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Contents

Biofuel Production Along with Remediation of Sewage Water Through Algae

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Highlights

- The study reveals that man-made lake systems, Bellandur and Varthur, Bangalore, performed well under higher organic load with a COD removal efficiency of 70 %, TN removal efficiency of 73 % and TP removal efficiency of 22 %.
- Facultative pond-based systems at Mysore were very effective in suspended solid (SS) removal of up to 93 % and BOD removal of up to 82 %.
- The extended aeration-based Sewage Treatment Plant (STP) systems, Bangalore West, were good in terms of SS removal of up to 88 %, COD removal of up to 74 % and BOD removal of up to 63 % but were highly ineffective in nutrient removal.
- The existing large lake systems and the facultative pond systems can be designed for a better photosynthetic yield resulting in higher algal biomass which would not only polish the wastewater but at the same time will act as substrate for lipid/biofuel generation by a novel algal trap mechanism.
- The treatment efficiency analysis showed that the facultative pond-based systems situated at Mysore were the most effective options for the urban wastewater systems compared to the lake-based systems as well as the energy-intensive mechanical systems with their nutrient-integrated treatment efficiency of more than 68 % and the final effluents with an adorable effluent quality for disposal for irrigation.

1 Introduction

Liquid waste generated in the domestic, commercial, industrial and agricultural sectors comprises organic and inorganic constituents. Wastewater mostly consists of water (~99 %) and solids (~1 %). Numerous treatment processes are being adopted to treat wastewaters depending on the nature, type and extent of contamination. The treatment of wastewater is essential to minimise the contamination of land, water and soil. Treated wastewater can then be reused for various applications that help in reducing freshwater usage. Treatment of wastewater requires an analysis of wastewater characteristics, which helps in finding appropriate technologies pertaining to the region. The quantum of domestic sewage generation has multiplied manifolds due to the rampant development, increased industrialisation and rapid urbanisation. It is estimated that water demand is about 42×10^6 MLD (million litres per day) (National Commission for Integrated Water Resource Development 2010) (NCIWRD 1999) (Fig. 4.1), and about 33.6×10^6 MLD domestic wastewater is generated in India. The urban pockets are the potential generator of wastewaters, i.e. 23,000 MLD, and out of which 5000 MLD is being treated. This necessitates cost-effective sustainable treatment options.

Urbanisation in India since the last century shows an increase in urban population, the number of urban centres

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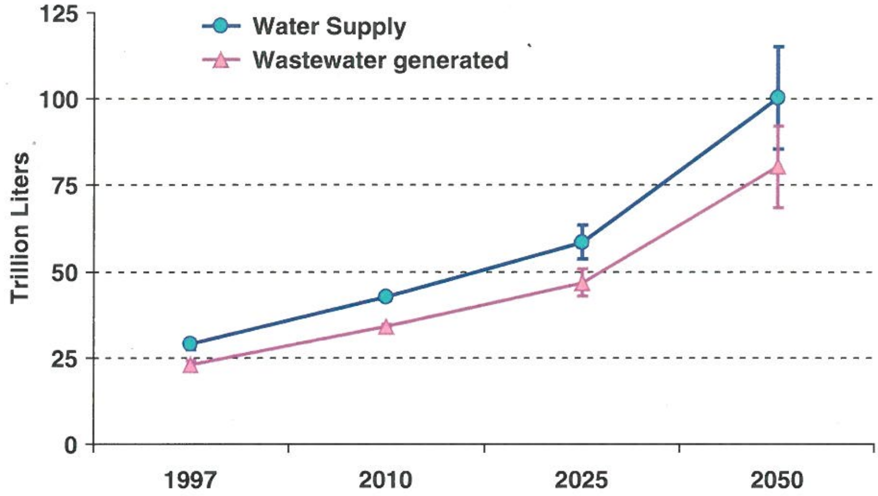


Fig. 4.1 Water supply (NCIWRD 1999) and wastewater generated in India

and a rapid rise after 1951. The number of urban dwellers has risen to 285 million from 25.8 million persons in 1901, highlighting an 11-fold increase in urban population over the period 1901–2001 (CPCB 2011). Due to increased population, substantial volume of domestic wastewater is being disposed into surface water bodies resulting in water pollution and is a consequent threat to the aquatic biota and human health. Indiscriminate disposal of wastewater has contaminated the groundwater and soil adding to the existing miseries of humankind.

The population of India is expected to stabilise at ~1.7 billion people by 2050 (NCIWRD 1999). As per the census of 2001, the urban population is 285 million, and keeping in view of the population projection for the year 2051, it is likely to be of the magnitude of 1093 million. Based on these, wastewater generation in 2051 would be about 132 billion litres per day (CPCB 2011). Hence, there is an urgent need for a proper, feasible, cost-effective (Onkal and Demir 2006) and less energy-intensive wastewater treatment approach to suit the tropical climatic scenario while attaining maximum wastewater treatment in urban centres. However, the associated costs need to be assessed before planning of the treatment plant projects (Asano 1991; Hernandez-Sancho et al. 2011).

A large number of algae grow copiously in wastewater capitalising on available organic carbon and inorganic nutrients (N and P) and also play vital function of remediation by removing N and P (Mahapatra et al. 2013a, b; Mahapatra and Ramachandra 2013; Ramachandra et al. 2013). The use of algae in wastewater treatment has been highly effective with the conventional oxidation (stabilisation) ponds or the suspended algal pond systems such as high-rate algal ponds (Green et al. 1995; Hoffmann 1998; Munoz and Guieysse 2006). In algal systems, photosynthetic algae with O_2 generation help in aeration avoiding the requirement of energy and labour-intensive mechanical aeration. Oxygenation of ponds through algae also aids in bioremediation of organic and inorganic compounds by heterotrophic aerobic bacteria (Oswald et al. 1957). Furthermore, algae-based remediation does not generate additional pollutants and provides an opportunity for efficient recycling of nutrients, while it is an environmentally sound and sustainable option to manage wastewater.

Algae can grow at higher densities in highly concentrated wastewaters (Wang et al. 2009) to secondary treatment wastewaters often also used for tertiary polishing of wastewaters (Oswald et al. 1957). Algae transform wastewater C (organic/inorganic C) into algal biomass C. It has been reported that a substantial amount of this C is also found as lipids in certain wastewater algae (Mahapatra et al. 2013a; Mahapatra and Ramachandra 2013; Ramachandra et al. 2013; Wang et al. 2009). Lipid synthesis in wastewater algae provides additional benefits of algal biofuel development coupled with nutrient removal and wastewater remediation and ensures maximum resource utilisation (Mahapatra et al. 2014). Earlier growth studies by culturing algae in wastewaters have revealed high biomass productivities with reasonable lipid yield (Mahapatra et al. 2013a, 2014; Mahapatra and Ramachandra 2013). Such investigations have also shown high potential of wastewater algae (Mahapatra et al. 2013a) and algal consortia (Mahapatra et al. 2014) for removing C, N and P (Oswald et al. 1957; Wang et al. 2009). This highlights the scope of wastewater-grown algae for biofuel production and as potential alternate energy sources. Experimental studies involving wastewater-grown algae will help in addressing the driving factors to maximise biomass production and subsequent efficient harvesting for optimal lipid extraction.

Algal biomass as a potential biofuel feedstock paves suitable path in exploring potential options to meet the energy shortfalls (Mahapatra et al. 2013a). The dwindling stock of fossil fuels coupled with escalating oil prices and growing concerns towards greenhouse gases due to global warming and consequent changes in the climate has necessitated exploration for viable energy alternatives (Ramachandra et al. 2009). Challenges in algae-based biofuel production are consistent supply of nutrients, harvesting of algae and effective lipid extraction techniques (Shen et al. 2009). The fuel production involves a series of unit processes as algal species selection, mass cultivation, biomass harvesting, biomass concentration, lipid extraction and refining. This entails an understanding of algal downstream processing and process optimisation for its sustainable utilisation and commercial exploitation.

Studies on efficiency of the wastewater treatment plants based on water reuse and alternative source of water resources have used analytical benchmarking method of DEA (Data Envelopment Analysis) (Hernandez-Sancho and Ramon 2009). Provisions are to be made to improvise the pond systems for better treatment efficiency and to improve the effluent quality and hence safeguard drinking water resources. Therefore, detailed studies are required for understanding the mechanism of the pond-based systems to tackle the problem in best possible way which completely reduces the organic and nutrient load and at the same time kills pathogens for its use in agriculture and other activities.

Earlier several studies have investigated the treatment plant efficiencies in many cities of India as New Delhi (Jamwal and Mittal 2010), Indore (Sharma and Dubey 2011), Yamuna basin (Sato et al. 2007), Bangalore West (Kumar et al. 2010) and Mysore (Shakunthala et al. 2010) and in other countries as Algeria (Driche et al. 2008), Greece (Andreadakis et al. 2003), Spain (Colmenarejo et al. 2006), Iran (Sadeghpoor et al. 2009), Mexico (Alcocer et al. 1993), South Africa (Samie et al. 2009), Brazil (da Costa and Medri 2002), etc. These studies however do not address the socio-economic aspects of the treatment systems. The main focus of the present study is to assess lipid and bioremediation potential of algae, which involves:

1. Evaluation of treatment efficiency of the large man-made lake systems with facultative pond-based systems and mechanical STP (using extended aeration and/or activated sludge processes)
2. Scope of biofuel production from algae growing in wastewater-fed lakes and facultative ponds
3. Valuation of the wastewater system considering the capital, environmental and societal aspects
4. Formulating an alternative treatment option for urban cities
5. Ranking/grading the plant performance considering critical parameters based on efficiency criteria

2 Materials and Methods

2.1 Study Area

The city of Bangalore spans over an area of more than 741 km^2 and is one among India's fastest growing city. A current temporal analysis of wetlands, however, indicates a decline of 58 % in Greater Bangalore which can be attributed to intense urbanisation processes. This is evident from a 466 % increase in built-up area from 1973 to 2007 (Ramachandra and Kumar 2008). The undulating topography, featured by a series of valleys radiating from a ridge, forms three major watersheds, namely, the Hebbal Valley, Vrishabhavathi Valley and Koramangala and Challaghatta Valleys that form important drainage courses for the interconnected lake system which carries storm water beyond the city limits (Mahapatra et al. 2013b). Bangalore, being a part of peninsular India, had the tradition of harvesting water through surface water bodies to meet the domestic water requirements in a decentralised way. After independence, the source of water for domestic and industrial purposes in Bangalore is mainly from the Cauvery River and groundwater. Untreated wastewater is let into the storm water drains which progressively converge at the water bodies (Mahapatra et al. 2013b).

The city of Mysore spans over an area of more than 130 km^2 and is a very first urbanising region. It has five major catchment districts. The topography of the city divides into five prominent drainage basins. The city's wastewater is let into three wastewater treatment plants through gravity draws. The northern region is handled by a 30.0 MLD STP (powered by aerators). The south-western regions' wastewater flows to STP (67.65 MLD) which uses organic microbe-mix inocula (OS-1 and OS-2) for treatment before entering Dalavai kere. Further south is the STP of 60 MLD at HD Kote Road working with microbial solutions as inocula to treat the wastewater. All these plants consist of facultative aerated lagoons followed by sedimentation basins. During the study period the treatment pond basically was functioning as an algal pond. The different wastewater treatment plants, their installed capacities and total water supply in Bangalore and Mysore are provided in Tables 4.1 and 4.2, respectively.

Table 4.1 Capacities of sewage treatment plants at Bangalore and Mysore

Sl. no.	Location	Capacity in MLD	Treatment facility
	Bangalore – CWSS stages I, II and III		
1	Vrishabhavathi Valley	180	Secondary: trickling filters
2	K&C Valley I	163	Secondary: activated sludge process
3	Hebbal Valley	60	Secondary: activated sludge process
4	Madivala	4	Secondary: UASB + oxidation ponds + constructed wetlands
5	Kempambudhi[a]	1	Secondary: extended aeration
6	Yelahanka	10	Activated sludge process + filtration + chlorination (tertiary)
	Bangalore – CWSS stage IV, phase I		
7	Mylasandra	75	Secondary: extended aeration
8	Nagasandra	20	Secondary: extended aeration
9	Jakkur	10	Secondary: UASB + extended aeration
10	K.R. Puram	20	Secondary: UASB + extended aeration
11	Kadubeesanahalli	50	Secondary: extended aeration
12	K&C Valley II	30	Secondary: extended aeration
13	K&C Valley III	55	Secondary: CMAS
14	Raja canal	40	Secondary: extended aeration
	Total	**718**	
	Mysore – HWSS stages I, II and III		
1	Kesare Valley	30	Secondary: alternate extended aeration
2	Vidyaranyapuram	67.5	Secondary: pond-based fermentative bacteria (OS)
3	Rayankere	60	Secondary: pond-based microbe solution (Fermenta)
	Total	**157.5**	

[a]Under progress

Table 4.2 Total water supply to Bangalore and Mysore cities

Sl. no.	Projects	Supply capacity (MLD)
	Bangalore (CWSS)	
1	Arkavathy (TG Halli)	60
2	Cauvery stage I	135
3	Cauvery stage II	135
4	Cauvery stage III	300
5	Cauvery stage IV, phase I	270
6	Cauvery stage IV, phase II*	(270)
7	Cauvery stage IV, phase III*	(500)
		900 (1670)
	Mysore (HWSS)	
1	Hongally WSS (stage I & II),	30
2	Hongally WSS (stage III),	45
3	Belagola WSS	43.5
4	Melapur WSS	41.5
		160

*in progress

1. Man-made lake systems: Varthur and Bellandur Lakes (~500 MLD), Bangalore South
2. Mechanical treatment systems: aeration and activated sludge (75 MLD), Bangalore
3. Facultative pond-based systems: STP (67.5 MLD), Mysore

2.2 Field Sampling and Laboratory Analysis

Field samplings of influent (1), middle (2) and effluent (3) water samples were carried out between March and August 2011 (Figs. 4.2 and 4.3). The qualities of influents and effluents were assessed to determine the efficiency of the treatment plant.

On-site analysis was performed to record pH, water temperature, electrical conductivity (APHA method 205), oxidation-reduction potential (ORP), total dissolved solids (TDS), salinity, dissolved oxygen (DO), dissolved free carbon dioxide (free CO_2) and turbidity using the standard methods. One litre subsample was analysed according to standard methods (American Public Health Association) (Public Health Association) AWWA WEF 1995): total biochemical oxygen demand over 5 days (BOD_5) (APHA method 507), filtered BOD_5; chemical oxygen demand (COD) (APHA, 5220 C); suspended solids (SS) (APHA method 209c); SAR (APHA 1206); turbidity (Hach turbidimeter, APHA method 214a); ammoniacal nitrogen (APHA method 417a); total nitrogen (TN) (APHA method 420a, total nitrogen) and phosphates (APHA, 4500-P D). In addition, visual clarity or transparency of the lake/STP wastewater was measured with a Secchi disc. Algal species collected from the lake systems and facultative ponds (both

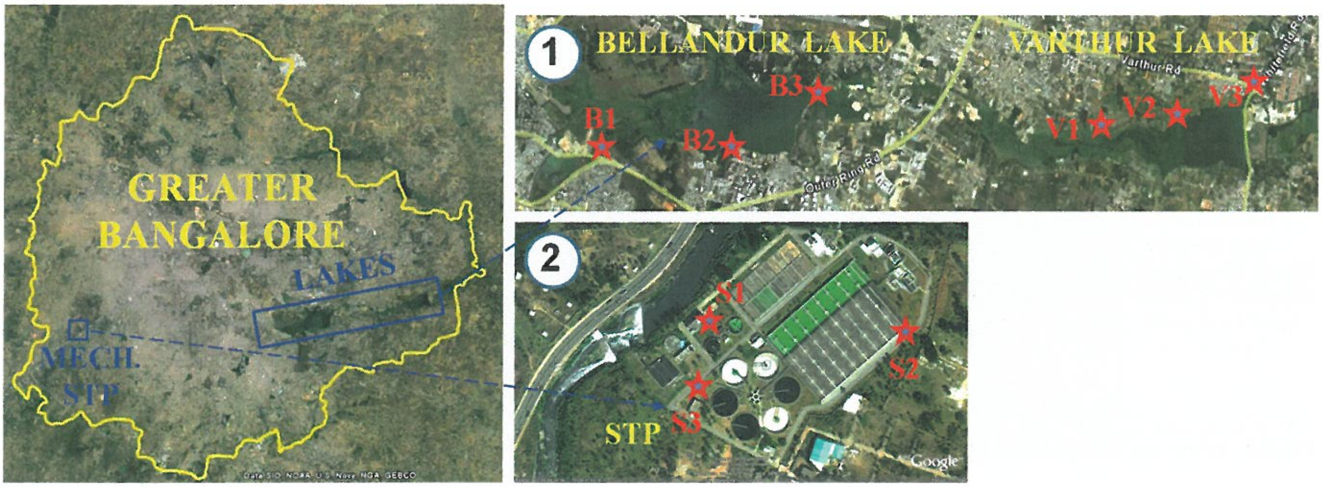


Fig. 4.2 Greater Bangalore: (*1*) lake systems and (*2*) sewage treatment plant

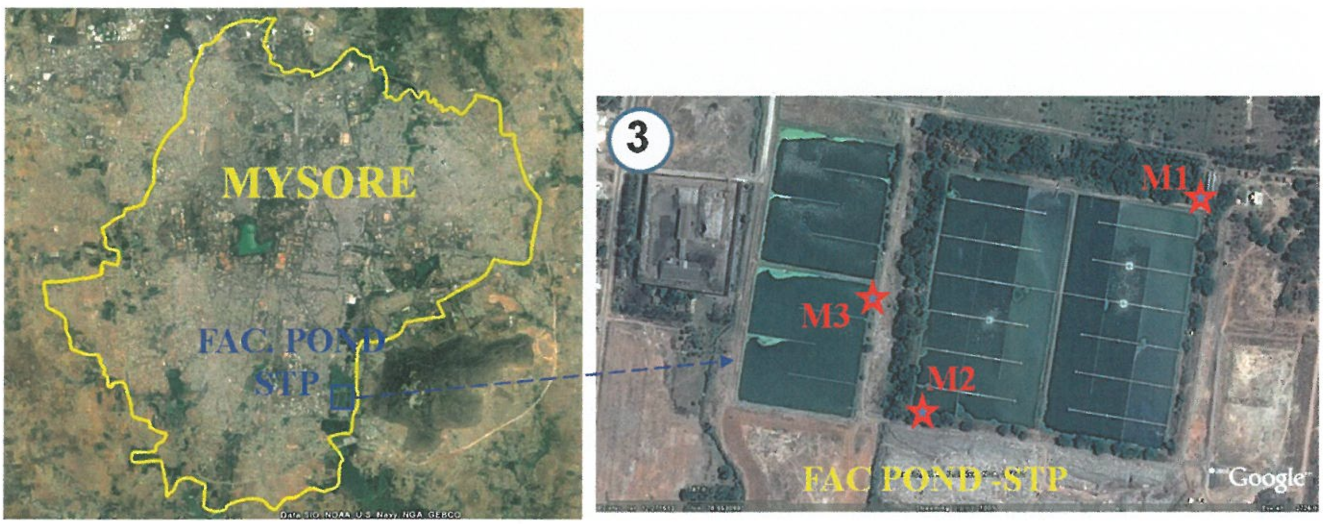


Fig. 4.3 Mysore: (*3*) facultative pond-based STP

unialgal and as algal consortia) were cultured and evaluated for their biofuel potential. Lipid quantification (gravimetry), extraction (cell disruption, solvent treatment, thin-layer chromatography and solvent separation) and FAME composition were conducted following earlier studies (Mahapatra et al. 2013a).

2.3 Process Description

2.3.1 Lake Systems

Lake systems were initially constructed for storage of water to meet the local drinking and other domestic purposes. But, with time, the water yield in the catchment has declined due to the unplanned urbanisation-driven rapid land use changes and also results in the generation of large quantum of wastewater. The series of interconnected lakes convey the city's wastewater. Consequently, these water bodies act as man-made lagoons performing primary, secondary and tertiary treatment due to the interaction of biotic and abiotic components with sufficient detention time (Mahapatra et al. 2011a, b). These water bodies are shallow, and the wind causes a great deal of turbulence aiding oxygen diffusion for adequate aeration and mixing. This process is further supplemented by rapid generation of dissolved oxygen by algal photosynthesis (Mahapatra et al. 2011b). Despite having a massive daily wastewater load of ~500 MLD, the prolific algal growth aided in the uptake of nutrients from these wastewaters further improvising the system's efficiency. Hydraulic retention time (HRT) for Bellandur Lake is ~7–8 d (Fig. 4.4) and Varthur Lake is ~5 d (Fig. 4.5), respectively.

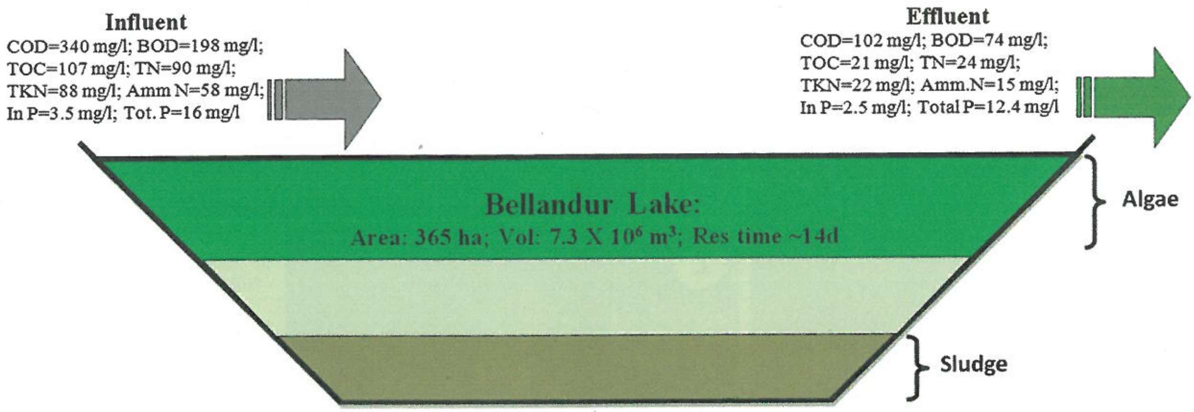


Fig. 4.4 Inflow and outflow process parameters at Bellandur Lake, Bangalore

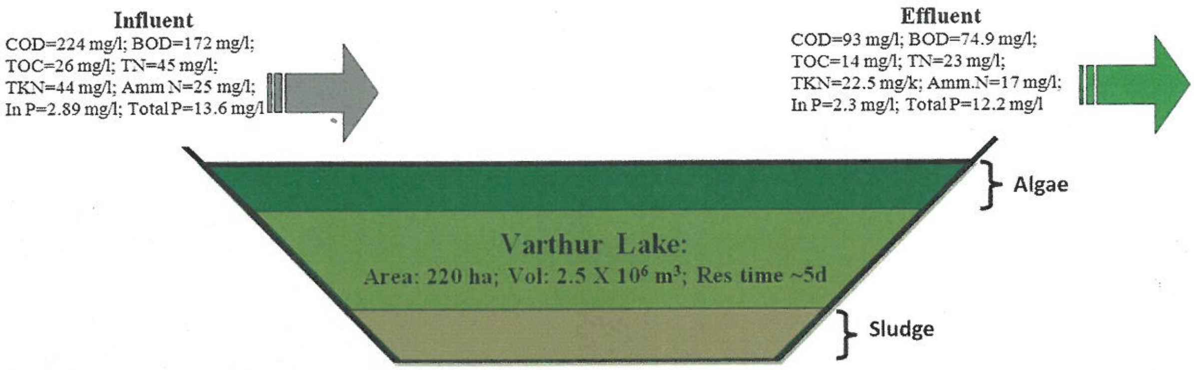


Fig. 4.5 Inflow and outflow process parameters at Varthur Lake, Bangalore

2.3.2 Facultative Ponds

The facultative treatment pond system consists of facultative and maturation ponds (Fig. 4.6). The organic matter is primarily removed in the initial anaerobic zone of the facultative pond. Subsequently algal growth takes place owing to availability of nutrients such as N and P. The high algal growth in the facultative ponds helps in suspended solid (SS) and carbon (C) removal. Maturation pond is meant for pathogen removal, nutrient balance and more importantly removal of suspended solids (stabilisation) (Mahapatra et al. 2013b) together with the removal of a little quantity of BOD. The HRT depending upon feed fluctuations for the initial facultative ponds and maturation ponds is ~3–9 d and ~2–6 d, respectively.

2.3.3 Mechanically Aerated Systems

The mechanically aerated systems comprise of a screen and a grit chamber installed before the aeration and activated sludge systems (Fig. 4.7). Raw wastewater passes through the screen and grit chamber to the aeration tanks (powered by surface aerators) and gets treated by activated sludge. These are continuously fed with recirculation sludge from the secondary clarifiers. The secondary clarifiers help in water detention as well as acts as a storage tank for the inoculum to be regularly supplied to the inflow wastewater. These extended aeration systems are designed with a depth of 4–6 m for a hydraulic retention time (HRT) of ~8 h.

2.4 Comparative Valuation of Treatment Systems: Economic, Environmental and Social Aspects

The total annual cost was calculated which essentially comprised of construction (infrastructure), operation and maintenance (O&M) and land costs (Sato et al. 2007). Infrastructure cost includes procurement of screen, grit chamber construction, wastewater treatment infrastructure, sludge treatment infrastructure, etc. at STPs. O&M costs include expenses on human resources (wages), energy requirement/power, repair and essential chemicals. Rs. 4.8/kWh was taken as the cost involved in power consumption. The wear and tear involved the repair costs for infrastructure/civil structures and mechanical and electrical equipments that are estimated annually as a certain factor/percentage multiplied by total construction cost. The annual repair cost for civil work was calculated at 0.4 % and 0.15 % of the capital cost for aeration with activated sludge processes (ASP) and pond processes, respectively. Likewise, the annual repair cost for mechanical and electrical equipment was calculated at 3 % of the total

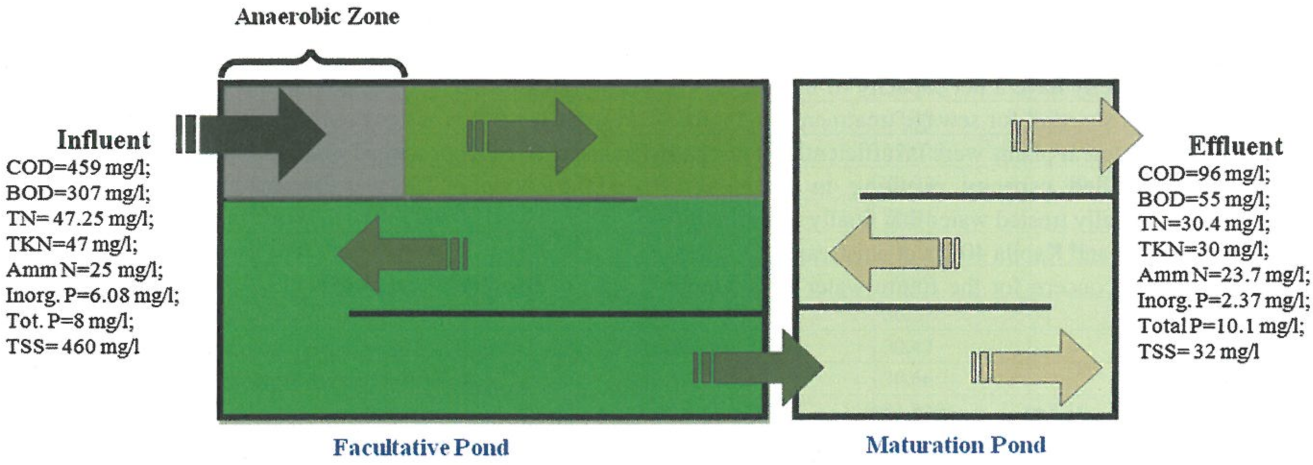


Fig. 4.6 Inflow and outflow process parameters at facultative pond, Mysore

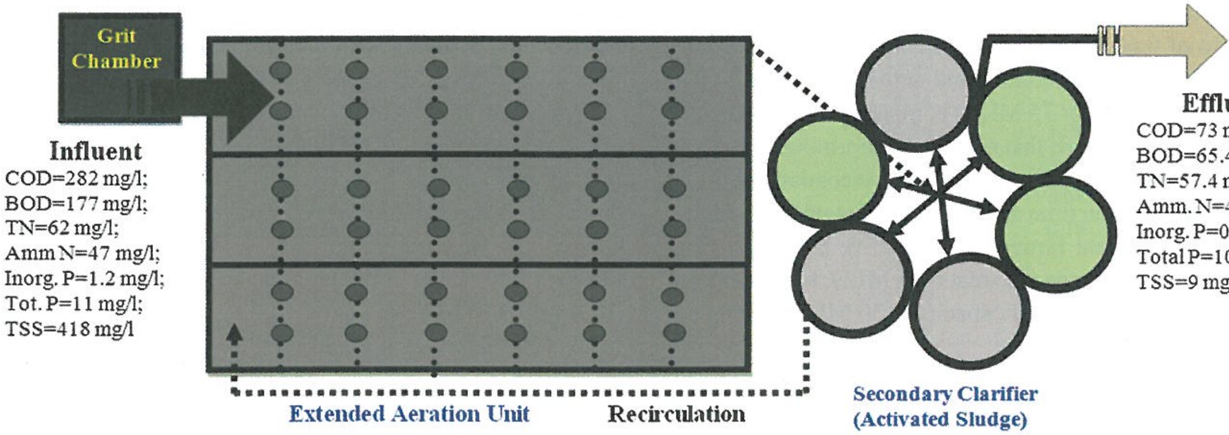


Fig. 4.7 Inflow and outflow process parameters at aeration and activated sludge STP, Bangalore

construction cost. In addition, it was assumed that mechanical and electrical equipment requires replacement every 6 years. This replacement cost was included in the repair cost. The service life of STP was estimated at 30 years, which served as the period for life cycle cost (JICA 2005). The total annual cost was calculated by Eq. (4.1):

$$AC_{TOTAL} = RF_{CAPITAL} \quad IC_{TOTAL} + OMC \tag{4.1}$$

where AC_{TOTAL} is the total annual cost, $RF_{CAPITAL}$ the capital recovery factor, IC_{TOTAL} the initial cost (e.g. for construction, land) and *OMC* the operation and maintenance cost (e.g. human resource, power/energy, repair, chemicals).

3 Results and Discussions

3.1 Water Allocation and Wastewater Generation

Bangalore city receives water of about 900 MLD from the Cauvery and about 600 MLD from groundwater. Out of this, wastewaters account to ~1200 MLD. The existing sewage treatment plants at Bangalore (under CWSS I–IV) handles only half of the wastewaters generated (718 MLD) with a modest treatment level, and the rest of the wastewater generated is directed to several lakes and streams. Many of these plants are running at half the installed plant capacity with partial treatment. Such circumstances and associated reasons make it imperative to find a less energy-intensive, cost-effective and sustainable wastewater treatment system for Bangalore to handle the city's wastewaters and treat to acceptable levels. The existing lake systems are playing a major role in treatment of these wastewaters up to satisfactory levels by virtue of its high detention time with the interplay of biotic and abiotic factors (Mahapatra et al. 2011a, b, c). The study of the functional aspects of the interactions between biotic and abiotic elements (Mahapatra et al. 2011a, b, c) in the lake systems has provided the basic understanding to design and formulate an optimal open algal pond treatment system which works on its own without much cost and maintenance to treat huge quantities of wastewaters.

In the case of Mysore, the water supply accounts to 160 MLD, and about 95 MLD is drawn from groundwater sources which sums up to 255 MLD. Assuming 80 % of the original water supply being wastewaters, the total wastewater generation in Mysore city hovers to ~204 MLD. Wastewater treatment plants in the city have a net capacity of treating 157.5 MLD indicating a shortfall for sewage treatment for another 50 MLD. The treatment plants were insufficiently running to its intended installed capacity resulting in voluminous untreated and partially treated water that finally joins the rivers Cauvery 12 km and Kapila 40 km downstream and is thus a matter of grave concern for the future water requirement and its security.

3.2 Raw Sewage Characteristics

Table 4.3 lists the raw wastewater characteristics and features and is comparable to domestic wastewater. Higher biodegradability of the wastewater is indicated by the BOD_5/COD ratio of 0.60. A meagre 50 MLD is treated up to secondary levels through aeration and activated sludge STP at Bangalore (installed for 75 MLD) compared to the Bellandur and Varthur lake systems that receive an enormous volume of >500 MLD treating the wastewater up to secondary levels by virtue of its detention time and algal nutrient uptake activity. The sewage treatment farm with facultative pond system at Mysore has been designed to treat 67.5 MLD, but it works at less than half of its installed capacity (~30 MLD) during the study period.

Table 4.3 Physico-chemical characterisation of raw sewage

Parameters	Mean	± Standard deviation
pH	7.73	0.20
Temperature (°C)	25.70	2.68
Elec. conductivity (μS/cm)	1013.80	277.70
Total dissolved solids (mg/l)	774.33	156.02
Total suspended solids (mg/l)	328.00	56.00
Turbidity (NTU)	229.23	42.84
Dissolved oxygen (mg/l)	0.22	0.35
Free CO_2 (mg/l)	48.59	19.48
COD (mg/l)	248.50	52.48
BOD (mg/l)	152.58	31.79
Nitrates (mg/l)	0.63	0.50
Ammonia (mg/l)	72.00	16.00
TKN (mg/l)	88.00	8.00
Phosphates (mg/l)	2.34	0.76
Total phosphates (mg/l)	10.20	4.60
Alkalinity (mg/l)	380.00	83.90
Total hardness (mg/l)	296.00	108.69
Calcium (mg/l)	72.00	12.00
Magnesium (mg/l)	28.00	6.60
Chloride (mg/l)	147.16	146.53
Sodium (mg/l)	254.02	420.04
Potassium (mg/l)	26.75	29.01
ORP (mV)	−121.33	85.91

Fermentative bacteria (organic solutions) are fed to this plant as inoculum which helps in COD/BOD, TSS and odour removal. Considering the population of both the cities, the average per capita water usage is considered as 120 l/d. The quantity of BOD produced was estimated at 18.2 g/d/person, and the amount of TSS was estimated at 39.36 g/d/person.

3.3 Biofuel Prospects

The algae abundant in facultative ponds and lakes showed total lipid contents of ~25–28 % (w/w). The morphological and cell surface studies (through electron microscopy) of euglenoids from these facultative ponds showed the presence of nano-lipid channels (pores) across the stria pattern that possibly help in cellular lipid secretions periodically under stress conditions (Mahapatra et al. 2013c). The Raman spectroscopic analysis with a confocal attachment of algal lipids in vivo revealed clusters of lipid scattered across the cell cytoplasm that were associated with pigments as chlorophyll and carotenoids (Mahapatra et al. 2013d). The unialgal species showed high unsaturated fatty acids (~52 %) compared to the algal consortia grown in batch mode that showed ~24 % unsaturated fatty acids. The order of the dominant fatty acids in the unialgal species is palmitic acid C16:0 (42 %)>linoleic acid C18:2 (22 %)>linolenic acid C18:3 (23 %)>stearic acid C18:0 (4 %) (Table 4.4) (Mahapatra et al. 2013a). The unialgal species showed higher polyunsaturated fatty acids (~47 %) compared to monounsaturated ones (~4 %).

The algal consortia tested in laboratory mostly comprising of euglenoids and members of Chlorophyceae showed ~76 % of saturated fatty acids compared to unialgal species. In contrast to unialgal species, monounsaturated fatty acids were high (~14 %) compared to polyunsaturated ones. The order of dominant FAME is given by palmitic acid C16:0 (42 %)>stearic acid C18:0 (~26 %)>oleic acid C18:1 (~11 %)>linoleic acid C18:2 (~5 %) (Table 4.4). In both unialgal and consortia of algae, the percentage of C16–C18 (desirable fatty acids from a biodiesel perspective) is >90 %. The FAME gas chromatograms of unialgal species and wastewater algal consortia cultured in laboratory (Mahapatra et al. 2014) reactors are elucidated in Fig. 4.8. Such algae have been also tested for its growth, nutrient removal and lipid production in continuous culture systems that yielded high biomass density close to 1 g/l with good lipid productivities ~50 mg/l/d with high P stocks (2–3 %) in algal cells (Mahapatra et al. 2013e) and thus can create new avenues in decentralised wastewater treatment and energy generation. During such continuous operations these mixed algal species form flocs, which float on the surface of the bioreactor (in the final stages) enabling easier harvesting and concentrating algae for biofuel production.

Table 4.4 FAME composition of algal lipids Mahapatra et al. (2013a, 2014)

No.	FAME (chemical name)	Chemical formula	RT	% FAME	
				Unialgal	Consortia
1	Butanedioic acid, dimethyl ester	C6:0	7.49	–	2.76
2	Dodecanoic acid, methyl ester	C12:0	19.023	0.04	–
3	Methyl tetradecanoate	C14:0	24.92	1.40	0.84
4	Tetradecanoic acid, 12-methyl ester	C14:0–12 CH_3	26.91	–	1.61
5	Pentadecanoic acid, methyl ester	C15:0	28.529	0.11	–
6	Methyl 4,7,10,13-hexadecatetraenoate	C16:4(4,7,10,13)	29.99	–	1.90
7	7,10-Hexadecadienoic acid, methyl ester	C16:2(7,10)	30.27	–	1.14
8	7,10,13-Hexadectrienoic acid, methyl ester	C16:3(7,10,13)	30.47	–	1.67
9	7-Hexadecenoic acid, methyl ester	C16:1(7)	30.66	–	1.38
10	9-Hexadecenoic acid, methyl ester	C16:1 (9)	31.038	3.36	–
11	Hexadecanoic acid, methyl ester	C16:0	31.61	42.05	42.30
12	Heptadecanoic acid, methyl ester	C17:0	34.42	0.11	0.95
13	8,11,14-Eicosatrienoic acid, methyl ester	C18:3(8,11,14)	35.92	–	0.05
14	Methyl octadecatetraenoate	C18:4(6,9,12,15)	35.94	–	0.30
15	6,9,12-Octadecatrienoic acid, methyl ester	C18:3(6, 9,12)	36.352	1.47	–
16	9,12-Octadecadienoic acid, methyl ester	C18:2(9,12)	36.49	22.22	5.27
17	9-Octadecadienoic acid, (Z)-methyl ester	C18:1(9)	36.74	–	10.87
18	11-Octadecadienoic acid, methyl ester	C18:1(11)	36.84	1.09	1.42
19	9,12,15-Octadecatrienoic acid, methyl ester	C18:3(9,12,15)	37.131	22.98	–
20	Octadecanoic acid, methyl ester	C18:0	37.63	3.68	25.69
21	Eicosanoic acid, methyl ester	C20:0	43.08	0.18	0.42
22	Docosanoic acid, methyl ester	C22:0	48.39	–	0.38
23	Tetracosanoic acid, methyl ester	C24:0	51.69	1.31	0.36
24	Hexadecanoic acid, methyl ester	C26:0	53.80	–	0.38
25	Octacosanoic acid, methyl ester	C28:0	55.52	–	0.32
	Saturated FA			48.89	76.00
	Unsaturated FA			51.11	24.00
	Monounsaturated FA			4.45	13.67
	Polyunsaturated FA			46.66	10.33
	Unsaturated to saturated FA ratio			1.05	0.32
	C16-C18 FA			96.95	91.04
	Total lipid content (%)			24.60	28.50

More than 1200 MLD of domestic wastewater is generated in Bangalore city (Mahapatra et al. 2011a). There is a scope of resource recovery from the nutrient-laden waters in the city (Chanakya and Sharatchandra 2008; Chanakya et al. 2013; Ramachandra and Mahapatra 2012). The algae-rich water bodies (urban algal ponds) help in 70–80 % nutrient and ~90 % C removal from influent wastewaters (Mahapatra et al. 2011a). These algae could be harvested for use as biofuels. Algae proliferate due to nutrient enrichment in the water bodies and subsequently die after the growth cycle. Apparently the organic matter, dead algal matter and other debris in the lower strata of these water bodies decompose and critically reduce dissolved oxygen (DO) rendering the system anaerobic favouring GHG emissions.

The present algal biomass productivity in the wastewater-fed algal reactor systems tested in the laboratory was ~0.1 g/l/d. It is reported that species like *Euglena* can potentially produce 6.52 tonnes of crude lipid per hectare per annum (Ramachandra et al. 2013). If algal ponds are used for treating the entire wastewater generated in Bangalore, then an average ~120 tonnes of algal biomass can be generated every day. If only 50 % of the biomass is harvested, with an average lipid content of ~25 % (as per present experiment), then daily 15 tonnes of crude lipid could be produced. As per earlier experiments 20–30 % of the crude lipids are TAG; therefore, ~3.75 tonnes/day of biodiesel can be generated that yields ~1125 tonnes of biodiesel/annum. Earlier studies have shown a reasonably high calorific value of the dried wastewater algae (heat value ~18 MJ/kg) showing the potential of whole cell algae for energy generation without cell disruption and expensive solvent treatments (Mahapatra et al. 2013f). After lipid extraction, the spent biomass that is left

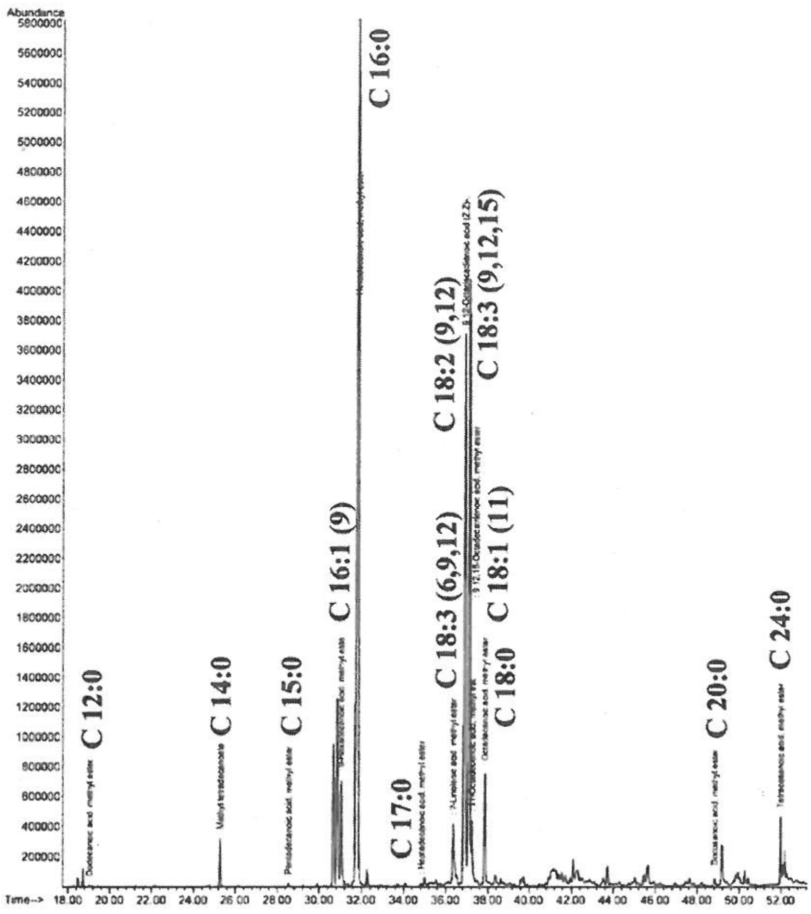


Fig. 4.8 Gas chromatogram of FAME mix from *Euglena* sp. (Mahapatra et al. 2013a)

out mainly comprising of carbohydrates and proteins can be reutilised for energy generation via fermentation yielding bioethanol (heat value ~30 MJ/kg) or pyrolysis producing liquid crude (heat value >30 MJ/kg). In the due course the sludge produced in these algal bioreactors could be used for biogas generation (heat value ~21 MJ/m^3), and the slurry left behind after bio-methanation can be used as potential manure (Chanakya et al. 2012).

3.4 Treatment Plant Efficiency

The treatment of wastewater has been assessed through conventional water quality parameters: COD, BOD, TSS, TDS, P and N. The differences at inlet and at outlets reveal the efficiencies of the respective treatment. The aeration-based mechanical treatment systems showed high removal of COD (74 %) and BOD (63 %; Fig. 4.9) but have low removal efficiency of total nitrogen (TN) (~8 %; Fig. 4.10) and P (~2 %; Fig. 4.11). TSS removal is about ~88 % (Fig. 4.12). These results are tabulated in Table 4.5.

Facultative pond-based treatment in Mysore has higher removal efficiency of BOD (82 %; Fig. 4.9) and TSS (93 %; Fig. 4.12) compared to N (36 %; Fig. 4.10) and almost no removal of P (Fig. 4.11). In the case of pond-based systems, the removal efficiencies are dependent on its working/operations, i.e. aerobically or facultatively (Table 4.5). As per earlier reports, the aerobic ponds have detention times of ~3–10 days and facultative ponds, 5–30 days (Reed et al. 1995). Longer retention in facultative ponds aids in the higher removal of N and pathogens (Water Environment Federation/American Society of Civil Engineers (WEF/ASCE) 1992; Mara 1997; Oakley 2005).

Earlier studies have reported high removal efficiency of BOD (90–95 %), TSS (90–95 %) and faecal coliforms (92–99.99 %) and lower removal of TP (10–20 %) and TN (15–25 %) in the mechanical treatment systems. The stabilisation/facultative pond-based treatment has comparably high removal efficiency of TSS (90–95 %) and faecal coliforms (90–99.90 %) but has medium to high removal efficiency of BOD (75–95 %) and low to medium removal efficiency of P (10–50 %) and TN (10–60 %) (Gilbert 1976; Pettygrove and Asano 1984; Palme et al. 2005; Hannah et al. 1986; Reed 1991; Reed et al. 1995; United Nations Environment Programme 1997; US 2002; Metcalf and Eddy 2003) as shown in Table 4.6.

The large lake-based system showed a moderate removal efficiency of COD (70 %; Fig. 4.9) and BOD (62 %; Fig. 4.9)

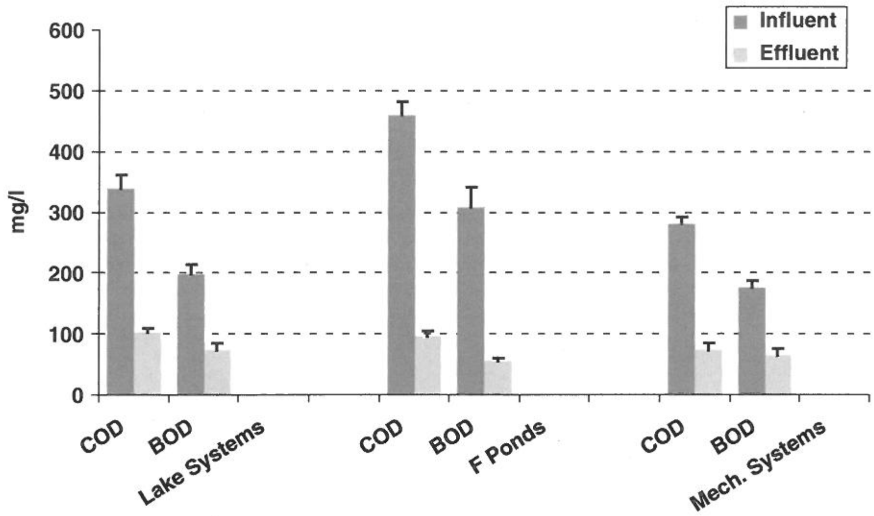


Fig. 4.9 COD and BOD removal in the three systems

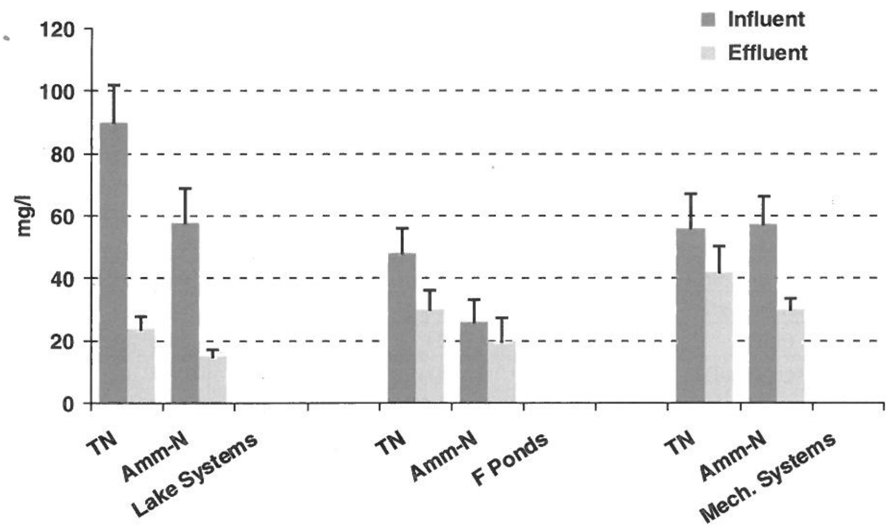


Fig. 4.10 TN and ammonia N removal in the three systems

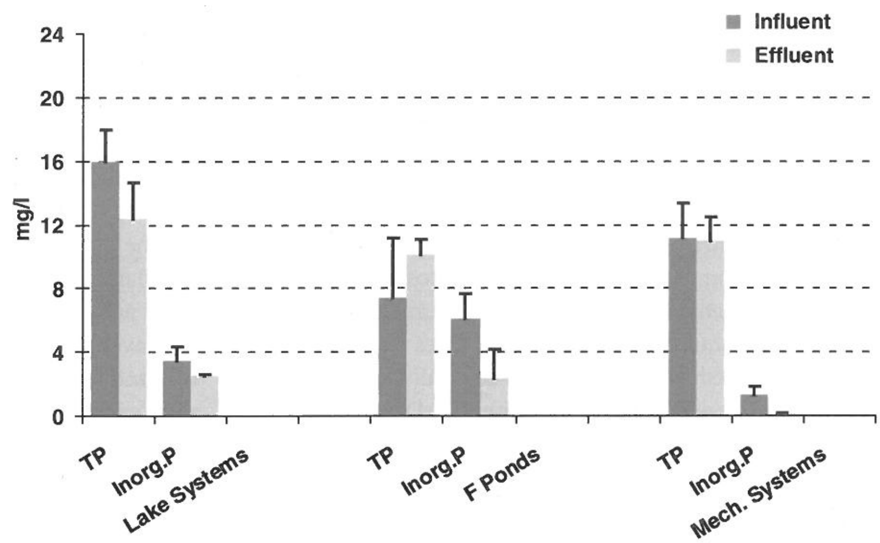


Fig. 4.11 TP and inorganic P removal in the three systems

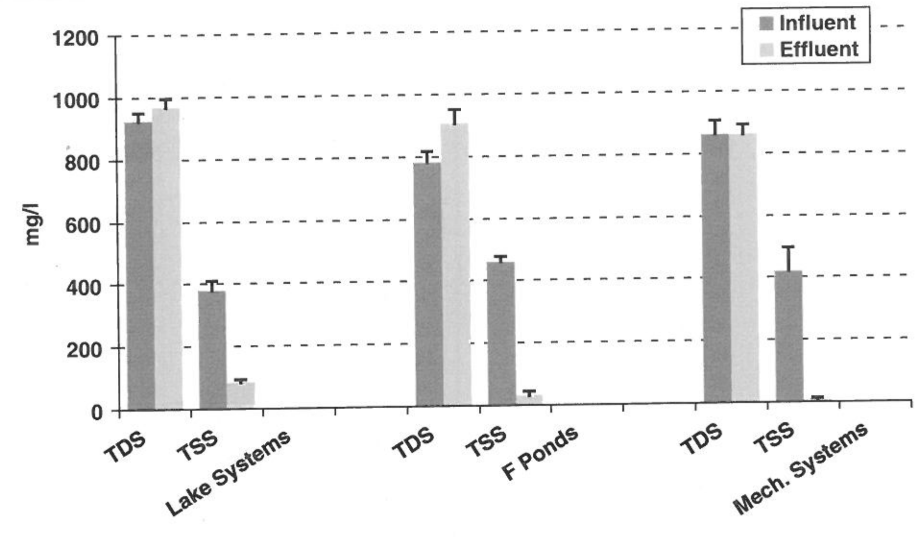


Fig. 4.12 TDS and TSS removal in the three systems

Table 4.5 A comparative analysis of the removal efficiencies (treatment parameters)

	Lake-based systems						Facultative pond			Mechanical aeration		
	Bellandur			Varthur			Mysore			Bangalore		
Parameters	Infl.	Effl.	%Rem	Infl.	Effl.	%Rem	Infl.	Effl.	%Rem	Infl.	Effl.	%Rem
COD (mg/l)	340	102	70	224	93	58.5	458.7	96	79.07	282	73	74
BOD (mg/l)	198	74	62	172	74.9	56.4	307	55.1	82.02	177	65.4	63
TSS (mg/l)	380	83.6	78	288	79	72.5	460	32	93.4	418	9	98
Turbidity (NTU)	386	71.2	81.5	325	65	80	326	16	95	329	6.58	98
TN (mg/l)	90	24	73	45	23	48	47.25	30.4	35.7	62	57.4	8
Ammonia N (mg/l)	58	15	74.1	25	17	32	25.67	20.99	18.2	42	29.8	29
Nitrates (mg/l)	0.72	0.88	−22	0.64	0.62	3	0.202	0.015	92.5	1.05	0.24	77
Inorganic P (mg/l)	3.5	2.5	28	2.89	2.3	20.4	6.08	2.37	61	1.28	0.126	90
Total P(mg/l)	16	12.4	22.5	13.6	12.2	10.2	7.36	10.12	−37.5	11.2	10.99	2

with a comparably high removal of N (73 %; Fig. 4.10) and TSS (78 %; Fig. 4.12). The characteristics of the effluent normally indicate treatment efficacy and also the nature of discharge options for potential reuse.

3.5 Valuation of Sewage Treatment Systems

3.5.1 Economic Evaluation

Figure 4.13 compares initial investment costs of the existing treatment systems in Indian cities. These analyses are based on the cost required to treat million litres per day (MLD). The analysis showed higher initial and O&M costs for mechanical systems with ~100 lakhs/MLD and ~6.8 lakhs/MLD/annum compared to pond-based systems with ~40 lakhs/MLD and ~1 lakhs/MLD/annum, respectively. The mechanical treatment systems are either suspended growth processes or attached growth processes. The suspended growth processes mainly involve two techniques as extended aeration and activated sludge. The former operates at lower organic loading and high cell retention time. However, the activated sludge process is conducive for small populations as a large bioreactor volume is required to attain high cell retention. The operating and process costs of both the techniques are influenced by the SS removal capacity and the age of the treatment unit. In addition to this in the case of activated sludge technique, the costs are related to the removal efficacy of organics.

The attached growth processes are pronounced for small populations. During the bacterial bed processes, the O&M costs are determined by the age of the treatment unit alone. However, the other variants of the attached systems as biodisc and peat bed techniques (Hernandez-Sancho et al. 2011) require material replacement at very frequent intervals, so the plant age becomes insignificant, and the SS removal efficiency decides the O&M costs of the treatment unit.

The final stages of the treatment involve various techniques for tertiary treatment as membrane bioreactors, ultrafiltration, microfiltration, ferric chloride-polyelectrolyte

Table 4.6 Comparative analysis of the STP treatment techniques with nutrient removal efficiencies

No.	Place (STPs)	Treatment approaches	Effective approach	% Removal efficiency	References
1	Ixtapan de la Sal, Mexico	[High-rate clarifier + anaerobic pond + facultative pond + maturation pond]; [anaerobic pond + facultative pond (2) + maturation pond]	[High-rate clarifier + anaerobic pond + facultative pond + maturation pond]	84 % BOD	Alcocer et al. (1993)
				70 % COD	
				45 % TS	
				55 % SS	
				43 % TDS	
				97 % F. coli	
2	Yamuna river basin, India (15 STPs)	UASB and facultative pond units	Facultative ponds	67 % COD	Sato et al. (2007)
				70 % BOD	
				−14 % N-NH_3	
				36 % TSS	
				8 % F. coli	
3	Mpumalanga, South Africa (14 STPs)	Ponds; activated sludge; [ponds + trickling filters]; [anaerobic digestion + trickling filters + maturation pond]; [activated sludge + ponds]; [activated sludge + ponds]; [tricking filter + activated sludge]; and [trickling filters + activated sludge + ponds]	[Activated sludge + ponds]	99 % F. coli	Samie et al. (2009)
4	Santa Catarina, Brazil (swine wastewater)	Stabilisation ponds	Aerobic facultative pond	83 % COD	da Costa and Medri (2002)
				85 % N-NH_3	
				65 % P-PO_4	
5	Mysore, India (3 STPs)	[Alternate aeration + maturation pond]; [pond-based fermentative bacteria]; [facultative microbes and stabilisation ponds]	Facultative ponds	82 % COD	Shakunthala et al. (2010)
				89 % BOD	
				87 % SS	
				9 % TDS	
6	Bangalore, India (2 STPs)	Extended aeration; high-rate aeration with biofilters	Extended aeration	28 % TS	Kumar et al. (2010)
				99 % TSS	
				97 % BOD	
7	New Delhi, India (16 STPs)	Activated sludge, extended aeration, trickling filters, high-rate aeration, oxidation pond, BIOFORE (physical, chemical and biological removal treatment)	Extended aeration, oxidation pond and BIOFORE	99 % F. coli99% BOD	Jamwal and Mittal (2010)
				96 % COD	
				68%TKM	
				99 % turbidity	
8	(a) Varthur and Bellandur Lakes, Bangalore India	Man-made lakes: huge open lagoons [Activated sludge + extended aeration + clarifier] [Facultative pond + maturation pond]	Facultative pond-based systems	79 % COD	Present study
	(b) Activated I sludge (aeration) STP, Bangalore			82 % BOD	
	(c) Facultative pond, Mysore, India			93 % SS	
				36 % TN	
				18 % N-NH_3	
				95 % turbidity	
				99 % bacteria	

F Coli, faecal coliform

addition, reverse osmosis, etc. These unit processes help in achieving a better water quality at the end of the chains if the treatment cascades. In such cases the O&M costs are directly influenced by the organic content left in the system and nutrient (N and P) removal efficiencies. The man-made lakes are almost free treatment units with the minimum cost. Operation and maintenance (O&M) costs associated with wastewater treatment comprise manpower and energy/power and replacement and reinstallation purchase of equipments and chemicals. Figure 4.13a illustrates cost requirement for mechanical treatment, which is ~2.5 times higher than a facultative pond system and ~5 times higher than man-made lake systems, if these options are implemented for treatment purposes. The higher cost in mechanical systems is due to

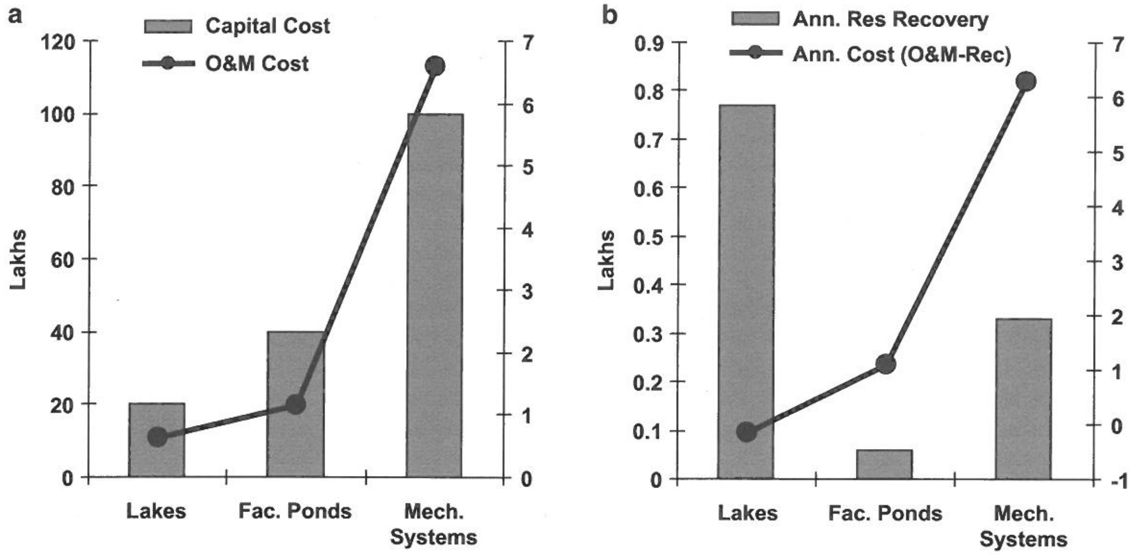


Fig. 4.13 (**a**) Comparative capital and O&M cost for different technologies and (**b**) comparative annual cost and annual resource recovery for different technologies

highly mechanised equipment with energy-intensive processes. In the present study massive algal biomass was observed in lakes and to an extent in certain parts of facultative ponds that had a lipid content ranging from 18 to 30 % (w/w) of the dry biomass. In such conditions the value-added algal biomass in turn can generate revenue by algal biofuel production. Considering the worth of algae from such non-mechanically aerated systems, an annual resource recovery of ~0.75 lakhs/annum can be derived from man-made lake systems compared to ~0.3 lakhs/annum in the case of mechanically aerated systems only when sludge biomethanation and recycled water selling are carried out. Thus, the annual cost (O&M resource recovery cost) is negative in the case of lake systems compared to higher annual costs of >6 lakhs in the case of mechanically aerated systems (Fig. 4.13b). The cost calculations are tabulated in Table 4.7.

The cost of community wastewater treatment (user cost) depends on the treatment process, its efficiency, population size served and the method adopted for the effluent discharge. The smaller population incurs more charges (user cost) than the larger population with a larger plant capacity. Therefore, the user costs can be too high to individuals in smaller communities, especially low-income dwellers. The pond-based systems are cost-effective as it can potentially reduce costs by at least one half (Helmer and Hespanbol 1997).

3.5.2 Environmental Evaluation

The energy consumptions are mostly due to the operation and maintenance costs during aeration and pumping of water and solids (Middlebrooks et al. 1981). Figure 4.14 depicts varied energy needs across different wastewater treatment technologies. Here, the activated sludge/aeration tank-based processes require more energy than either facultative ponds or lake-based systems. Higher carbon footprint is associated with high energy use. For a population of 1000 people, the activated sludge system may generate ~1400 tonnes of CO_2 for operation and 50 tonnes of CO_2 for maintenance over a period of 15 years (Emmerson et al. 1995).

Among many viable approaches, algal pond-based systems help in treating wastewater while generating energy. The type of material selection for the treatment technology has its own embodied energy. The conventional mechanical treatment systems comprise of concrete infrastructures with an embodied energy of 18.4–1580 MJ/M litres (Horvath and Hendrickson 1988). The energy analysis (Fig. 4.14) showed that the mechanically aerated systems require much larger energy (~0.72–6.36 million units/MLD) compared to facultative ponds (~0.36–1.68 million units/MLD) and a very low energy of ~0.02–0.24 million units/MLD is required for lake systems accounted for energy cost (weed removal, sludge clearance, etc.) and incurred for electricity and maintenance.

3.5.3 Social Evaluation

Public participation is an important criterion while selecting a suitable wastewater treatment system for a particular community. People's participation and their opinion on treatment and disposal options would help in the further refinement. In India most of the urban dwellers are unaware of the type of wastewater treatment happening around them. At the same time they pay charges to the urban bodies for sanitation services. One of the essential criteria for assessing the role of the public is the assessment of level of knowledge/awareness

Table 4.7 Valuation of treatment (economies and net annual costs) technologies

Evaluation approaches	Unit	Existing lake systems	Facultative pond systems	Mechanical systems
Economic				
Construction costs (land + infrastructure costs)	Rs in lakhs/MLD	20	40	100
Operation and maintenance	Rs in lakhs/MLD	0.62	1.16	6.6
User cost	Rs/month	–	18	30
Annual resource recovery	Rs in lakhs/year	0.77	0.06	0.33
Net annual cost = O&M resource recovery	Rs in lakhs/year	−0.15	1.1	6.27
Environmental				
Average energy use	kWh/MLD (kWh/m^3)	0.05×10^6	1.7×10^6	5.98×10^6
Chemical oxygen demand (COD)	% Removal	70	79	74
Biochemical oxygen demand (BOD)	% Removal	62	82	63
Total suspended solids (TSS)	% Removal	78	93	88
Turbidity (NTU)	% Removal	80	95	98
Nitrogen (TN)	% Removal	73	36	8
Phosphorus (TP)	% Removal	22	–	2
Social				
Public participation	Qualitative measure	Yes	No	No
Community size served	Population/MLD	8000	13000	11428
Aesthetics	Measured level of nuisance from odour	Moderate	Moderate	High
Human resources to operate plant	Staff/MLD	–	0.2	0.32
Level of education/awareness	Operational requirements	Average	Good	Higher
Availability of open space	Hectare/MLD	1	0.6	0.08

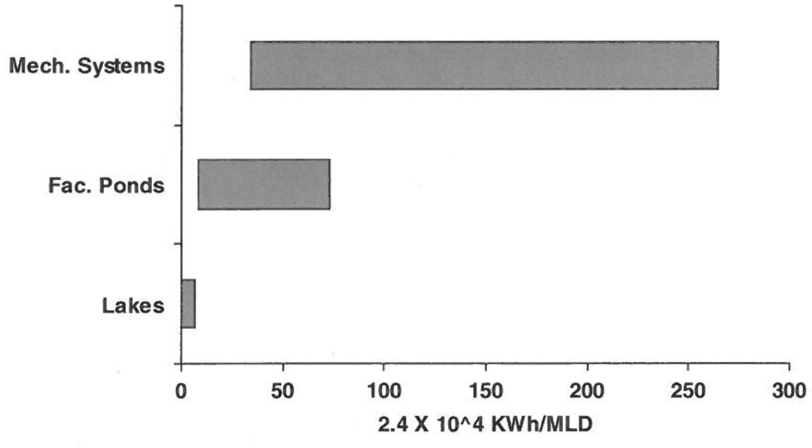


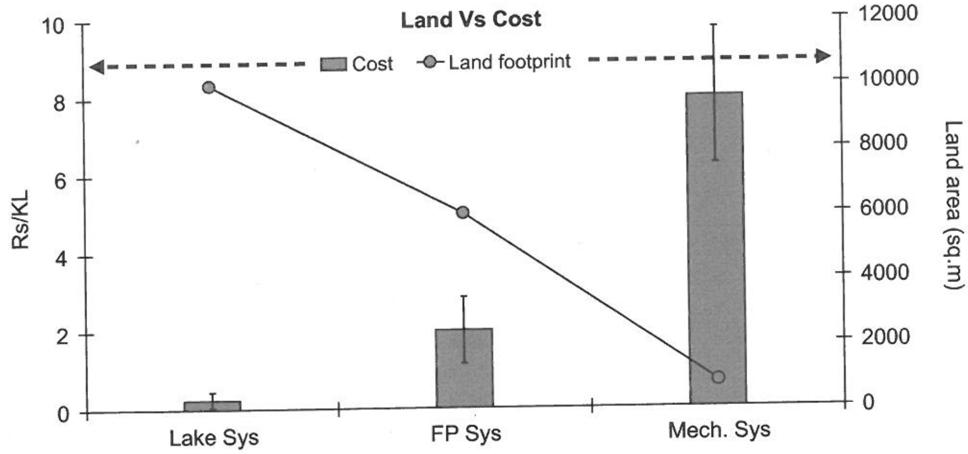
Fig. 4.14 Total energy requirements in different wastewater treatment plants

among the users (Palme et al. 2005). Today affordability and the appropriateness of the technology are considered critical leading to the adoption of cost-effective appropriate technology over more mechanised technology (Sperling 1996).

A larger plant capacity is indicative of a large population. Mechanical and pond-based systems can meet the treatment requirements for a large population than other treatment processes. In this context the mechanically driven systems are opted over pond-based systems in urban areas in India where there is low land/open space availability. In this context for assessment of sustainability of any treatment systems, suitable ways of evaluation of such systems are a prerequisite. This involves computing appropriate mass balances, assessment of nutrient fluxes from a systems perspective and cause-consequence evaluation. This helps in proper estimation of nutrients in various subsystems in the treatment process that helps in evading the accumulation/deficiency of nutrients.

The gaseous by-products during the wastewater containment and treatment may generate foul odour. This results in hampering the aesthetics, raises societal concerns and seeks regulatory measures. Forced aerated systems have a higher foul odour generation potential compared to pond-based systems due to unhandled solids/particulates. In mechanically

Fig. 4.15 Land vs. cost trade-off for wastewater treatment systems



aerated systems, the aeration and activated sludge systems at Bangalore, the foul odour problems emanate from wastewater containment in pipes, storage basins, pumping units and manholes in different locations. However, the foul odour from treatment units can be due to higher total maximum daily load (TMDL) or due to accumulation of surface scum and also from sludge deposits. Sludge accumulation from facultative pond-based systems may also contribute to the problem. According to WEF (1992) the unit processes in treatment plants as primary clarifiers and trickling filters have a higher odour potential compared to aeration which has a moderate odour potential, and finally the lagoon-/pond-based systems and secondary clarifiers have a low/moderated odour potential. In the present study the lake systems were found to have a small odour compared to the other technologies attributed to a higher organic load and release of H_2S.

Human resource requirement depends upon the plant capacity. According to WEF (1992), an average of one member (staff) is needed to manage the treatment plant (1 MLD). Thus, smaller pond-based plants require small work force, contrary to mechanically driven systems that need more staff.

Awareness and the level of environmental aspects is a crucial social factor for the treatment practice survival processes. The level of sophistication/complexity of a wastewater treatment system often decides the type of operator skill needed for the plant operation based on their educational skills. In the present study the STP based on more mechanisation as in the case of the extended aeration-based treatment process involved more technically sound labourers, supervisors and well-qualified plant engineers unlike the pond-based system where there is not much requirement of a technical staff. Earlier studies show that factors like lack of proper systems understanding in process control and operation leads to limitation in the performance in treatment plants (Water Environment Federation/American Society of Civil Engineers (WEF/ASCE) 1992).

Open space availability is yet another important evaluation criterion where in the mechanical systems having a short hydraulic retention time (HRT) of 3–8 h (Metcalf and Eddy 2003) is indicative of a much smaller land requirement compared to the facultative pond-based systems that require more land area due to a longer detention time. The minimum land area requirement for energy-intensive mechanical systems (extended aeration/ASP), facultative pond systems and partial mix aerated pond systems varies from 0.1acre/MLD and 12–42 acre/MLD to 7–12 acre/MLD (Metcalf and Eddy 2003). The land requirement for the current study showed 0.08 Ha/MLD, 0.6 Ha/MLD and >1 Ha/MLD for mechanical systems, facultative pond-based systems and lake-based systems, respectively (Table 4.7). The land to total cost trade-off of the various wastewater treatment systems currently studied is illustrated in Fig. 4.15.

3.6 Sustainability of the Treatment Systems

Here the sustainability of the existing wastewater treatment systems has been studied considering the economic, environmental and social aspects.

The conventional mechanical systems are capital and energy intensive apart from higher running costs leading to high user cost. Furthermore, such systems have high foul odour generation affecting the aesthetics of the surrounding region. These systems contribute less to the economy of a community by employing the less number of staff per plant capacity, than other treatment systems. Such energy-intensive processes being control systems driven require less human resources and meagrely contribute to the revenue/economy of the society when compared to other treatment systems as ponds. Despite these setbacks in achieving sustainability, the mechanical systems of wastewater treatment are efficient in BOD, TSS and pathogen removal.

The facultative pond-based processes are economical while providing a large community open space and efficiently tap nutrients as N and P through bioremediation. Aeration of the pond systems usually adds additional costs in terms of infrastructure and energy (O&M cost) compared to non-aerated pond systems (US 2002). Foul odour generation is seasonal (especially in summer) in ponds. However, the studied facultative pond systems did not pose any type of odour. In terms of cost (infrastructure and O&M) and energy usage, the pond systems are beneficial with high solid, nutrient and pathogen removal providing maximum stabilisation to the treated effluent that makes them appropriate for treatment at decentralised/community levels.

The design of the existing pond systems can be further improvised by increasing the number of ponds and specifically constructing an anaerobic pond that provides better C removal and solid settling. The BOD in the effluent of the pond systems is mainly the algal BOD. Therefore, a suitable algal trap mechanism (dark algal settling chamber) is envisioned. This design/alternative treatment option would function by integrating the wastewater treatment algal pond systems with the algal capture mechanism by providing a novel settling chamber (unpublished design).

Although these pond systems require large area than mechanised systems, they can contribute more to the economy of the plant by generating revenue by algal biomass capture and subsequent lipid production. Of all three systems, the facultative pond-based treatment systems have the least overall impact (Table 4.7) and also the integrated nutrient treatment efficiency (Table 4.8). Advantages of facultative pond-based systems are lower infrastructure and O&M cost and low energy footprint and results in a small user cost with high BOD, SS, N and pathogen removal and low foul odour generation. The land-intensive pond systems garner a large open space for societal interaction and provide better employment, which adds revenues to the local economy. Finally, the algal biomass growing in this type of wastewater is useful as feedstock for biofuel thus fostering sustainability. The present study highlights algae-based lake systems and facultative pond-based systems to be a more sustainable choice, considering economic, societal and environmental issues.

3.7 Nutrient-Integrated Treatment Efficiency for the Various Sewage Treatment Systems

The investigation on the physical, chemical and biological parameters reveals efficiencies considering the influent wastewater characteristics, detention time and performance of micro-biota in bioremediation. This suggests the need to devise a cumulative efficiency indicator/index that determines the systems efficiency of the treatment unit which aids as an important decision-making tool for further downstream treatment and management of the wastewater.

Colmenarejo et al. (2006) reported an efficiency indicator in terms of treatment parameters (TSS, COD, BOD5 and NH_3-N) to evaluate the efficacy of treatment units. In the present study, new nutrient-integrated treatment efficiency is suggested by considering the mean of TSS, BOD, TN and TP efficiencies in removal. Ideally the efficiency of such systems in the tropical climate should be closer to 90 %:

$$\mathrm{NITE} = 1/4[\mathrm{E}_{\mathrm{TSS}} + \mathrm{E}_{\mathrm{BOD5}} + \mathrm{E}_{\mathrm{N}} + \mathrm{E}_{\mathrm{P}}]$$

where NITE is the nutrient-integrated treatment efficiency in (%), E_{TSS} is efficiency of turbidity removal (%), E_{BOD5} is efficiency of BOD5 removal (%), E_N is efficiency of N removal (%) and E_P is efficiency of P removal (%).

The above results reveal a very low nutrient-integrated efficiency of the effluent indicating an immediate requirement of an additional detention unit which would help the improvement of the NITE values.

4 Conclusion

The present study reveals that man-made lake systems as Bellandur and Varthur Lakes in Bangalore appreciably treated the influent wastewater having higher organic load. The treatment resulted in 70 %, 73 % and 22 % removal of COD, TN and TP, respectively. However, the facultative pond-based systems in Mysore were very effective in removal of suspended solid (SS) (93 %) and BOD (82 %). The mechanically aerated (extended aeration) STP in

Table 4.8 Nutrient-integrated treatment efficiencies

Treatment unit	Area (ha)	Capacity/flow rate (MLD)	Nutrient-integrated treatment efficiency (NITE) (%)	Desired NITE (%)	Driving factor
Bellandur Lake	365	595	58.75	90	TN
Varthur Lake	220	600	43.17	90	TN
Facultative ponds	25	67.5	62	90	BOD
Aeration and activated sludge STP	7.5	75	42.75	90	TSS

Bangalore was superior in removal of SS (88 %), COD (74 %) and BOD (63 %) but were highly ineffective in nutrient removal.

The wastewater algal biomass present in ponds and lakes showed promising lipid contents, and the FAME analysis revealed high C16:0 (>40 %) followed by C18 fatty acids that further provides scope for algal biofuel generation to meet the regional energy demand. Such biofuel generation requires efficient methods of harvesting algae periodically. This necessitates an efficient algal capture mechanism to capture algal biomass from the final treatment plant effluent that helps in removing algal BOD and solids.

The economic evaluation of treatment processes assessed through the capital investment, annual O&M costs, COD removal cost and land needs reveals that the mechanical systems require five times more capital and O&M costs than facultative ponds. Evaluation of treatment systems in terms of capital investment, human resources, chemical usage, wear and tear repair, electricity needs and land requirement showed that lake-based systems followed by facultative pond-based system are economically a better alternative than mechanically aerated technologies. Finally, it was found that large algal pond-based systems could economically be a potential option for the country considering all factors that include expenses and treatment efficiency.

The existing large lake systems and the facultative pond systems can be innovated for a better photosynthetic yield resulting in higher algal biomass which would not only polish the wastewater but at the same time will act as substrate for lipid/biofuel generation by specific algal trap mechanism.

The treatment efficiency analysis for the period of study showed facultative pond-based systems to be the most effective options for the urban wastewater systems compared to the lake-based systems as well the energy-intensive mechanical systems with a nutrient-integrated treatment efficiency (NITE) of >68 % with the treated water that can be reused for irrigation and domestic purposes.

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