

Municipal wastewater is considered a limitless source of water due to its high biodegradability and low toxicity profile (Fane et al., 2011). Globally, 80% of the wastewater generated is disposed of in the environment, causing hazardous impacts on the receiving water bodies (WWAP, 2017). The burden of environmental degradation and water scarcity can be significantly reduced by utilizing treated wastewater as a water source (Coe and Lavery, 1972). Several industrial and domestic activities do not require reliance on high-quality potable water but can utilize reclaimed water to obscure the issue of water scarcity. By observing the trend of water demand and the definition of relevant quality criteria, raw wastewater can be treated to produce a secondary water source (Reyes, 2022). The circular economy approach should be combined with integrated water and wastewater management to obtain sufficiency in water, leading to collection of raw wastewaters from source, till it is reclaimed using an appropriate technology and reutilized by the community.

To form a strong foundation for this study, an elaborate literature review was performed. Firstly, to understand the relevance of wastewater reclamation in different cities and to understand related initiatives and expertise, a detailed literature review of the global scenario in terms of wastewater reclamation was performed. Next, a review of all the factors that affect implementation of reuse focused IWWM system was done to understand the areas that need to be included in this study. Following it, to obtain the critical factors, a review of multi-criteria decision-making methods was done to obtain the most suitable method for identifying the key influencing factors and to establish interrelationships between them. Further, a detailed review of reuse purposes and their

quality criteria was performed to obtain safe and suitable quality prescriptions. Next, a review of reuse purposes and related guidelines issued by the government was performed for quantification of reuse purposes and estimation of demands. Thereafter, a comprehensive review of secondary treatment technologies, emerging treatment technologies and tertiary treatment technologies was done to identify all the technologies, their land, energy, capital cost, and O&M costs, and the respective performance efficiencies corresponding to prescribed quality parameters. Then, a review of methods to select the most appropriate treatment technology was performed. Finally, a detailed review of economic methodologies was done to obtain the optimum water pricing technique and a review of decision support systems available in literature as well as those specific to selection of treatment technologies was performed to form a base of the study. In the later part of this chapter, the identification of research gaps and definition of the objectives of the present study was performed.

## **2.1 Global Scenario in Wastewater Reclamation**

Wastewater reclamation is being viewed as a feasible alternative to combat water scarcity and create a new source of water. The motive behind the process is not just creation of new sources but also conservation of existing freshwater resources. Due to varying spatial-temporal conditions and population boom, water-stressed scenarios can be seen in different parts of the world, therefore, utilization of treated wastewater for potable or non-potable purposes can help obtain water-sufficiency in communities. The history of reuse of wastewater can be traced back to the Minoan civilization where cities and places were found with sewerage systems (Asano and Levine, 1996). As per Angelakis and Spyridakis (1996), for agriculture, the use of wastewater can be traced back to about five thousand years ago. In 1918, California laid down the first kind of guidelines prescribing quality criteria for treated wastewater for irrigation purposes (Olivieri et al., 2020). In

Grand Canyon Village, Arizona, wastewater reuse has been done for cooling, boiler feed, toilet flushing and irrigation since 1925 (Garthe and Gilbert, 1968). However, direct release of wastewater into surface water systems in the 19<sup>th</sup> century led to the spread of waterborne diseases and subsequently to “The Great Sanitary Awakening” marking the identification of linkage between diseases and untreated wastewater and boosted the current practice of wastewater treatment (Winslow, 1923). Coe and Laverty (1972) emphasized that reclamation of water from wastewater and delivery of this reclaimed water to the community is relatively lower than the process of extracting water from natural water system. They also predicted the imminent water crisis and how reclaimed water can be beneficially utilized for non-potable purposes. Shuval (1977) regarded wastewater reclamation as an economically feasible alternative to address water scarcity. In Israel, the policy development for wastewater reclamation was started in 1960s for non-potable purposes, by 2005, about 85% of wastewater was treated biologically in the region by processes such as oxidation ponds, activated sludge plants, and soil aquifer treatment (Arlosoroff, 2007). Wastewater reclamation for potable purposes is performed in Windhoek, Namibia to satisfy the increasing water demands (Lahnsteiner et al., 2018). Similarly, in various states of USA, wastewater reclamation is being done for producing water of potable-use quality, mostly using the ultrafiltration process, while in Singapore, dual membrane filtration followed by UV disinfection is utilized for production of potable water (Roccaro and Verlicchi, 2018). Therefore, given the efficient performance of advanced treatment technologies, most of the countries in the present time have already embarked upon the journey to explore wastewater reclamation as a new potential source of water for potable as well as non-potable purposes.

In India, wastewater reclamation is not prevalent at a national scale but only at very few places. There is not a single city in the country that has adopted hundred percent

wastewater reclamation. However, since last four decades the installation of STPs in India has increased. Under Yamuna Action Plan, Ganga Action Plan and National River Conservation Plan, several STPs were installed across India, but entirely targeting safe disposal in river systems (Tare and Bose, 2009). As per the latest report on the status of STPs in India (CPCB, 2021), the total sewage generation from urban centres in India is about 72,368 MLD and there is a total of 631 installed and approved to be installed STPs in India, which accounts for a total of 36,668 MLD of treatment capacity across 35 states and union territories. Out of the total, there are 1093 operational STPs with a treatment capacity of 20,235 MLD, which is 55% of the total installed and approved to be installed capacity. There are only 578 STPs out of the operational STPs that comply to the quality criteria for safe disposal in river system, which accounts for only 12,200 MLD, which is 33% of the total installed or approved to be installed STPs. Since 20,235 MLD is the total operational capacity of STPs, that means that only about 28% of the sewage is treated and the remaining sewage is untreated and directly released on land or water bodies. Most of these STPs produce effluent of disposal level quality only.

## **2.2 Identification of Potential Factors Affecting Wastewater Reclamation**

Several factors govern the implementation of a IWWM towards wastewater reclamation. These "factors" form the base for assessing the feasibility of the project undertaken. The factors may belong to different "categories" at a broader level, such as physical, chemical, biological, economic, technical, sociological, administrative, operational, and cultural. Deciding factors are essential as the abundance or limitation of these factors may affect the project's feasibility. Different studies used different decision criteria for technology suggestion, demand estimation (Yang and Abbaspour, 2007; Kalbar et al., 2012; Sharma and Rawal, 2020) but the correct set of criteria, the importance hierarchy, and interrelationships are not yet established.

In a study performed by Zhang et al. (2020), the impact of influent concentrations and desired effluent concentrations on technology selection was illustrated. It was reported that higher influent concentrations require high-performing advanced and costly technologies. In a study conducted by Kalbar et al. (2012), six technologies were ranked based on seven decision criteria (eutrophication potential, global warming potential, land requirement, manpower requirement, the robustness of the system, sustainability, and life cycle costs) using the Multi-Criteria Decision Making (MCDM) tool, Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). A decision support system was developed to select treatment technologies based on the different technologies' physical, chemical, and biological aspects (Ullah et al., 2013). Fuzzy-Analytic Hierarchy Process (AHP), Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE), and Grey Relational Analysis (GRA) were used to rank technologies while using decision criteria: social and environmental criteria, economic criteria, and technical criteria in a study conducted by Ilangkumaran et al. (2013). An environmental decision support system was developed wherein the social, economic, and technical aspects affecting technology selection were integrated into a single platform, and results were validated by comparison to real projects (Castillo et al., 2017). AHP and ELECTRE II methods were used of ranking technologies based on twelve decision criteria identified out of 48 potential criteria by assigning normalized weights representing the significance and appearance of the concerned criterion in the published literature and taking top-twelve criteria (Lizot et al., 2021). Selection of wastewater treatment technologies based on treatment efficiency and cost comparison was performed by Maurya et al. (2018). Chang and Ma (2012) emphasized that for implementing an efficient wastewater reclamation system, local administrative orders, price of reclaimed water, desired reuse purpose, the quality required for the reuse purpose, and social acceptance play a crucial

role. Sgroi et al. (2018) suggested that a holistic study that considers all the factors associated with reuse should be conducted to implement a sustainable water reuse system. They identified factors such as selection of a suitable system, whether centralized or de-centralized, ease of operation, associated costs, site characteristics, environmental impact on local resources, policy and regulations, land requirement, power requirement, monitoring costs, the effect of seasonal or daily variation on treatment performance, etc. Lahlou et al. (2021) stated that public awareness is the key factor that can influence social acceptance and help create demand for reclaimed water among the masses. Goyal and Kumar (2020) underlined the importance of the demand for treated wastewater, associated costs, social acceptance, and wastewater availability in developing a reuse project. Baawain et al. (2020) studied the public's perception of using treated wastewater for urban reuse purposes. Chen et al. (2017) stated the quality standards used for different reuse purposes such as vehicle washing, toilet flushing, irrigation, industrial cooling, etc., in China and emphasized the significance of quality criteria satisfaction in reclaimed water production. Sharma and Rawal (2021) employed the analytic hierarchy process for technology selection using land, power, capital cost, and operation and maintenance cost as the decision criteria. Yang and Abbaspour (2007) estimated the demand for treated wastewater using primary data while presenting an optimized reclaimed water supply using a linear programming model. Capodaglio (2021) stated that the purpose of reuse is a significant determinant for an efficient wastewater reuse project development. Neczaj and Grosser (2018) studied the challenges and barriers to developing an IWWM network and identified post-distribution network and treatment technology selection as crucial barriers. Smith et al. (2018) highlighted the problem of greenhouse gas emissions from Wastewater Treatment Plants (WWTPs) during treatment and suggested switching to low energy consuming treatment technologies.

In this study, twenty-two factors have been identified from the literature review as shown in Table 2.1. Sgroi et al. (2018) suggested that a holistic approach comprising all influencing factors is needed; therefore, this study will provide a more organized set of influencing factors necessary for planning an efficient management system for integrating wastewater reclamation in the traditional system.

**Table 2.1. Potential influencing factors identified from literature review**

S. No.	Factor	Description
1	Reuse Purpose	The reuse purpose and the quality criteria required are essential to determine the degree of treatment to be given to raw wastewater. Stricter the quality criteria for a reuse purpose, more work is to be done for its treatment. Experts may have given higher importance to this factor as it decides the system's performance, acceptability, and infrastructure.
	<b>Source:</b> Sgroi et al., 2018; Capodaglio, 2021	
2	Post-Treatment Distribution Network	This factor refers to the pipe network engaged in the delivery of treated wastewater to its utilization centers. This factor will require investment in infrastructure and should be durable to serve the expanding population during its design period. In Japan, dual reticulation systems are used in the IWWM network.
	<b>Source:</b> Asano et al., 1996; Sgroi et al., 2018	
3	The demand for Treated Wastewater	The reuse potential is crucial for wastewater reclamation as lesser demand for treated wastewater would lead to lower cost-effectiveness. If the need for treated wastewater is more, higher revenue will be generated, and the cost invested in the infrastructure could be recovered.
	<b>Source:</b> Goyal and Kumar, 2020; Lahlou et al., 2021	
4	Power Requirement	For pumping raw wastewater to WWTPs and then delivery to utilization centers, power is required.

	<b>Source:</b> Castillo et al., 2017; SgROI et al., 2018; Capodaglio, 2021	Availability of energy is one of the most considered factors in published literature aimed at wastewater treatment technology selection. Constraint in energy availability (for example- rural areas) can influence treatment technology selection.
5	Material Requirements	For the treatment of raw wastewater, materials such as chemicals, grit, pebbles, filter media are required.
	<b>Source:</b> SgROI et al., 2018; Singh et al., 2019	Availability and cost feasibility of this factor plays an important role in determining the expenditure in a reuse-based network, which affects the project's operation and maintenance process.
6	Nutrient Recovery	This factor can add revenue and cause material sufficiency. Metals, sludge, etc. can be recovered from treatment systems and reutilized for purposes such as fertilizers.
	<b>Source:</b> Lyu et al., 2016	
7	Manpower Requirement	For proper working and maintenance, skilled manpower is required. Availability of this factor is crucial in the case of sophisticated technologies. The more the manpower required, the better the skill required, higher will be the O&M cost.
	<b>Source:</b> Nhapi et al., 2003; Lyu et al., 2016;	
8	Capital Cost	In most studies, the capital cost is the determining factor, and it relates to the direct cost of setting up a reuse-based treatment network, such as the cost of technology, pipe network, etc. In India, technology selection is primarily based on capital cost, but a shift to more scientific selection with the due significance of other factors is required.
	<b>Source:</b> SgROI et al., 2018; Capodaglio, 2021	
9	Operation and Maintenance	This factor relates to the cost for operationalizing treatment technologies. These are varying costs and

	(O&M) Cost	include cost pertaining to salaries of employees, cleaning costs, etc. The more skilled or more sophisticated the technology, the higher is the O&M cost incurred.
	<b>Source:</b> Nhapi et al., 2003; Capodaglio, 2021	
10	Water Pricing	An optimum reclaimed water price is essential as it is the only significant revenue source for an IWWM network. The costs incurred in planning, implementation, operation, and maintenance of the system can only be recovered by levying an optimum charge on the reclaimed water usage to alleviate the financial burden of IWWM management from the operating agency.
	<b>Source:</b> Lyu et al., 2016; Sgroi et al., 2018	
11	Availability of Raw Wastewater	For the working of a wastewater treatment plant (WWTP) and subsequent re-utilization, raw municipal wastewater from the community needs to be collected and led to the treatment facility. Underloading of WWTP can lead to underperformance of the plant and hence disrupt the process. Availability of wastewater will determine whether there exists a reliable source of influent to STPs.
	<b>Source:</b> Lyu et al., 2016; Sgroi et al., 2018	
12	Ease of Operation	This factor refers to the flexibility and simplicity in the operation of a WWTP. Skilled manpower requirement is dependent on this factor. If the operability of a system is simple, local people can be employed for its operation. So, for efficient management and performance of the system, this factor is essential.
	<b>Source:</b> Sah, 2004; Gikas et al., 2007; Sgroi et al., 2018	
13	Social Acceptance	Some communities in various countries are not yet ready to accept treated wastewater reuse. This factor

	<b>Source:</b> Engin and Demir, 2006; Chang and Ma, 2012;	is vital as their acceptance determines the demand for treated wastewater and affects the successful implementation of the reuse focused IWWM network.
14	Treatment Technology	The treatment technology employed primarily affects the quality of reclaimed water, the capital cost, Operation and Maintenance (O&M) cost, land requirement, power requirement, etc. The success of the IWWM network for wastewater reclamation will only be achieved when the desired quality criteria are met at optimum resource needs.
	<b>Source:</b> Sgroi et al., 2018; Capodaglio, 2021	
15	Technical Durability	The design life of treatment units determines the period till which the installed technology will produce the desired effluent. Lesser design life is not feasible as setting up a WWTP itself is a massive task in itself, and any failure in performance will lead to a waste of investment.
	<b>Source:</b> Ghazy and El-Senousy, 2008; Capodaglio, 2021	
16	Centralized or Decentralised WWTPs	Depending upon the policies in the city and the community requirement, the treatment systems can be centralized or decentralized in nature. In a centralized system, collected wastewater is led to a single WWTP, while in a decentralized system, a more significant number of smaller WWTPs are installed near the wastewater source. The type of system required determines the kind of technology, plant capacity, and the extent of resources to be used.
	<b>Source:</b> Sgroi et al., 2018; Singh et al., 2019	
17	Land Requirement	Land requirement is one of the most crucial features in the IWWM network at places of high population

	<b>Source:</b> Chang and Ma, 2012; Salama et al., 2014; Sgroi et al., 2018	densities. It refers to the land area that needs to be occupied with the setting up of WWTP and the collection and distribution of untreated and treated wastewater.
18	Harmful By-Products and Greenhouse Gas Emissions	Working of WWTP or construction of WWTP may lead to the formation of unwanted by-products or emission of greenhouse gases (GHGs). GHG emissions are considered in life cycle assessment studies of WWTPs to determine the project's environmental impact, contributing to global warming.
	<b>Source:</b> Sgroi et al., 2018; Singh et al., 2019	
19	Value of Saved Water	Reutilisation of treated wastewater leads to the preservation of freshwater, which can be utilized for potable purposes. Also, since wastewater treatment prevents the discharge of raw wastewater into river streams, water environment and quality are saved, and this factor has high environmental value.
	<b>Source:</b> Yang and Abbaspour, 2007; Sgroi et al., 2018	
20	Policy and Regulations	Administrative policy and regulations play a significant role in the IWWM network as it reflects the support from the regional government, funding availability, acceptance, and awareness about the project. These are responsible for maintaining the efficient functioning of a WWTP.
	<b>Source:</b> Mu'azu et al., 2020; Lahlou et al., 2021	
21	Funding Availability	The involvement of stakeholders is necessary for planning an IWWM network as the financial resources needs to be mobilized for setting up such a system. Lack of funds will cause compromise in treatment, technology, and other needs, leading to underperformance and wastage of all the resources.
	<b>Source:</b> Lyu et al., 2016; Capodaglio, 2021	

22	Weather and Climatic Conditions	This factor stands for the variability in the performance of wastewater treatment technology in different conditions. The efficiency of technology often varies with daily and seasonal changes, like temperature changes. So, the WWTP should be reliable in all prevailing scenarios.
	<b>Source:</b> Sah, 2004; Lyu et al., 2016	

### **2.3 Methods for Selection of Key Factors and the Interrelationships**

It was observed through literature review that the technology selection was performed based on specific decision criteria, but the reason or the procedure for justifying the taken criteria was not provided. In most studies, decision criteria selection was based on past appearances in published literature and perceived significance. The factors may work independently or dependently, it is crucial to establish the interrelationships between the factors for an efficient design of the system. To provide a rational reason for consideration of key factors out of the identified lot of factors and to establish linkages between the factors, a review of methodologies was performed to select the most suitable method for isolating key influencing factors.

In a complex system comprising several influencing factors, approaches like Analytical Network Process (ANP) and Interpretive Structural Modelling (ISM) are utilized to establish their interrelationships. It is tough to ascertain interactions between a cluster of criteria; therefore, ANP fails to achieve the target of establishing dependencies (Wu, 2008). In contrast, ISM enables the establishment of dependencies and shows the direction and criticality of each factor (Thakkar et al., 2005). Several studies have been conducted to establish hierarchies and interrelationships between the influencing factors. The relationship between Sustainable Development Goals (SDGs) was established using ISM in a study conducted by Kumar et al. (2018) to establish priorities for resource allocation. For cleaner production in Small Medium Enterprises (SMEs) of batik producers, ISM was applied for obtaining barriers that caused wastewater generation in the process (Pujotomo et al., 2018). Application of ISM for identifying factors affecting stone crushing industries in India for better planning and management was performed by Ganguly and Das (2020). ISM was also applied to identify factors affecting construction projects (Sandbhor and Botre, 2014), to identify barriers to six sigma implementations in

the supply chain (Ali et al., 2020), to establish interrelationships between barriers affecting integrated flood risk management (Mercado et al., 2020), to identify barriers faced by Indian farmers in adopting organic farming methods (Dixit et al., 2022), to identify and analyse factors that prevent healthcare industry from adopting Internet of Things in India (Desingh, 2022), and to identify factors that affect acceptability of energy-efficient appliances in India (Aggarwal et al., 2022).

#### **2.4 Reuse Purpose and Quality Criteria**

Municipal wastewater is being widely explored as a new potential source of water. A significant step while planning a responsible municipal wastewater treatment plant is to identify the potential reuse purposes in the concerned city (CPHEEO, 2013). The degree of treatment to be given to the wastewater depends upon the quality of effluent required. For doing so, the consideration of biological quality characteristics of water required for different reuse purposes is mandatory. The stricter the quality required, the more sophisticated is the treatment and other associated costs. The State of California (1994) defined the quality criteria for reclaimed water use in non-potable purposes by prescribing limits only in terms of total coliform given in Annexure 3. Similarly, the Florida Department of Environment Protection (Florida, 1995) defined quality criteria for non-potable reuse in terms of total coliform (TC), total suspended solids (TSS) and biochemical oxygen demand (BOD) (Annexure 3). United States Environment Protection Agency (USEPA, 2012) also prescribed quality criteria for utilization of water, along with treatment suggestions, quality monitoring frequency for different parameters, and site for sampling (Annexure 3). Chen et al. (2017) conducted a study demonstrating the benefits of redirecting treated effluents from a central wastewater treatment facility for non-potable reuse purposes in the city of Tianjin, with quality criteria prescriptions (Annexure 3).

As per CPHEEO (2013), in India, quality criteria for water are defined for release into inland surface waters (Annexure 3). Also, the designated best use (DBU) quality criteria for water, which are largely followed in India for irrigation, fisheries, outdoor bathing are as shown in Fig. 2.1 (CPCB, 2007).

Designated Best Use	Class	Criteria
Drinking Water Source without conventional treatment but after disinfection	A	1. Total Coliforms Organism MPN/100ml shall be 50 or less 2. pH between 6.5 and 8.5 3. Dissolved Oxygen 6mg/l or more 4. Biochemical Oxygen Demand 5 days 20 °C, 2mg/l or less
Outdoor bathing (Organised)	B	1. Total Coliforms Organism MPN/100ml shall be 500 or less 2. pH between 6.5 and 8.5 3. Dissolved Oxygen 5mg/l or more 4. Biochemical Oxygen Demand 5 days 20 °C, 3mg/l or less
Drinking water source after conventional treatment and disinfection	C	1. Total Coliforms Organism MPN/100ml shall be 5000 or less 2. pH between 6 and 9 3. Dissolved Oxygen 4mg/l or more 4. Biochemical Oxygen Demand 5 days 20 °C, 3mg/l or less
Propagation of Wild life and Fisheries	D	1. pH between 6.5 and 8.5 2. Dissolved Oxygen 4mg/l or more 3. Free Ammonia (as N) 4. Biochemical Oxygen Demand 5 days 20 °C, 2mg/l or less
Irrigation, Industrial Cooling, Controlled Waste disposal	E	1. pH between 6.0 and 8.5 2. Electrical Conductivity at 25 °C micro mhos/cm, maximum 2250 3. Sodium absorption Ratio Max. 26 4. Boron Max. 2mg/l
	Below-E	Not meeting any of the A, B, C, D & E criteria

**Fig. 2.1 Designated Best Use (DBU) quality criteria for water (CPCB, 2007)**

## 2.5 Reclaimed Water Demand Estimation and Allocation

Due to changing climate, the flow rates of existing resources of surface and underground water are predicted to be severely reduced leading to water-scarce conditions in different parts of the world (IPCC Report, 2014). This will lead to significant pressure on the utilization of water in competing sectors. Such a scenario would require boosting existing resources with new sources of water, with the most promising alternative being treated wastewater (SgROI et al., 2018). In the present time, the management of water resources in different countries has already seen a shift towards an integrated management system in which both the demand and the supply end of the system are being considered. This integrated management approach has been regarded as the best way of managing

limitations in supply and increase in demand (Maldonado-Devis and Almenar-Llongo, 2021). Therefore, management of demand is an important aspect of achieving water sufficiency in the coming times, such an approach will be just, efficient, and sustainable. In developing countries, numerous factors such as the income of household, quality of water, pricing structure, seasonal variations, climatic conditions, standard of living, play a significant role in water demand estimation (Nauges and Whittington, 2010). Several studies have been conducted to estimate the demand for water in a community. Chu et al. (2004) mentioned that the reliability of demand estimation depends a lot on the availability of precise data and knowledge about all water resources and applied a linear optimization model to estimate the maximum demand of reclaimed water that could be satisfied and associated costs for consumers. In India, NITI Aayog (2018) also emphasized on the lack of volumetric data as a prime reason behind the inability to accurately predict water demand. Jodicke et al. (2001) applied mixed integer linear programming model to predict optimum water demand, Hochstrat et. al, (2005) applied mass balance-based approach to calculate demand for water, Adewumi et al. (2008) utilized a non-linear optimization model for the study of water demand calculation. Goyal and Kumar (2020) applied a linear optimization method for the estimation of demand for reclaimed water in Delhi city in India. In NBC (2016), a revised version of IS Code 1172 (1993), approximations for calculation of water demands were established by the government in which per capita water allocation values were defined for different sectors. India estimates water demand by levying a defined volume of water per person per day based on the population of a city and standard of living. In MoWR (2004), the breakup of domestic demand for different purposes was presented as shown in Table 2.2.

**Table 2.2. Domestic demand distribution for different purposes (MoWR, 2004)**

<b>S. No.</b>	<b>Type of Purpose</b>	<b>Water Demand</b>
1.	Drinking Purposes	4 %
2.	Cooking and other Kitchen Works	8 %
3.	Personal Hygiene	29 %
4.	Washing of Clothes	10 %
5.	Toilet Flushing	39 %
6.	House Cleaning/ Gardening	10 %

Therefore, setting up of a common methodology supported by primary data collection is important for reliable data generation for water demand estimation.

The shrinkage in freshwater availability due to increasing population and pollution has led to an imbalance between imposed water demand and supply. Competition for water has emerged for utilization of water for potable purposes against non-potable purposes. If the freshwater available is reserved for potable purposes, distribution of reclaimed water for non-potable demands needs to be done in a socio-economic manner, so that, the needs of the community are not compromised against the economic benefit of allocating water to commercial sectors. Water allocation requires complex decision-making as it is sensitive to social, economic, environmental, political and technical factors (Babel et al., 2005). Several studies have been conducted exploring the role of these factors in the field of water allocation. Bielsa and Duarte (2001) proposed a constrained-maximization model for water allocation based on institutional, environment and economic aspect for hydropower and irrigation sector, a model based on economic optimization was proposed by Reca et al. (2001) for water allocation in for water-scarce regions, Benk et al. (2000) applied a non-linear programming model to allocate water, Chen et al. (2004) allocated demand based on the availability of water and economic

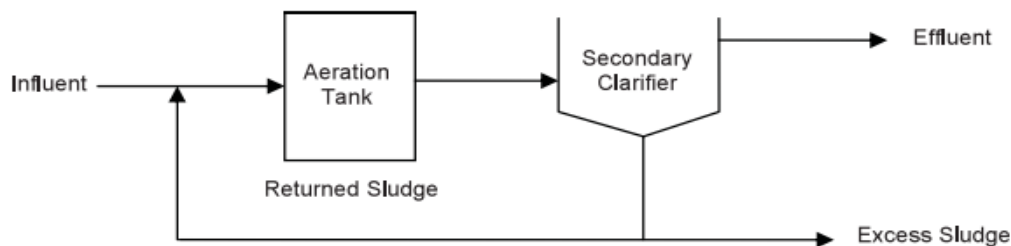
feasibility by linear optimization, Divakar et al. (2013) used linear programming optimization for water allocation considering socio-economic aspects, Roozbahani et al. (2015) presented a model based on multiple objectives to address the social, economic and environment factors of demand allocation for water, Banihabib et al. (2019) also presented a similar model incorporating fuzzy approach to multiple objective modelling to allocate water and improve net profits generated by farmers, Zhang et al. (2020) presented a methodology for allocation of water using the economic and ecological aspect of extraction and distribution, Musa (2021) applied goal programming model to optimize the allocation of water in case competing water demands exist, Izady et al. (2021) presented a framework for water allocation from subsurface dams using a risk-based simulation-optimization, Zhao et al. (2021) developed a goal programming model based on user's priorities for optimization of allocation based on socio-economic, ecological, and environmental aspects, Yuan et al. (2022) presented a multiple objective non-linear programming technique to address the social, economic and environmental aspects of allocation for water. In Indian scenario, the problem is lack of availability of precise data. Also, for allocation of reclaimed water, consideration of technical aspects plays a significant role. Limited studies have considered technical aspects as part of water allocation problem.

## **2.6 Review of Wastewater Treatment Technologies**

Wastewater treatment has been recognized as one of the most important steps toward water conservation. The treatment of wastewater takes place in several steps such as preliminary treatment, in which the large floating materials are removed from the raw wastewater, primary treatment, where through sedimentation, the settleable solids are removed, biological treatment for decomposition of organic matter, tertiary treatment for further polishing of wastewater (Peavy et al., 1985). The biological treatment is the most important part of an STP. The sewage treatment technologies depend on biological processes for the decomposition of dissolved and suspended organic material present in wastewater. They employ cultured microorganisms to decompose organic matter and aid reproduction. Therefore, more populations of microbes become available for biological decomposition of organic matter to obtain treated wastewater. The oxygen required by microorganisms to carry out this process is referred to as Biochemical Oxygen Demand (BOD). These treatment processes can take place in the presence or absence of oxygen, known as aerobic decomposition and anaerobic decomposition respectively. The associated microorganisms are also categorized as aerobic and anaerobic bacteria respectively. Low-strength wastewater can be preferably treated by aerobic processes ( $\text{bCOD} < 1000 \text{ mg/l}$ ) while the anaerobic process is considered suitable for high-strength wastewater ( $\text{bCOD} > 4000 \text{ mg/l}$ ) (Sikosana et al., 2019). The performance of STPs based on biological treatment can be improved by augmenting them with emerging technologies which are based on biological nutrient removal (CPHEEO, 2013) or tertiary technologies that are used for further polishing the secondary effluent (Nemerow et al., 2009). Various treatment technologies are discussed in this section.

### 2.6.1 Activated Sludge Process (ASP)

The activated sludge process is an aerobic process in which the microorganisms remaining in suspended form, called the activated sludge, are utilized for wastewater treatment. The process mainly consists of three components, that are, aeration tank, in which the raw wastewater is introduced and mixed with air in a continuous flow, plug flow, or tapered flow form of aeration, a secondary clarifier, in which, the activated solids are separated via settlement from the effluent, and return activated sludge (RAS) equipment to pump the activated sludge back to the initial tank for aeration and re-seed the incoming raw wastewater and attain required mixed liquor suspended solids (MLSS) concentration to facilitate decomposition of organic matter, which is a mix of raw sewage and activated biological floc. When the desired concentration of MLSS is exceeded in the initial tank, excess sludge is wasted. The food to microorganisms (F/M) ratio is maintained in the system to prevent filamentous growth of microorganisms causing sludge bulking (Tare and Bose, 2009). The diagram of the process flow of ASP is presented in Figure 2.2.



**Fig. 2.2. Schematic representation of ASP (Source: Tare and Bose, 2009)**

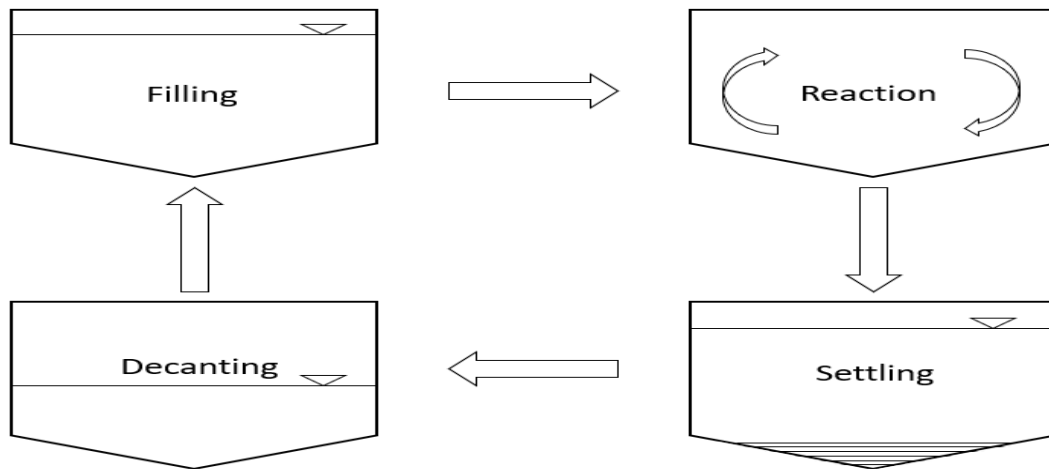
- i. Advantages
  - a) It can efficiently reduce BOD and SS concentrations.
  - b) It has lower land requirements.
  - c) Resistant to shock loading

ii. Disadvantages

- a) It is not recommended for the removal of nutrients from wastewater.
- b) It has higher energy requirements.
- c) It produces a large volume of sludge requiring disposal.
- d) It needs skilled manpower.
- e) It may fail when conditions like foaming occur as oxygen supply may get interrupted.
- f) It requires regular monitoring.

**2.6.2 Sequencing Batch Reactor (SBR)**

SBR technology is a modified version of ASP. SBR operates in batch mode and all the physical and biological processes take place in the same basin in a time-sequenced manner. This process takes place in four phases: filling, in which raw wastewater is filled in the basin in batch mode; reaction, in which, the air is supplied and mixed with the wastewater in the basin; settling, the solid and liquid phases are left to separate via settling, and decanting, in which, the treated wastewater is drawn from the basin. A minimum of two basins are required for the operation of SBR, such that while one basin is in the reaction phase, the other basin is in the settling phase and decanting. The process has higher efficiency due to better sludge-settling characteristics (Surampalli et al., 2000). The diagram representing the process flow of SBR is shown in Figure 2.3.



**Fig. 2.3. Schematic representation of SBR (Source: Tare and Bose, 2009)**

i. Advantages

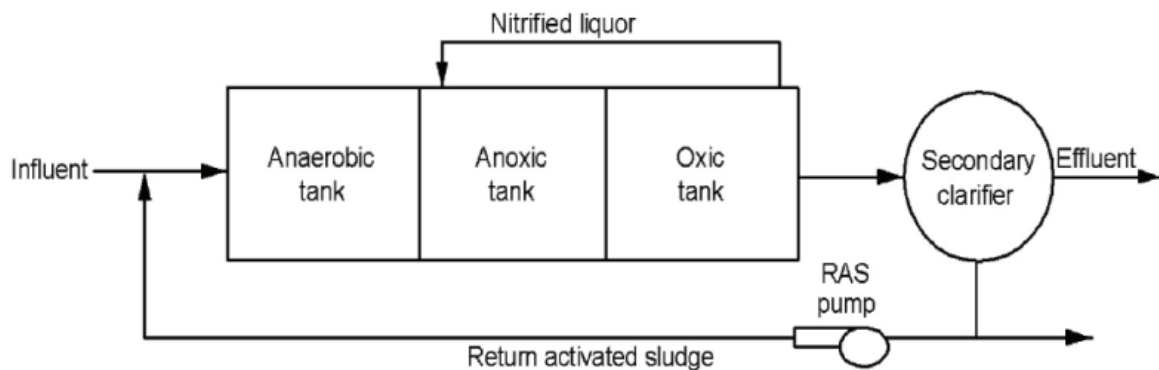
- a) It can remove nutrients N and P from wastewater.
- b) Separate settling tanks or RAS equipment are not required.
- c) Better aesthetics and no odor.
- d) Simply constructed basins are required.
- e) Resistant to shock loading.
- f) Automatic control reduces manpower requirements.
- g) High performance and better quality of effluent.

ii. Disadvantages

- a) High energy requirements.
- b) Requires sludge disposal.
- c) Skilled manpower and monitoring are required.

### 2.6.3 Anaerobic-Anoxic-Oxic (A2O) Process

A2O process is also a modified version of ASP which is primarily focused on enhancing nutrient (Nitrogen and Phosphorous) removal. The raw wastewater is firstly fed into the anaerobic tank, in which due to the absence of oxygen, the microorganisms begin to release phosphorous in the form of dissolved ortho-phosphates. The second tank is an anoxic tank, in which no oxygen is supplied, and microorganisms start utilizing oxygen from nitrates present in the wastewater for energy. This nitrate is obtained when the ammoniacal-nitrogen present in the wastewater gets oxidized to nitrate form in the oxic tank and the nitrified liquid is recirculated back into the anoxic tank. Also, in the oxic tank, the dissolved ortho-phosphates are taken up by the active Phosphate Accumulating Organisms (PAOs) and converted to polyphosphates which do not dissolve in water, this undissolved biomass is later drawn out through the secondary clarifier (CPHEEO, 2013). Therefore, this process requires a sludge thickener. The process flow diagram of A2O process is shown in Figure 2.4.



**Fig. 2.4. Schematic representation of A2O Process. (Source: CPHEEO 2013)**

- i. Advantages
  - a) High N and P removal is obtained.
- ii. Disadvantages
  - a) Skilled manpower is required.
  - b) High energy consumption.
  - c) A larger volume of tanks is required.
  - d) Equipment required for recirculation.

#### **2.6.4 Cyclic Activated Sludge Technology (C. Tech)**

C.Tech is a modified version of SBR technology that operates in extended aeration mode. This technology was developed to make the operation of the technology simpler, control the nature of activated sludge in the reactor and promote phosphorous and nitrogen removal. The addition of a biological selector, automatization of technology using programmatic logic controller (PLC) system, monitoring of oxygen uptake rate, fine air bubble diffusers, and stainless-steel decanter are some features of C.Tech. The biological selector at the front end of the tank acts as an anoxic/anaerobic zone and facilitates the release of the phosphorous, it also eliminates the issue of sludge bulking due to low F/M and hence denser biological flocs are formed. When activated sludge is recycled to the selector zone, a low oxygen condition is encountered, this leads to the uptake of phosphates by PAOs. The removal of organic matter takes place in the aeration phase and the oxygen uptake is monitored using a PLC system. Upon decrease in oxygen concentration below defined levels, oxygen is supplied to prevent the proliferation of filamentous micro-organisms. The excess sludge is wasted from the system using pumps (Tare and Bose, 2009).

- i. Advantages

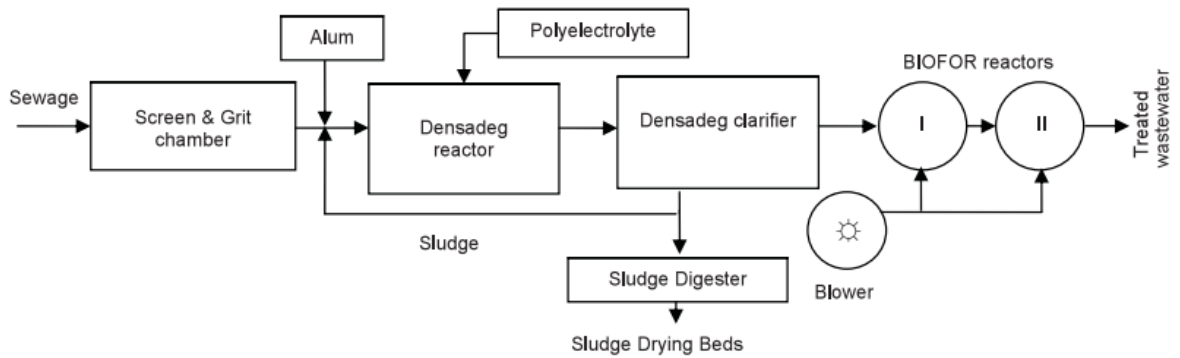
- a) Simple in operation and management.
- b) Better aesthetics and odor control.
- c) Better control on SVI (Sludge Volume Index).
- d) Foaming and bulking are suppressed.

ii. Disadvantages

- a) Requires more oxygen input per organic matter decomposed.
- b) Requires equipment for return sludge and the wasted sludge.

### **2.6.5 Biological Filtration and Oxygenated Reactor (BIOFOR)**

BIOFOR process is an aerobic attached growth treatment method. It is employed for achieving a high degree removal of organic matter, suspended solids, and nitrogen concentration. The process comprises an enhanced primary densadeg clarifier that facilitates optimal flocculation, tube settling, sludge thickening, and primary sludge recirculation. The effluent from the densadeg clarifier is introduced at the bottom of the reactor, which moves upwards through the biolite media characterized by high surface area. The filter media expands with the upward flow and the fixed film biomass decomposes the organic matter present in the wastewater. The air diffusers, at the bottom of the reactor, supply oxygen to keep optimal conditions for biomass growth, also facilitating higher contact and retention. It does not require a secondary clarifier and offers a better economy of space and high performance (Tare and Bose, 2009). The schematic representation of BIOFOR process is shown in Figure 2.5.

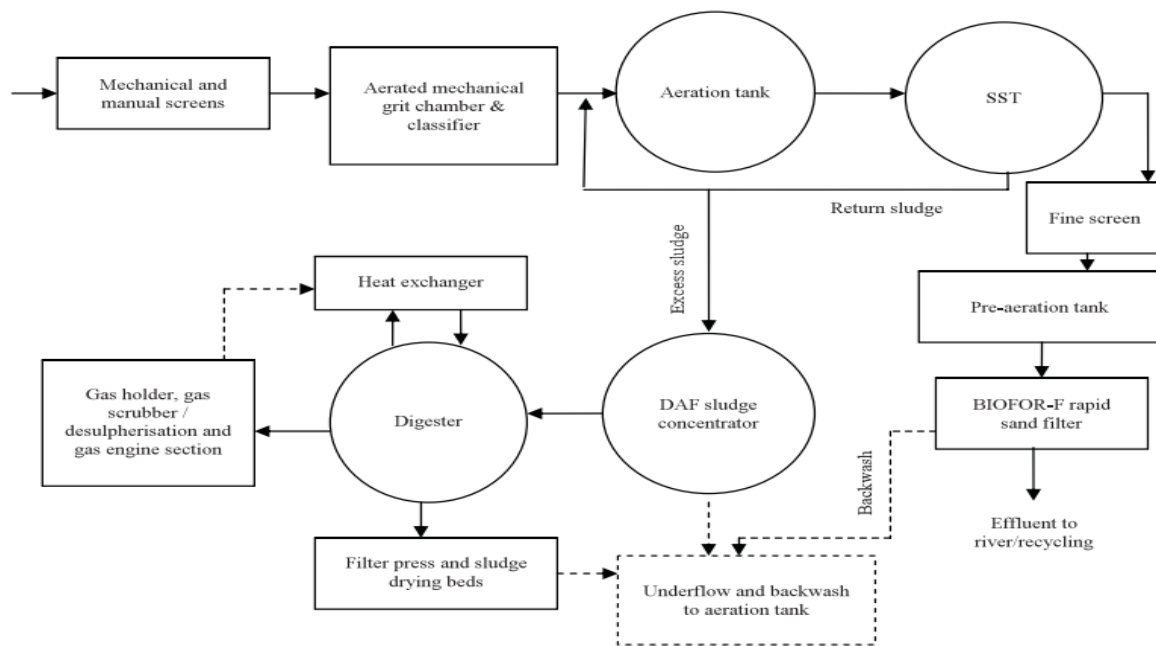


**Fig. 2.5. Schematic representation of BIOFOR process (Source: Tare and Bose, 2009)**

- i. Advantages
  - a) Robust and compact process
  - b) Simultaneous air supply along with upflowing of influent in reactor assures higher aeration.
  - c) Secondary clarifier is not required.
  - d) High quality of effluents is obtained.
  - e) Space economy
  - f) Resistant to shock loads
  - g) Absence of foaming, corrosive gases, and foul odor.
- ii. Disadvantages
  - a) Primary clarifier with coagulation, flocculation, tube settlers, and sludge digesters is required.
  - b) Larger volume of sludge is produced due to chemical dosing.
  - c) Skilled manpower is required.
  - d) Costly filter media is required.

### 2.6.6 High Rate Activated Sludge BIOFOR-F Technology

BIOFOR-F is a highly sophisticated and mechanized treatment process. Although it is similar to BIOFOR in the sense that it employs biological filtration combined with aeration, it does not require primary clarifier but an aerated grit chamber, tapered air diffusion in the aeration tank, followed by secondary clarifier, and utilizes a dual media filter for biological filtration with co-current aeration. The process also includes an elaborate sludge management process, where, the temperature of the sludge digester is maintained for maintaining proper anaerobic conditions, the contents of the digester are mixed using biogas, and dissolved air floatation is utilized for concentration of sludge. Using gas engines, electrical and thermal energy are co-generated in the system dynamically (Tare and Bose, 2009). The schematic process flow of the BIOFOR-F is as shown in Figure 2.6.

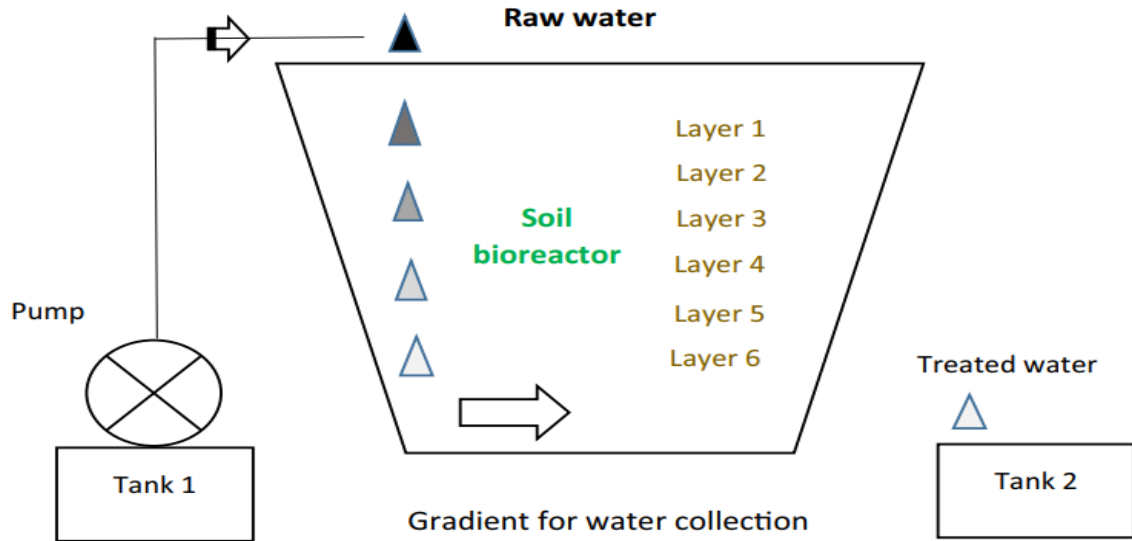


**Fig. 2.6. Schematic process flow of BIOFOR-F (Source: Tare and Bose, 2009)**

- i. Advantages
  - a) Robust and compact in nature.
  - b) Space economy
  - c) Higher performance
  - d) Good performance of digester and production of biogas
  - e) Self-sufficient without odor nuisance and corrosive gases.
- ii. Disadvantages
  - a) Capital cost and O&M costs are high.

### **2.6.7 Soil Biotechnology (SBT)**

SBT is also referred to as Constructed Sand Filter (CSF) technology. It can be constructed of RCC, stone masonry or soil bunds and utilizes gravel, pebbles, sand, or rocks as filter media. This technology utilizes natural physical, chemical, and biological processes such as filtration, sedimentation, respiration, photosynthesis, bacteriological degradation for the removal of organic matter and nitrogen present in wastewater. The process also utilizes a combination of cultured micro and macro-organisms for the treatment. The technology consists of different layers of filtration media and the influent wastewater is made to flow from top to bottom layers. While flowing through the media, the cultured biomass degrades the organic matter, the mineral composition of the filter media maintains pH in the system, the earthworms cultured for the system maintain the oxygen level, and no sludge but vermicompost is produced at the end of the process. The plants planted in the top layer of the SBT act as bio-indicators, whose photosynthesis assures proper functioning of the system beneath (Stefan et al., 2017). The schematic representation of SBT is shown in Figure 2.7.

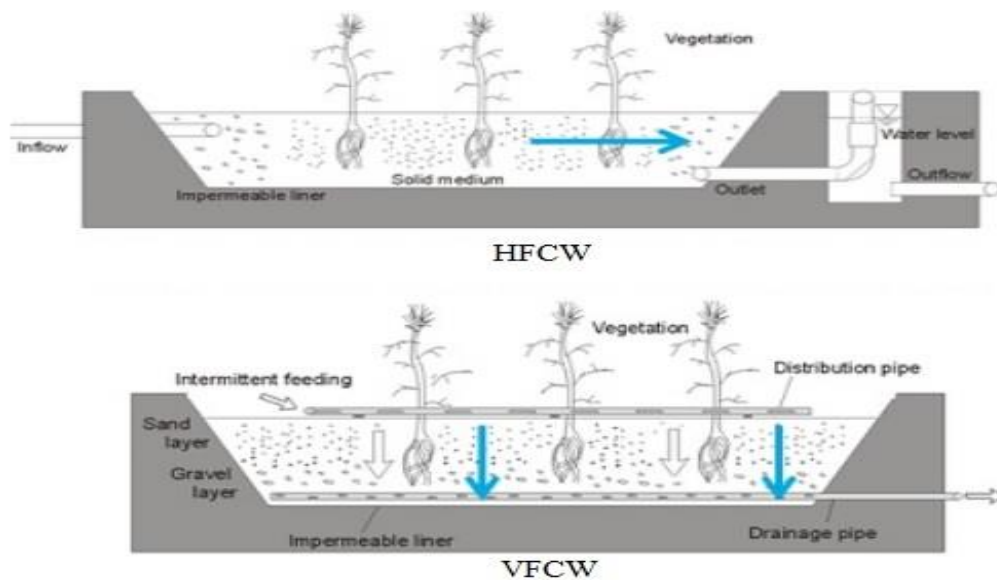


**Fig. 2.7. Schematic representation of SBT (Stefan et al., 2017)**

- i. Advantages
  - a) It does not require aeration equipment.
  - b) Requires less space.
  - c) Produces high-quality effluent.
  - d) Requires minimal maintenance.
  - e) Can treat any kind of wastewater.
  - f) No chemicals needed.
  - g) It does not produce sludge but vermicompost is obtained.
  - h) Good aesthetics and odor control.
  - i) Skilled manpower is not required.
- ii. Disadvantages
  - a) Needs to be covered during the winter season as falling temperature affects the functioning of biomass.

### 2.6.8 Constructed Wetlands (CW)

Constructed wetlands technology refers to a submerged artificial system that mimics wetlands of natural origin. Firstly, the water slowly enters the system leading to the settlement of large particles, the roots of plant species take up nutrients from the system, the filter media removes the large particles and the substrate attached to the media degrades the organic matter. The constructed wetlands produce high-quality effluents, and they can be used both as secondary technology and tertiary technology. Based on the direction of flow, the technology is of two types, vertical flow (VFCW) and horizontal flow constructed wetlands (VFCW). Wetlands are natural processes like stabilization ponds. The process flow of constructed wetlands is shown in Figure 2.8.



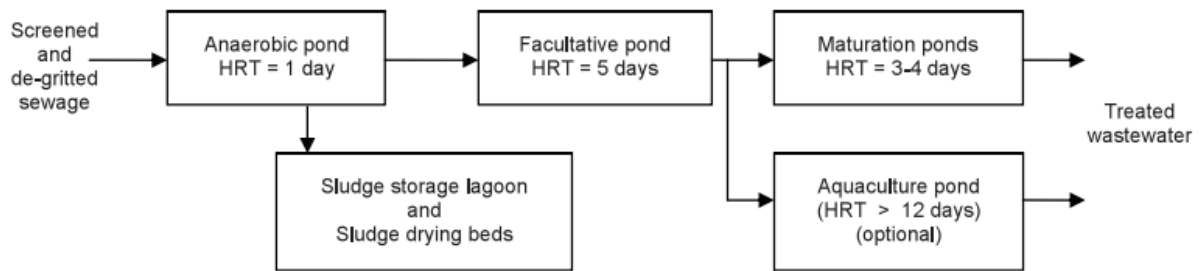
**Fig. 2.8. Schematic representation of constructed wetlands (Ramachandra et al., 2017)**

- i. Advantages
  - a) Suitable for greywater and municipal wastewater
  - b) Simple construction

- c) Low O&M and energy requirements
- d) High nutrient removal
- ii. Disadvantages
  - a) Long retention time
  - b) Large area
  - c) Affected by climatic variations.
  - d) N and P removal is low
  - e) GHGs are emitted to the atmosphere.

### **2.6.9 Waste Stabilization Pond (WSP)**

Waste stabilization ponds are artificial earthen structures constructed for wastewater treatment. This method has a higher detention period and produces good quality effluent which can be used for irrigation, aquaculture, or safe for discharge into the river system. It employs three types of ponds, each utilizing a different kind of microorganism for removing organic matter. Firstly, the raw wastewater is led into the anaerobic pond that has a higher depth and lower surface area, anaerobic decomposition takes place in this pond and the sludge produced is sent to drying beds. The effluent from the anaerobic pond is fed into the facultative pond which has a higher surface area and comparatively lesser depth than the anaerobic pond, promoting sunlight, to penetrate into the pond, and facultative microorganisms to decompose the organic matter. Thereafter, the wastewater enters the maturation pond that has complete aerobic conditions and aerobic microorganisms actively decompose the organic matter, producing very little sludge and high-quality effluent is obtained at the end. The process flow diagram of the WSP is as shown in Figure 2.9.



**Fig. 2.9. The schematic representation of WSP (Source: CPHEEO, 2013)**

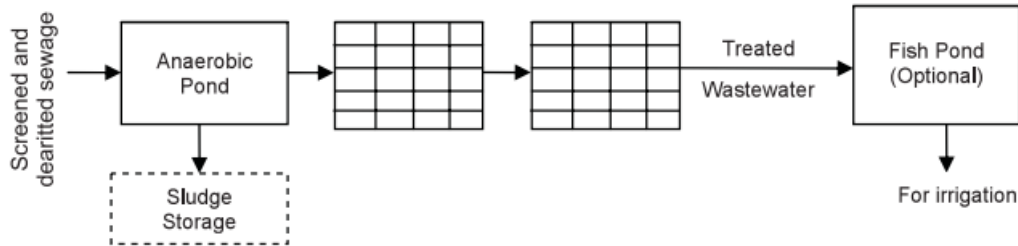
- i. Advantages
  - a) No external mechanical equipment required for aeration.
  - b) Low energy requirement
  - c) Simple construction
  - d) High-quality effluent
- ii. Disadvantages
  - a) Land requirement is high.
  - b) Detention period is high.
  - c) Lining cost of the structure is high.
  - d) Odor nuisance or breeding of mosquitoes is possible.
  - e) Algal growth can affect the quality of effluent.

#### **2.6.10 Duckweed Pond System (DPS)**

The duckweed pond system is an artificial earthen structure-based technology that utilizes thick layer of duckweed plants for the removal of organic matter and nutrients. To reduce the effect of wind and waves on the functioning of the pond, it is divided into cells with the help of bamboo or other materials. The ponds are shallower and the top layers act as facultative ponds while the lower layer functions as an anaerobic pond. It has a larger

detention time and proper management of the plants is required for optimum functioning of the system. The harvested duckweed plants are used as fish feed due to large protein content.

The process flow of DPS is shown in Figure 2.10.



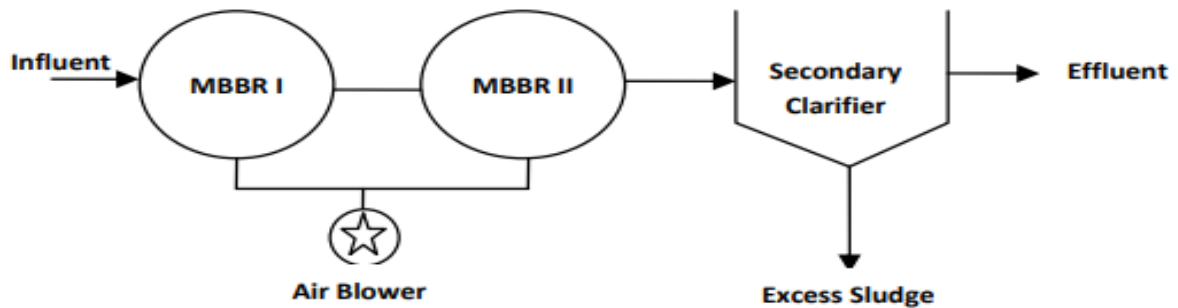
**Fig. 2.10. The schematic representation of DPS (Source: CPHEEO, 2013)**

- i. Advantages
  - a) Resistant to shock loading
  - b) No odor nuisance or insect breeding scenario as these are sheltered ponds.
  - c) Low O&M costs and energy requirement
  - d) Using fish feed generates revenue.
  - e) High organic matter and nutrient removal
- ii. Disadvantages
  - a) High detention period
  - b) Pathogen removal is low.
  - c) Duckweed plants need proper management and are intolerant of the winter season.

### **2.6.11 Moving Bed Biofilm Reactor (MBBR)**

The process uses patented media in suspension form under aerobic conditions for the treatment of wastewater. It is an attached growth process where the biomass grown on the

media surface decomposes the organic matter present in the wastewater. The plastic media, lighter in weight, has the tendency to float, and hence the downward mixing is facilitated with the help of air diffusers mounted on sides of the reactor. The nitrification process is carried out by the biomass on the periphery of the media while the inside layer of the biomass attached to the media exists in the anoxic phase and carries out denitrification. The process flow of MBBR is shown in Figure 2.11.

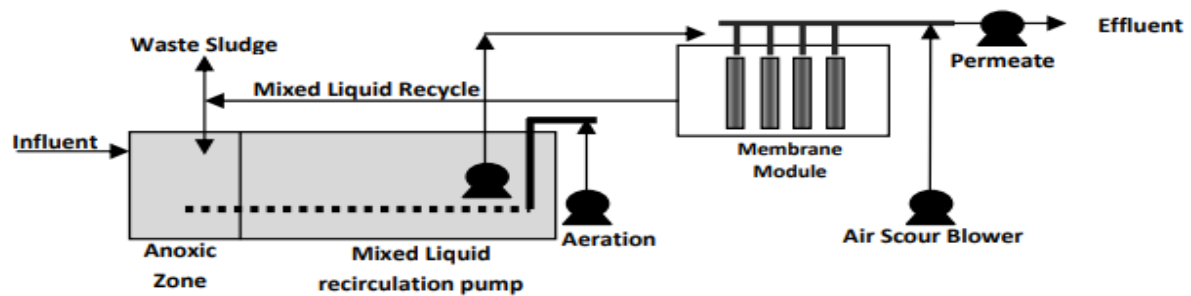


**Fig. 2.11. The schematic representation of MBBR (Source: Tare and Bose, 2009)**

- i. Advantages
  - a) Primary treatment not required.
  - b) Low detention period
  - c) Low space requirements
  - d) Resistant to shock loading
- ii. Disadvantages
  - a) High energy requirements
  - b) Skilled labor required.
  - c) Low N and P removal

### 2.6.12 Membrane Bioreactor (MBR)

A membrane bioreactor utilizes patented microfiltration low-pressure membranes in the size range of 0.1 to 0.4  $\mu\text{m}$ . The biomass exists in suspension form and the membrane helps in liquid-solid separation. The process does not require primary or secondary clarifiers or facility for disinfection. The reactor consists of aerobic and anoxic zones while the membrane is placed in the former zone. Suction pumps are used to withdraw mixed liquor from membranes leading to filtration and separation of liquids and biosolids. Air diffusers installed at the bottom force air and liquid to continuously wash out the membranes. The process flow diagram of MBR is shown in Figure 2.12.



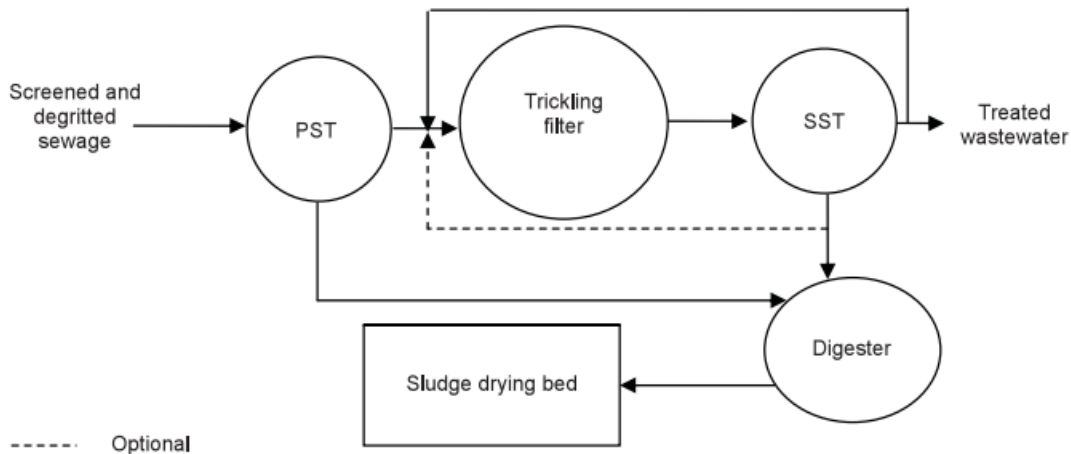
**Fig. 2.12. The schematic representation of MBR (Source: CPHEEO, 2013)**

- i. Advantages
  - a) Low land requirements
  - b) Resistant to shock loading
  - c) Sludge volume is lower.
- ii. Disadvantages
  - a) The cost of constructure is high.
  - b) O&M cost is high.
  - c) Cleaning of membranes is required frequently.

- d) The cost of the membrane is high.
- e) Membrane needs frequent replacements.

### 2.6.13 Trickling Filter

The trickling filter technology is the most basic form of an aerobic attached growth process. It utilized pebbles, gravels, rocks, or brick stones, organized in the form of a honeycomb structure for proper natural aeration, as filter media on which biomass growth takes place. The raw wastewater passing through the filter experiences mechanical straining and biological decomposition. After the biomass layer attached to the media thickens, the inner layer of biomass becomes anaerobic in nature due to lack of air penetration and subsequently gets sloughed due to the hydraulic loading rate. This process is referred to as sloughing. A clarifier is employed in this system for the removal of such sloughed biomass. Trickling filters were modified to increase the efficacy by recirculating the treated effluent back to the filter for higher organic removal. The process flow diagram of the trickling filter is shown in Figure 2.13.

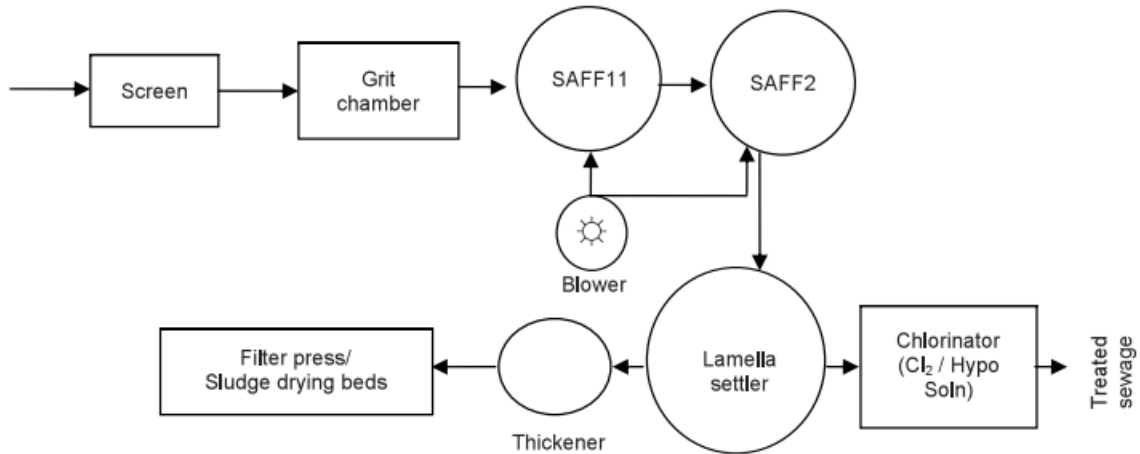


**Fig. 2.13. The schematic diagram of the Trickling Filter (Source: Tare and Bose, 2009)**

- i. Advantages
  - a) The operation is simple.
  - b) Media is not costly.
  - c) Land requirement is not very high.
  - d) BOD removal is high.
  - e) Energy requirement is low.
  - f) Settling characteristics of sludge is better.
  - g) Skilled labor is not mandatory.
- ii. Disadvantages
  - a) Odor and fly nuisance
  - b) Frequent clogging

#### **2.6.14 Submerged Aerated Fixed Film (SAFF)**

SAFF technology involves a two-stage biological oxidation process in which submerged plastic media is used to form an externally aerated submerged fixed media trickling filter, providing a higher void ratio and surface area for biomass growth and organic matter removal. This technology works on longer solid retention time and under low F/M conditions. It does not require PST and digesters for sludge. The process flow diagram of SAFF is shown in Figure 2.14.



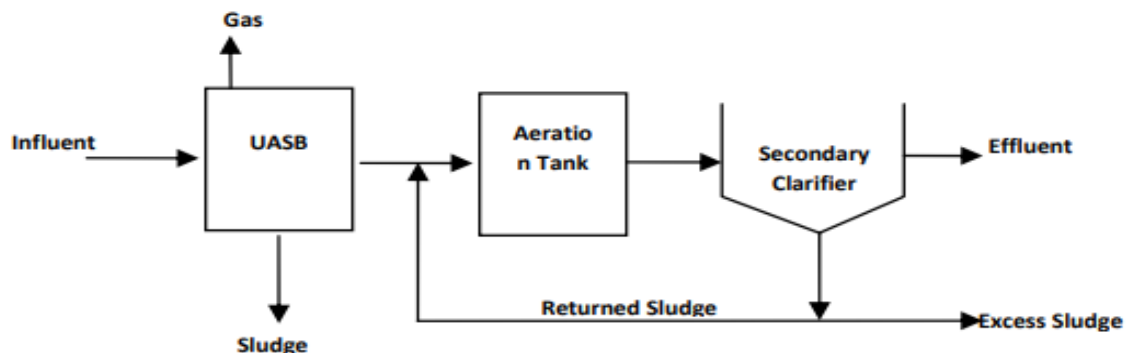
**Fig. 2.14. The schematic representation of SAFF technology (Source: Tare and Bose, 2009)**

- i. Advantages
  - a) Land requirement is low.
  - b) No need of sludge digester due to stable sludge.
  - c) No odor nuisance
  - d) High performance
  - e) Can treat diluted influents effectively.
- ii. Disadvantages
  - a) Costly special grade plastic media
  - b) External equipment required for aeration.
  - c) Skilled labor is required.
  - d) Filter gets clogged frequently.

### **2.6.15 Up-flow Anaerobic Sludge Blanket (UASB) Reactor + Extended Aeration (EA)**

The upflow anaerobic sludge blanket reactor is a suspended growth process in which the influent is directed into the reactor from the bottom, which agitates the settled activated

sludge blanket in the reactor causing mixing and removal of organic matter from the system. The technology, therefore, does not require external equipment for mixing the sludge with the influent and leads to energy savings. The effluent is withdrawn from the reactor from the top portion while the gas produced is also collected. Since UASB is an anaerobic process, the effluent is unstable in nature and has high immediate oxygen demand, this makes it unfit for release into the river system. Hence, the reactor is followed by an aeration tank which operates in extended aeration mode and stabilizes the effluent obtained. The biomass in the extended aeration phase is in the endogenous respiration phase (low F/M and high air supply) and leads to stabilized sludge formation, which is further settled in the secondary clarifier. The schematic representation of UASB followed by extended aeration process is shown in Figure 2.15.



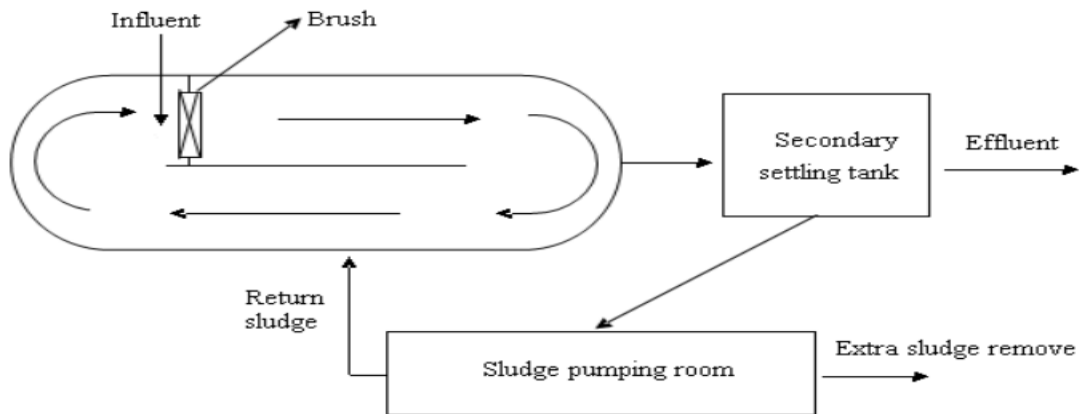
**Fig. 2.15. The process flow diagram of UASB + Extended Aeration (Source: CPHEEO, 2013)**

- i. Advantages
  - a) Power requirement is low.
  - b) The operation is simple.
  - c) Gas collected can be used for energy production.

- d) Sludge produced is stabilized.
  - e) Resistant to shock loadings
  - f) PST is not required.
- ii. Disadvantages
- a) More land is needed.
  - b) Labor requirements are high.
  - c) Coliform removal is low.
  - d) N and P removal is low.
  - e) Odor nuisance is prevalent.

#### **2.6.16 Oxidation Pond (OP)**

The oxidation pond method is employed in places where land availability is not a constraint. It operates in extended aeration mode and comprises a long oval channel, earthen or made up of RCC, or brick, along with external equipment for aeration (brush aerators) across the channel surface. The cross-section of the ditch is trapezoidal to maintain uniform velocity. The aerators provide a horizontal drift to the wastewater causing mixing of sludge with wastewater. They do not require a PST, but a clarifier is required for sludge removal. They are characterized by long detention periods. The schematic representation of oxidation pond is shown in Figure 2.16.



**Fig. 2.16. The process flow diagram of the oxidation pond (Source: Zheng et al., 2013)**

i. Advantages

- a) Easy to operate and maintain.
- b) Resilient to shock loading
- c) N and P removal is also obtained
- d) Sludge production is lesser.
- e) Energy requirement is lower.

ii. Disadvantages

- a) Land requirement is high.
- b) Detention period is long.
- c) Suspended solids concentration in withdrawn effluent is more.
- d) Odor and fly nuisance

**2.6.17 Anaerobic Lagoon followed by Stabilization Pond (AL+SP)**

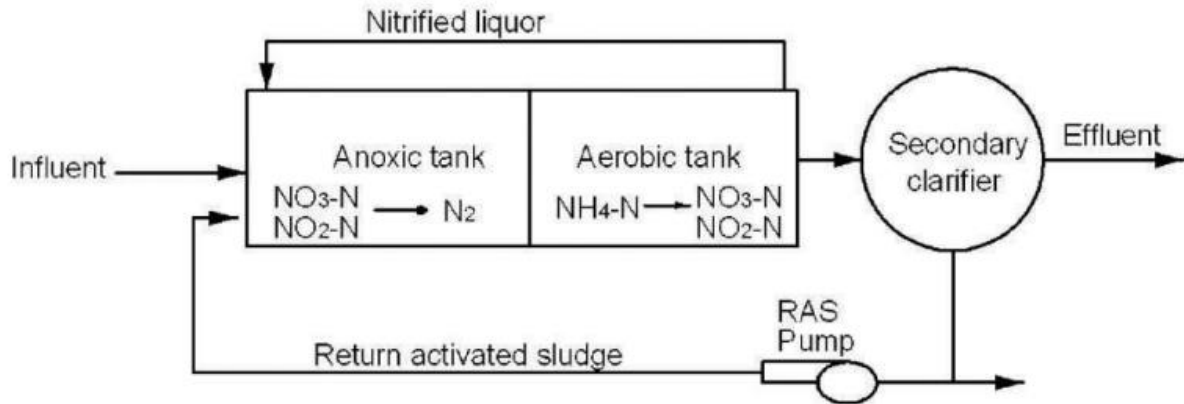
This technology combination utilizes the same principle as UASB + extended aeration combination. The stabilization pond is employed after the anaerobic pond to stabilize the effluent produced from the anaerobic lagoon. The anaerobic lagoon process is used to

decompose the organic matter present in wastewater anaerobically while flowing through an earthen basin. The basin is deeper, facilitating sedimentation and digestion of sludge. The effluent produced is very unstable and is followed by a stabilization pond which provides aerobic conditions for the stabilization of the effluent.

- i. Advantages
  - a) PST is not required.
  - b) High-quality effluent is obtained.
  - c) Resilient to shock loading
  - d) Low energy requirements
  - e) Skilled labor is not required.
- ii. Disadvantages
  - a) Odor and fly nuisance
  - b) Land requirement is high.
  - c) Long detention period

#### **2.6.18 Modified Ludzack Ettinger (MLE) Process**

The technology employs an anoxic zone followed by an aerobic zone for the removal of organic matter and nutrients. In this process, firstly, the ammonia present in the wastewater is nitrified in the aerobic basin, and then the nitrified liquor is recirculated into the anoxic basin, fixed with mixers, for the denitrification process. This process is followed by a clarifier for the removal of sludge and has high N removal efficiency. The process flow diagram of the MLE process is shown in Figure 2.17.



**Fig. 2.17. The schematic representation of MLE process (Source: CPHEEO, 2013)**

i. Advantages

- a) High N removal

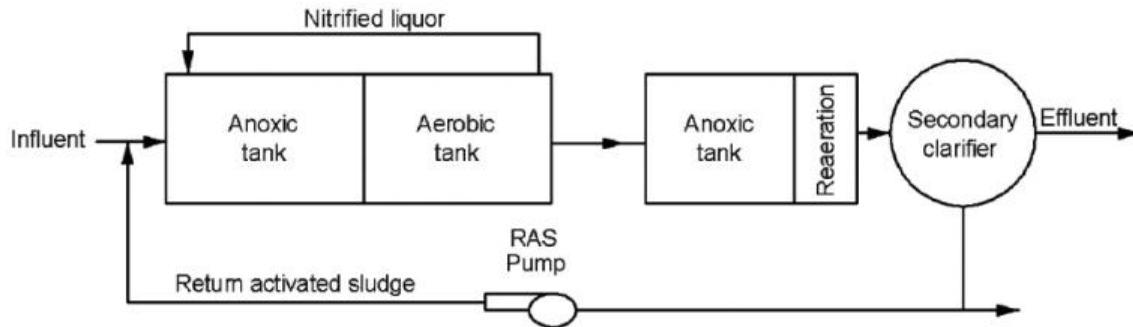
ii. Disadvantages

- a) Stringent pH, DO, temperature, and alkalinity levels need to be maintained.
- b) External equipment required for mixing.
- c) Prevalence of inhibiting or toxic substances needs to be checked.

### 2.6.19 Bardenpho Process (BP)

The bardenpho process consists of a 4-stage system in which the first two stages are similar to the MLE process, followed by a third stage which is an anoxic zone, and finally a re-aeration zone. The first two stages, as seen for the MLE process (anoxic, aerobic, recirculation), can effectively reduce carbon and nitrogen concentrations. Additional stages are employed in this process, to facilitate phosphorus removal and nitrogen removal to very low concentrations. The third zone is provided to denitrify the nitrified liquor which could not be recirculated to the first zone. In this stage, carbon is used as the electron donor while the nitrate present in the wastewater is utilized as the electron acceptor. Often, the C/N ratio decreases till this stage, and external carbon source addition is required for effective

denitrification. The last zone of re-aeration is provided to balance the lost DO in the wastewater, facilitate phosphorus removal, and stripping of nitrogen still left in the wastewater. The process flow diagram of bardenpho process is shown in Figure 2.18.



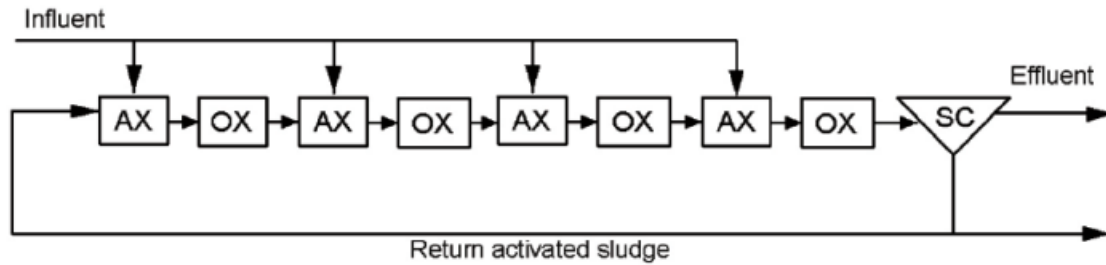
**Fig. 2.18. The schematic representation of the Bardenpho process (Source: CPHEEO, 2013)**

- i. Advantages
  - a) High N and P removal
- ii. Disadvantages
  - a) A large reactor volume is required.
  - b) Control on maintenance of proper zones in different stages is required.
  - c) External carbon sources may be very costly such as methanol.

#### **2.6.20 Step-feed Biological Nitrogen Removal (BNR) Process**

The technology comprises several anoxic-oxic stages. It follows the principle of the proportionate influent introduction at each stage and recirculation of sludge to the first stage, for higher SRT and better removal efficiency. The denitrification process is carried out in the anoxic zones when the nitrified liquor from the oxic zone is recycled to the anoxic zone while carbon, N, and P removal take place in the oxic zones. The process flow diagram of

step-feed BNR process is shown in Figure 2.19.



**Fig. 2.19. The schematic representation of the step-feed BNR process (AX: Anoxic zone; OX: Oxic zone; SC: Secondary Clarifier) (Source: CPHEEO, 2013)**

i. Advantages

- a) Resilient to shock loading
- b) Instances of peak oxygen demand are lowered, and uniform oxygen uptake is obtained
- c) SRT and HRT can be managed effectively.
- d) Better sludge settling characteristics are obtained.
- e) Capital cost is reduced as the duration of air supply is lower.

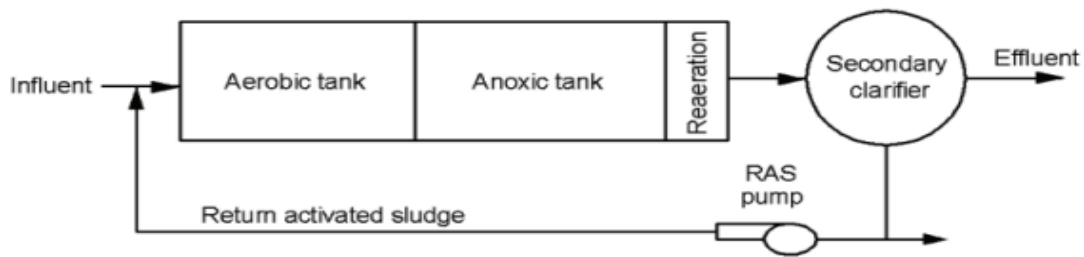
ii. Disadvantages

- a) External equipment is required for sludge recirculation and multiple feedwater introduction.

### 2.6.21 Wuhrmann Process (WP)

The wuhrmann process is also referred to as a post-denitrification process. In this process, a single stage system consisting of aerobic zone, anoxic zone and another aeration zone. This method also employs a secondary clarifier from which the sludge is recirculated to the head of the basin. The last aeration zone is provided to make up for the low C/N ratio and increase

the DO concentration in the effluent and sludge so that efficient denitrification is achieved in the anoxic zone. But it also leads to the problem of loss of nitrified effluent from the clarifier leading to lesser N removal efficiency. In MLE process, anoxic zone is placed before oxalic zone to address this problem of low carbon availability and to achieve high N removal efficiency. The process flow diagram of the wuhrmann process is shown in Figure 2.20.



**Fig. 2.20. The schematic representation of the Wuhmann process (Source: CPHEEO, 2013)**

- i. Advantages
  - a) High N removal
- ii. Disadvantages
  - a) Low C/N is often seen in the anoxic zone.
  - b) Precise monitoring and maintenance of zones is required.
  - c) The design can be more simplified.

#### **2.6.22 Coagulation + Flocculation + Rapid Sand Filters (C-F-RSF)**

The technology is used in combination to remove fine suspended and colloidal particles, which cannot be removed through the normal settling process. A suitable coagulant is dosed to the influent and rapidly mixed to disperse the coagulant throughout the influent. Later,

under the flocculation process, gentle mixing is done to promote the formation of flocs, this influent is then passed through the rapid sand filter which subsequently removes the finely dispersed and colloidal particles through mechanical straining. This process is often utilized for polishing purposes.

i. Advantages

- a) Better BOD, COD, and fecal coliform removal is obtained.
- b) Cost is less than other polishing technologies.

ii. Disadvantages

- a) Excess sludge is produced.

### **2.6.23 Microfiltration/ Ultrafiltration and Reverse Osmosis (MF/UF + RO)**

Membrane filtration is employed to achieve high quality effluent, requiring low concentrations of total dissolved solids, suspended solids, inorganic solids or organic solids. These are costlier than other tertiary processes but are high performing in nature. Different membranes correspond to the removal of different sizes of particles, hence in this chapter, microfiltration (0.1 to 5 micrometer), ultrafiltration (0.005-0.1 micrometer), and reverse osmosis (0.1-1 nanometer) are discussed.

Microfiltration can remove particles in the range of 0.1 to 5  $\mu\text{m}$ . Impurities, pathogens, and several other particulates fall in this range. In this process, through a microporous membrane, the influent is passed under low pressure, leading to removal of contaminants. Similarly, in ultrafiltration, through a permeable membrane, influent is passed to separate suspended solids having sizes greater 0.005-0.1  $\mu\text{m}$ . Reverse Osmosis (RO) membranes can reject salts due to high density or composite nature of membrane. It uses a semi-permeable membrane to pass the influent under pressure so as to let very small particles only to pass. The pressure

applied to force the separation of salts in this process is referred to as osmotic pressure. This process, however, leads to high rejection volume, which needs to be re-treated and may require extra equipment or set-up.

- i. Advantages
  - a) High contaminant removal
- ii. Disadvantages
  - a) High quality influent is required.
  - b) Associated costs are high.
  - c) High rejection rates
  - d) High volume of backwash water and rejected water containing high dissolving particle concentration.

## **2.7 Performance Characteristics of Wastewater Treatment Technologies (WWTTs)**

The municipal wastewater treatment process starts with preliminary treatment which involves mainly three operations: screening for removal of large floating materials, grit chamber for removal of sand and grit, and skimming tank for removal of oil and grease to avoid any inhibition to bioactivity of microorganisms. Around 15-30% reduction in BOD is observed after this stage of treatment (Peavy et al., 1985). Primary treatment is the second stage in wastewater treatment. This stage may or may not be employed depending upon the technology utilized in the secondary treatment. It aims at the removal of large organic materials from wastewater by settling and comprises a sedimentation tank which generally causes a 50-70% reduction in BOD (CPHEEO, 2013). This stage is followed by secondary treatment which aims at the removal of biodegradable dissolved compounds from wastewater by employing aerobic or anaerobic micro-organisms (Metcalf et al., 1991).

Normally secondary treatment lacks the removal of nitrogen from water due to more time required for nitrification to start. To aid nutrient removal, various emerging technologies are being employed, which utilize alternative oxic and anoxic phases to promote simultaneous removal of nitrogen and phosphorus from wastewater (CPHEEO, 2013). Tertiary treatment is employed for obtaining more polished effluent quality (Metcalf et al., 1991). All these stages are utilized simultaneously in a sewage treatment plant where the quality of effluent required is remarkably high. Different technologies belonging to secondary, tertiary, and emerging category and their reported performance efficiencies were obtained from literature review. The accuracy of the DSS\_IWWM will depend entirely on the preciseness of data as no other assumptions are being made in this work. The treatment efficiencies are obtained from working STPs in India and from case studies based on different technologies around the world. The values of treatment efficiencies can be utilized in tropical countries while changes may be required for different climatic scenarios outside India. The data regarding the performance of technologies is based on claimed efficiencies (CPCB, 2013) and case studies of applications in published literature and are provided in the methodology section.

## **2.8 Land, Energy, Capital Cost and O&M Cost Requirements of WWTTs**

Land cost falls under fixed cost category, that is, it is incurred independent of the functioning of the plant and depends on the desired treatment capacity only. Energy cost refers to the cost corresponding to the energy or power required for operating a technology. Capital cost falls in the fixed cost category. It is the investment made in machinery, technology installation, automobiles, equipment etc. O&M cost refers to the cost incurred for the functioning of the plant. It includes salaries, rent etc. (Tare and Bose, 2009; CPHEEO, 2013). The list of above resources required for different WWTTs is provided in the methodology

section.

## **2.9 Water Pricing**

Water pricing has been identified as an important tool to promote water conservation to prevent unsustainable utilization of water resources and create a business model to recover costs incurred (Renwick and Archibald, 2018). The imposition of a price structure leads to indirect management of demand and ensures sufficiency, efficiency, and equity in the system (D'odorico et al., 2020). In the European Water Framework Directive, an overarching approach to managing water resources is emphasized that includes pricing as a means to value water and recover costs (Berbel et al., 2019). However, since water consumption is a necessity for the survival of life, water should be treated as a special economic good and consideration of the sensitivity of the community to pricing and understanding the response of consumers is also very important (Mathur and Thakur, 2003). Therefore, several economic instruments have been identified to address water from a socio-economic perspective.

Several economic instruments, largely based on three basic mathematical approaches were found in the published literature, especially taken from the India focused literature (MoUD, 2010):

(a) fixed cost, in which a constant cost (say A) is levied on households, and it is independent of the amount of water consumed.

$$\text{Total Cost per month} = A \text{ (constant)}$$

(b) uniform volumetric rate, in which a fixed per unit price of water (say B) is levied, the cost increases with volumetric consumption (say V volume consumed in a month) at a uniform rate.

$$\text{Total Cost per month} = A * V$$

One variation in this approach is charging a constant base price (say C) and also costing volumetric price.

$$\text{Total Cost per month} = C + A * V$$

In this case, even if the consumption is zero, the base charge is paid by the consumer.

(c) Block Price, in this approach, the unit price of water changes once a threshold volume of water is consumed, therefore, unit prices vary based on the slab in which the volume consumed falls. The block approach can be increasing block or decreasing block, if the unit price of water increases with increasing slabs or if the unit price of water decreases with increasing slabs respectively.

If 'a' unit price is levied till first 30 liters of water, 'b' till next 30 liters and 'c' till next 30 liters, while total volume consumed is 50 liters.

$$\text{Total Cost per month} = 30 * a + 20 * b$$

Similar to the uniform volumetric rate approach, a base constant price can also be included in this approach.

In earlier attempts to institutionalize water pricing, a lot of resistance from society was seen. Since different countries and different areas within countries grapple with different challenges and strains, a price that is fair socially, that will not overburden the poor communities but still ensure recovery of costs is required, sensitive to necessities of all different regions and sectors (Babel et al., 2005). Berbel et al. (2019) emphasized the sensitivity of water pricing to the type of economic sector and geographic location, such as in agriculture, different factors such as land, output, fertilizers, and labour play a role while in the industrial sector, the type of industry, the product, quantity, output, production process,

labour will play a significant role. If secure and innovative instruments and policies are not developed, water scarcity can become a hard-hitting reality within a few decades. Therefore, to tackle this issue and to put an innovative solution in place, many countries have embarked upon the journey to explore possible water pricing structures. A failure in preventing unsustainable use of water was observed in Ghana due to lack of association between water pricing and efficient consumption (Soto Rios et al., 2018). Similarly in a study conducted by Exposito and Berbel (2017) in Spain concluded that inefficient consumption of water cannot be avoided by using fixed cost approach. The uniform volumetric pricing approach, adopted by France, led to better and management of water resource. In India, the municipal bodies are finding it hard to even pay expenses for running of the STPs (Parween jet al., 2021). Mathur and Thakur (2003) emphasized that setting appropriate prices is indispensable to providing adequate water to India's growing urban population. In a report published by the Ministry of Urban Development (MoUD, 2010), a comparison of different water tariff models was presented. The study evaluated the models based on the four principles of setting water prices, that are, recovery of cost, efficiency in economic recovery, equity in cost levying, and affordability, defined by Whittington (2002). As per the study, the uniform volumetric rate model was rated most convenient along all the four principles while the fixed cost approach was rated most ineffective in conserving water. The increasing block approach was rated poor for equity since large poor households would be charged more while decreasing cost approach was rated poor in affordability and equity as it would lead to unsustainable consumption and lesser costs (MoUD, 2010).

Water Pricing is an effective tool for controlling the unsustainable utilization of water, but very conscious decisions need to be made while dealing with commodities of such relevance

and sensitivities. Therefore, an approach that considers the social condition of a region or country while also accounting for the cost recovery aspect is required. The needs of the socially prioritized sections of society should always be preceded before satisfying the economic requirements.

## **2.10 DSS for Appropriate Wastewater Treatment Technology Selection, Demand Allocation and Water Pricing**

The approach of a decision support system enables effective decision-making based on the comprehensive analysis of background information using efficient tools and methods. It is being widely applied in the wastewater management field. Several factors play a significant role in the installation and operation of an STP, therefore, making the wastewater-related DSS a multi-criteria decision-making problem (Arroyo and Molinos-Senante, 2018). Several DSS were developed in the past two decades aimed at increasing the efficiency and reclamation capacity of STPs (Bottero et al., 2011). Chamberlain et al. (2013) developed a DSS for the selection of sustainable solutions to the problem of wastewater treatment. A DSS was developed by Sadr et al. (2018) for the technology selection by using fuzzy-TOPSIS and AHP. Garrido-Baserba et al. (2019) presented a DSS based on knowledge collection for the selection of treatment technologies. Several studies have been conducted for the selection of appropriate technology for specific type of wastewaters, e.g., domestic (Kalbar et al. 2012), molasses-based wastewater (Syutsubo et al. 2013), industrial wastewater (Castillo et al. 2017), disinfection technologies selection for reuse (Gomez-López et al. 2009), etc. However, the procedure for the selection of an appropriate technology that suits both local environment and reuse quality criteria is not yet defined. Till

now, technology selections are entirely based on past results and perceived efficiencies of previously installed technologies, thereby leading to under-performance of STPs and huge debt-burden on governing agencies (CPCB 2013). The investment in sewerage and sewage treatment infrastructure does not reflect as gain to water economy.

Multi-criteria decision-making (MCDM) tools have been used for appropriate wastewater treatment technology selection in different fields. Analytic Hierarchy Process (AHP) is the most applied MCDM tool in environmental decision-making problems owing to its more realistic, easy implementation, and transparent methodology. In a study conducted for technology selection for coking wastewater, AHP was applied using four major decision criteria, namely technical, economic, environmental, and administrative factors, and six alternatives were obtained by varying oxygen phases in an ASP (Wei et al., 2020). Zeng et al. (2007) applied AHP with gray relational analysis (GRA), (which is effective in solving relationship problems between different parameters) for optimal wastewater technology selection and four alternative conventional technologies were rated against technical, economic, administrative, and performance criteria. It was reported that GRA fails to give a feasible result (Wei, 2009). Kalbar et al. (2012) utilized the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method for ranking of four alternative technologies against seven criteria including several environmental indicators including sustainability, eutrophication, etc., and operational indicators such as land needs, manpower needs, and cost attributes. TOPSIS often suffers from rank reversal problem which compromises the accuracy of results (Yang, 2020). Ilangkumaran et al. (2013) utilized fuzzy AHP and Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) tools for optimal wastewater treatment technology selection out of 5 technologies: electro-

coagulation, SBR, reverse-osmosis, ultrafiltration, and anaerobic digestion based on three criteria: (1) Social and environmental, (2) Economic, and (3) Technical. Dursun (2016) suggested the Vlse Kriterijska Optimizacija I Komoromisno Resenje (VIKOR) method for obtaining appropriate technology. Zhou et al. (2020) employed the AHP-VIKOR method for the selection of technologies for municipal sludge disposal, but the VIKOR method is complex in nature and cannot be used for performance-based problems (Kraujalienė, 2019). Alfonsín et al. (2015) utilized life cycle assessment (LCA) to study the environmental viability of two biological treatment methods, namely, bio-trickling filter and biofilter, and two physical/chemical processes such as activated carbon tower and chemical scrubber. But LCA is a very detailed and time-consuming method. It is not feasible while working in multiple criteria and multiple alternatives scenarios (Wastiels and Decuyper, 2019). It also does not provide a direct interpretation of the result (Hermann et al. 2007). In a complex problem where multiple criteria need consideration, it is necessary to include weightings for reflecting the impact of different criteria (Ling et al., 2021). Gherghel et al. (2020) applied weighted sum method to converge the role of multiple indicators to a single index while assessing municipal wastewater treatment system. Similarly, a weighted sum method was applied to evaluate sustainability of sewage treatment plants by Molinos-Senante et al. (2016). It was also utilized for assessment of tertiary treatment technologies and as an efficient approach to include the impact of necessary pillars of sustainability by Plakas et al. (2016).

## **2.11 Identification of Research Gaps**

Water stress has become a constant problem in many parts of the world (Lyu et al., 2016). Wastewater reclamation can be seen as a potential source of water, which if treated, can boost water availability as well as prevent environmental degradation (van Zyl and Jooste, 2022). By observing the trend of water demand and the definition of relevant quality criteria, raw wastewater can be treated to produce a secondary water source (Reyes, 2022). Several countries have started exploring wastewater reclamation as a potential solution to the imminent water crisis (Roccaro and Verlicchi, 2018). However, the concept of wastewater reclamation is not yet well-established in India. This statement stems from the fact that installed STPs and even the proposed to-be-installed STPs are not reuse-focused (CPCB, 2021). The effluents from these STPs are treated majorly for safe release in the nearby river systems or for agriculture only (CPHEEO, 2013). Non-abidance to quality criteria and direct release in the river system is one of the biggest reasons behind unabated water pollution (Herbig, 2019). The gap between wastewater generated, collected, treated, and re-used need to be bridged to obtain self-sufficiency in terms of water availability (Sgroi et al., 2018). Since the installation and operation of treatment technologies in sewage treatment plants is the most important element necessary for the success of the wastewater reclamation approach, many studies have been conducted to suggest the most suitable treatment technology while considering different decision criteria and methodologies (Kalbar et al., 2012; Ullah et al., 2020). Decision Support Systems have also been recognized as an efficient tool that enables smooth decision-making in case of complex problems (Paredes-Arquiola et al., 2010). DSSs have also seen application in the selection of wastewater treatment technology based on different approaches such as life cycle assessment, multi-criteria

decision making and knowledge-based approaches.

The following observations were made after a comprehensive review of the published literature in the field of integrated water and wastewater management:

- There is a lack of systematic approach to institutionalize wastewater reclamation in cities.
- A nationwide and self-sufficient integrated water and wastewater management network is yet to become a reality as most countries are at a very nascent stage in this field of development.
- A comprehensive study of factors affecting an integrated water and wastewater network and interactions between the factors is required to better understand the dynamics of the proposed approach.
- A re-use focused and socio-economically feasible approach to wastewater treatment technology selection is lacking.
- Definition of proper guidelines and framework for establishing an integrated water and wastewater management is required in areas such as, appropriate treatment technology selection, quality criteria prescription for different reuses, demand estimation and allocation for urban reuse purposes and sustainable water pricing for cost recovery.
- Remodeling of the linear water cycle of communities into a circular economy through localised or specialized city-wise models is needed.
- Development of a feasible business case is required to attract investors and to bridge the financing gaps.

## **2.12 Scope of the Present Study**

Due to changing climate, exploding population and shrinking freshwater resources, above observations call upon the need to develop an integrated water and wastewater management network, that would make a community self-sufficient in water resource management. Therefore, this study aims to develop a DSS for integrated water and wastewater management (DSS\_IWWM) that:

- Identifies the key factors affecting reuse focused IWWM,
- Combines the quality criteria experiences from across the world to obtain those for different reuse purposes,
- Estimates and allocates the reclaimed water demand meeting the socio-economic and technical feasibilities,
- Based on the desired reuse purpose, suggests the most appropriate treatment technology combination, from its library of technological combinations,
- Suggests sustainable reclaimed water prices for cost recovery,
- Facilitates localized planning of reclaimed water around STPs.