducing wastewater pollution. Air bubbles introduced by the aerator shake the carriers, causing them to move. The biodegradable mass is then allowed to settle. MBBR requires skilled manpower and a high energy supply for its operation [2]. There are a variety of biofilms available for treatment [9]. BOD, COD, TSS, and Faecal Coliform removal by MBBR are stated in Table 1. MBBR requires skilled manpower and a high energy supply for its operation leading to higher expenses. Its primary characteristic is that it can achieve the precise removal of various metals by employing a specialized membrane [2].

| Description of WWTTs | ASP | UASB | BIOFOR | MBBR |
|----------------------|-----|------|--------|------|
| Area of land required m²/MLD | 1000 | 2000 | 400 | 550 |
| Capital cost Rs/MLD | ₹ 50,00,000 | ₹ 30,00,000 | ₹ 11,00,000 | ₹ 1,14,19,000 |
| Annual operation and maintenance cost Rs/MLD | ₹ 9,00,000 | ₹ 12,50,000 | ₹ 12,00,000 | ₹ 1,10,00,000 |
| Power required daily in kWh/MLD | 225 | 150 | 335 | 280 |
| % TSS removal | 75-90 | 70-80 | 90-95 | 85-90 |
| % BOD removal | 84-95 | 75-78 | 75-90 | 85-90 |
| % COD removal | 75-94 | 70-80 | 90-95 | 85-90 |
| Faecal Coliform removal | Log Scale unit 2-3 | Log Scale unit 2 | Log Scale unit 2-3 |
3. Life Cycle Cost Analysis (LCCA)
Life-cycle cost analysis (LCCA) method is used to calculate all of a project's, product's, or measure's expenses throughout time. It considers all expenses, which include initial costs like invested capital, acquisition, and setup, as well as future cash flows such as power, operating costs, maintenance costs, capital cost of repairs, and interest expense, as well as any resale, salvage, or disposal costs incurred during the system's or product's life cycle. The Life Cycle Cost Analysis (LCCA) method can be used to make long-term financial assessments of a system's life span.[3][10].

In this study, LCCA is done by the Present Value (PV) method according to IS 13174. The method is often referred to as the Net Worth or Present Value or Present Worth (PW) method. PW is an approach that requires all future cash flows to be converted to baseline, taking into account both inflation and the opportunity cost of capital [11][12]. PW is an economic approach for discounting future costs to their present equivalents and adding these up, taking into account the inflationary effects and depreciation and also the anticipated return on investment over time.

3.1. Components of LCCA

3.1.1. Capital costs - Capital cost comprises civil, mechanical, electrical and any other related items during the construction of the plant. Land purchase, equipment costs, building and infrastructure costs, contingency, materials, and planning are all elements of capital expenditures [5].

3.1.2. Operation and maintenance costs (O&M) - O&M costs incurred usually account for labour requirement, energy, chemicals, repair and replacement of electro-mechanical materials [13][5].

3.1.3. Energy costs – The cost of total power (electricity) required by wastewater treatment technology to operate is energy costs [5].

3.1.4. Replacement costs - Replacement cost is the sum of all repair and equipment replacement costs anticipated over the life of the system [5].

3.1.5. Salvage value - The monetary sum expected from the disposal of an asset at the end of its economic life, or at the end of the study period. Also, termed as resale value or scrap value in certain cases depending upon how the asset may be treated after disposal [5].

3.2. Some important definitions used in LCCA

3.2.1. “Discounting - A technique for converting future cash flows to equivalent amounts at present or on an agreed prior date” [11].

3.2.2. “Discount Factor - A multiplication number for converting cost and benefits occurring at different times to a common baseline” [11].

3.2.3. “Discount Rate - The rate of interest reflecting the investor’s time value of money, used to determine discount factors for converting benefits and costs occurring at different times to a baseline” [11].

\[
\text{Discount rate} = \frac{(1+\text{interest rate})}{(1-\text{inflation rate})} - 1 \quad [14]
\]

3.2.4. “Life Cycle Cost - It covers all the costs from project conception to final scrapping and disposal and includes all costs of operation, repairs, maintenance, energy consumption, rentals, insurance. etc, in addition to the initial costs of development and/or acquisition, all discounted to the same point in time” [11].



3.2.5. “Present Worth/Present Value” - The value of a benefit or cost found by discounting future cash flows to the baseline” [11].

3.2.6. “Present Value Factor/Present Worth Factor” - The discount factor used to convert future benefits and costs to the present” [11].

4. Methodology
This study takes some assumptions in LCCA for baseline consideration. They are as follows:
   a) The study period (economic life) of each technology is considered as 20 years. (n)
   b) The inflation rate is considered and assumed as 4.5%
   c) The interest rate is assumed to be 10%
   d) The discount rate is assumed to be 5%
   e) The cost of land is considered at rate of Rs.100/m² and the rate of power is assumed to be Rs. 8/kWh unit.
   f) The replacement cost is taken as 10% of capital cost. The replacement is considered at 10 years of its life.
   g) The salvage value is taken as 10% of civil construction cost.

The capital costs, annual operation and maintenance costs of each technology are obtained from various literature & sources referred in the study and are noted in Table 1. Table 1 also contains the amount of energy required daily by the respective technology to treat 1 MLD of wastewater, as well as the amount of land required by the technology to treat 1 MLD of wastewater. Both of these values are derived from resources. The cost of required land is factored into the total capital cost [13]. The cost of land is estimated as shown in the equation below at a cost of Rs. 100 per m². During the life of the wastewater treatment process, the operation and maintenance costs reoccur on an annual basis. The energy costs are not included in operation and maintenance costs and are evaluated separately for LCCs. Because it is a recurring cost, the values of daily energy required by each technology are transformed annually. The salvage cost is assumed to be 10% of the construction cost, hence the construction cost is taken as 60% of the capital cost for ASP, 55% of the capital cost for UASB, 58% of the capital cost for BIOFOR, and 40% of the capital cost for MBBR. Table 2 below summarises the calculated capital costs, energy costs, replacement costs, and salvage costs.
Table 2. Costs and performance of wastewater treatment technologies (WWTT)

| Row no | Description | WWTTs |
|--------|-------------|-------|
|        |             | ASP   | UASB | BIOFOR | MBBR  |
| (1)    | Rate of land Rs/m² | ₹ 100 | ₹ 100 | ₹ 100 | ₹ 100 |
| (2)    | Area of land required m²/MLD | 1000  | 2000 | 400    | 550   |
| (3)    | Cost of land Rs/MLD | ₹ 1,00,000 | ₹ 2,00,000 | ₹ 40,000 | ₹ 55,000 |
| (4)    | Capital cost Rs/MLD | ₹ 50,00,000 | ₹ 30,00,000 | ₹ 11,00,000 | ₹ 1,14,19,000 |
| (5)    | Total Capital cost Rs/MLD | ₹ 51,00,000 | ₹ 32,00,000 | ₹ 11,40,000 | ₹ 1,14,74,000 |
| (6)    | Annual Operation and Maintenance cost Rs/MLD | ₹ 9,00,000 | ₹ 12,50,000 | ₹ 12,00,000 | ₹ 1,10,000 |
| (7)    | Rate of power Rs/kWh | ₹ 8   | ₹ 8   | ₹ 8    | ₹ 8   |
| (8)    | Power required daily kWh/MLD | 225   | 150   | 335    | 280   |
| (9)    | Energy Costs Rs/MLD | ₹ 6,57,000 | ₹ 4,38,000 | ₹ 9,78,200 | ₹ 8,17,600 |
| (10)   | Salvage cost Rs/MLD | ₹ 3,00,000 | ₹ 1,65,000 | ₹ 63,800 | ₹ 4,56,760 |
| (11)   | Replacement cost Rs/MLD | ₹ 5,00,000 | ₹ 3,00,000 | ₹ 1,10,000 | ₹ 11,41,900 |

*Salvage Cost is 10% of construction cost. Construction cost is some percentage of capital cost.

The equations used to calculate the costs are as follows.

Cost of land = Rate of land per m² × Area required for treatment m²
Total Capital cost = Capital cost + Cost of land.
Energy Cost = Rate of energy per kWh × Energy required kWh × 365
Salvage Cost = 10% × Given percentage for each technology to convert capital cost to construction cost (60 for ASP; 55 for UASB; 58 for BIOFOR; 40 for MBBR) × Capital cost

The LCC is sum of present values of Capital, O & M, Energy, Salvage and Replacement costs. These costs are converted to discounted present value by multiplying itself to present value factor. The present value factors are of two kinds

Uniform Present Value factor – The costs recurring annually are converted to present value cost by this factor. Denoted as UPV/UPWF

\[
UPWF = \frac{(1+d)^{n-1}}{d(1+d)^n} \quad [14]
\]

where n – life of study in years; d - discount rate

Single Present Value factor – For converting the initial investments or one-time costs. Denoted as UPV/UPWF
SPWF = \frac{1}{(1+d)^n} \quad [14] \tag{3}

The values of SPWF and UPWF are given in Table 3. The present value factors for different costs are different because they vary with the number of years.

Table 3. Discount factors

| Calculation of SPV and UPV | Discount rate (d) | Number of years (n) | Discounting factor | Round up value |
|---------------------------|-------------------|---------------------|--------------------|---------------|
| SPV₁                      | 0.05              | 1                   | 0.95238095         | 0.95          |
| SPV₁₀                     | 0.05              | 10                  | 0.61391325         | 0.61          |
| SPV₂₀                     | 0.05              | 20                  | 0.37688948         | 0.38          |
| UPV₂₀                     | 0.05              | 20                  | 12.4622103         | 12.46         |
### Table 4. Life cycle cost calculation

| Row no. | Costs                                      | WWTT                |
|---------|--------------------------------------------|---------------------|
|         |                                             | ASP                | UASB               | BIOFOR             | MBBR               |
| (1)     | Capital base cost in Rs/MLD                | ₹ 51,00,000         | ₹ 32,00,000        | ₹ 11,40,000        | ₹ 1,14,74,000      |
| (2)     | Capital present value cost in Rs/MLD       | ₹ 48,45,000         | ₹ 30,40,000        | ₹ 10,83,000        | ₹ 1,09,00,300      |
| (3)     | Annual O&M base cost in Rs/MLD            | ₹ 9,00,000          | ₹ 12,50,000        | ₹ 12,00,000        | ₹ 1,10,00,000      |
| (4)     | Annual O&M present value cost in Rs/MLD   | ₹ 1,12,14,000       | ₹ 1,55,75,000      | ₹ 1,49,52,000      | ₹ 88,01,99,320     |
| (5)     | Annual Energy base cost in Rs/MLD         | ₹ 6,57,000          | ₹ 4,38,000         | ₹ 9,78,200         | ₹ 8,17,600         |
| (6)     | Annual Energy present value cost in Rs/MLD| ₹ 81,86,220         | ₹ 54,57,480        | ₹ 1,21,88,372      | ₹ 1,01,87,296      |
| (7)     | Replacement base cost in Rs/MLD           | ₹ 5,00,000          | ₹ 3,00,000         | ₹ 1,10,000         | ₹ 11,41,900        |
| (8)     | Replacement present value cost in Rs/MLD  | ₹ 3,05,000          | ₹ 1,83,000         | ₹ 67,100           | ₹ 6,96,559         |
| (9)     | Salvage base cost in Rs/MLD               | ₹ 3,00,000          | ₹ 1,65,000         | ₹ 63,800           | ₹ 4,56,760         |
| (10)    | Salvage present value cost in Rs/MLD      | ₹ 1,14,000          | ₹ 62,700           | ₹ 24,244           | ₹ 1,73,569         |
| (11)    | Life Cycle Cost in Rs/MLD                 | ₹ 2,44,36,220       | ₹ 2,41,92,780      | ₹ 2,82,66,228      | ₹ 15,86,70,586     |
| (12)    | Life Cycle Cost in Lakh Rs/MLD            | ₹ 244              | ₹ 242              | ₹ 283              | ₹ 1,587           |

The Life Cycle Cost (LCC) takes into account the present value costs of each cost component. The Table 4 tabulates the LCC calculations, wherein the costs are first converted to present costs by multiplying its by respective discount factors and then summed up for total LCC. The capital cost is multiplied by single present value factor (SPV₁) to obtain its present cost because it is a one-time investment cost at the initial year of life cycle. The annual operation and maintenance as well as annual energy costs recur every year throughout the lifetime in same amount hence it is multiplied by UPV₂₀ for present cost conversion. For purpose of obtaining present cost of replacement cost of WWTTs it is multiplied by SPV₁₀ since the replacement period is assumed to be 10 years. Similarly, the salvage cost...
is procured at the end of life hence it is multiplied by SPV_{20} for further calculations. The last row represents the approximate total LCC in Lakhs required to treat 1 MLD of wastewater.

5. Results and Discussions

UASB is the technology with the highest area requirement of the four technologies. The limitation of UASB is that it cannot withstand discharge standards on its own; the effluent requires tertiary treatment before discharge or reuse. It is incapable of removing faecal coliform from wastewater. UASB generates biogas, which is a great source of revenue. UASB does not require any mechanical aeration device, which reduces its energy requirement and ensures that its performance is unaffected by power fluctuations[8]. UASB, despite having the lowest LCC, is not recommended for decentralised treatment because it may require tertiary treatment before reuse, and the generation of biogas puts it at a disadvantage due to its odour (for decentralised).

ASP is the technology with the second lowest LCC. Because of its high level of treatment and low cost, it is the most widely used technology. However, ASP necessitates a larger land area than BIOFOR and MBBR. It has operational issues during the winter season and is impacted by power fluctuations.[8]

BIOFOR is ranked third among LCCs. BIOFOR is a compact treatment system because it takes up less space and has the lowest capital cost. However, because of the continuous chemical and power requirements, the LCC is affected by O & M cost, despite the fact that it requires less manpower for supervision.[8] It has the highest energy requirement, resulting in a high LCC.

Because of its high capital and operating and maintenance costs, MBBR has a very high LCC. Such high costs are observed as a result of the membrane used for treatment, which provides the best effluent quality of the four technologies.

Wastewater treatment technologies are being used around the country to treat domestic and industrial wastewater. Recent cost data for wastewater treatment technology is not explicitly accessible. And the expenses for LCCA are acquired from literature; if the expenses are not as specified, the analysis will be inaccurate. The expenses computed may or may not be predicated on India's schedule of rates (SOR).

Figure 1 depicts a comparison of the area required by each technology. The highest area required is by UASB compared to other three and BIOFOR requires lowest space to treat 1 MLD of wastewater.

Figure 1. Area required for wastewater treatment technologies (WWTTs)
Figure 2 depicts the total capital cost and annual operation and maintenance (O & M) costs for treating 1 MLD of wastewater using all four technologies. MBBR being the technology with highest capital and O & M cost because of the use of membrane adopted for treatment. And BIOFOR has lowest capital cost as it requires minimum area when compared to others and ASP with lowest operation and maintenance as it does not involve any expensive material to maintain.

![Figure 2. Capital and O & M cost of wastewater treatment technologies (WWTT)](image)

Figure 3 depicts a comparison of area versus Life Cycle Cost (LCC) for each technology. The LCC is highly dependent on area requirement and its cost. Cost of land changes geographically and temporarily hence it is an uncertain factor. The cost of land influences the capital cost and thus affecting the LCC. In case of UASB, the land required is much higher than its LCC and hence the higher price of land will highly affect the LCC of UASB. Same is for ASP. While for MBBR, if the price of area is high it will increase the LCC, but comparatively it won’t have much significant effect as in case of UASB.

![Figure 3. Area requirement and life cycle cost comparison](image)
Figure 4 shows a graph of the cost components of each technology per MLD. There are two vertical axes shown for comparing the costs; the primary vertical axis is reference for life cycle costs of all four technologies while the secondary axis on right side is reference for values of capital costs, energy costs and annual operation and maintenance (O & M) costs. It can be seen through the graph that O & M costs highly affects the LCC of wastewater treatment technologies (WWTT). BIOFOR has highest energy cost which makes its LCC higher than the other two (ASP and UASB).

6. Conclusions
i. The selection of wastewater treatment technology is a critical decision that is influenced by a variety of factors. All of these factors, as well as the costs of the technologies, should be presumed in relation to the purpose of installing the treatment technology.
ii. LCCA can be used to assess costs. The findings indicate that the order of LCC of the four technologies is UASB<ASP<BIOFOR<MBBR.
iii. The present LCCA study is a literature-based cost assessment of the four wastewater treatment technologies.
iv. UASB is a cost-effective option if there is no land limit and effluent quality is not a primary concern for treatment. It has the lowest treatment efficiency of the four technologies. It is being installed in sewage treatment plants with tertiary treatment.
v. If land is not a major consideration, ASP is a viable option. It can be installed to treat a larger volume of sewage or to provide centralised treatment. ASP outperforms UASB in terms of removal efficiency.
vi. Because it takes up less space, BIOFOR may be a good choice for decentralised treatment. BIOFOR has a higher percentage of COD and TSS removal than MBBR.
vii. MBBR can be used where cost is not an issue due to its high treatment efficiency. MBBR can be installed for decentralised treatment. Because of the medium, the filter used for treatment, MBBR has the highest capital and maintenance costs. MBBR is used for both industrial and domestic wastewater treatment.

viii. The LCCA is affected by change of any of the cost components and depends on the actual site conditions where it is adopted.
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