Biofuel production potential from wastewater in India by integrating anaerobic membrane reactor with algal photobioreactor

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Abstract

A critical analysis of the novel sewage treatment concept of anaerobic digestion followed by CO_2 capture by microalgae has been carried out, with particular reference to India. The anaerobic process would convert the sewage COD into methane and CO_2, the latter being converted into microalgae in a photobioreactor process, using sunlight as an energy source. The microalgae can be used to produce biofuels, co-fired with high yielding fuels (like coke) or just recycled back into the anaerobic digestion cycle as a substrate for methane production. Overall, this process would allow, at least in principle, the conversion of all the carbon in the municipal wastewaters into fuels. This study reports data on municipal wastewater generation and treatment facilities across the globe. The focus is then given to sewage generation and treatment in Indian cities, classified into metropolitan, Class-I and Class-II cities. Aerobic and anaerobic digestion processes for sewage treatment are then compared with a discussion on the advantages of the anaerobic membrane bioreactor (AnMBR). The advantages and limitations of photobioreactors for microalgae growth are discussed. Mass balances are then carried out with reference to sewage flows and concentrations in India, and the potential energy generation from the process is estimated. Overall, the complete process is envisaged to produce about 1.69×10^{8} $kWhd^{-1}$ of energy from biogas and microalgae. This has the potential to replace 3% of the recent total petroleum product consumption in India. The study goes towards "zero discharge" of waste to the environment, thus representing a promising sustainable development.

Keywords: Anaerobic digestion; Biogas; Photo-bioreactor; Microalgae; Municipal wastewater; Renewable energy.

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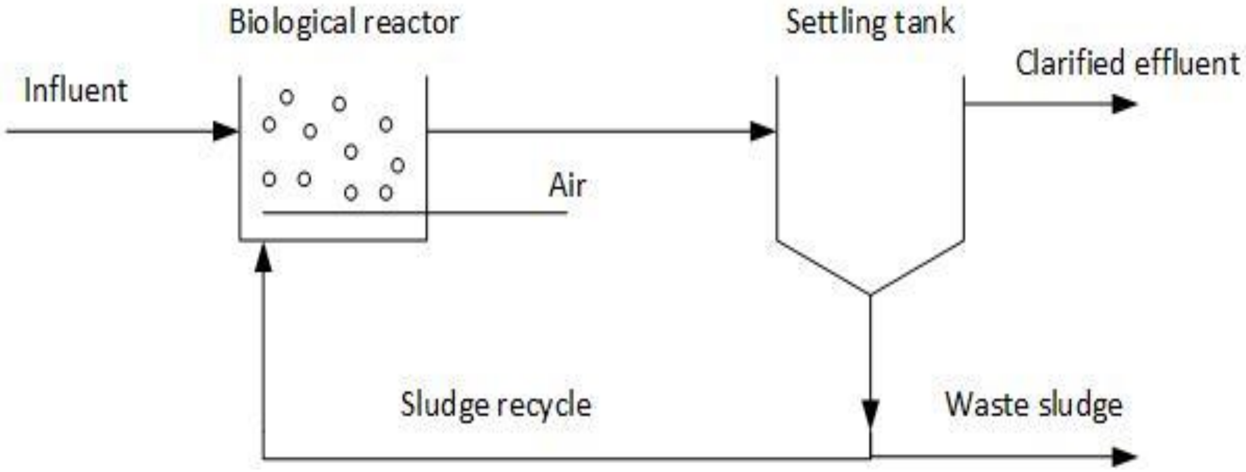
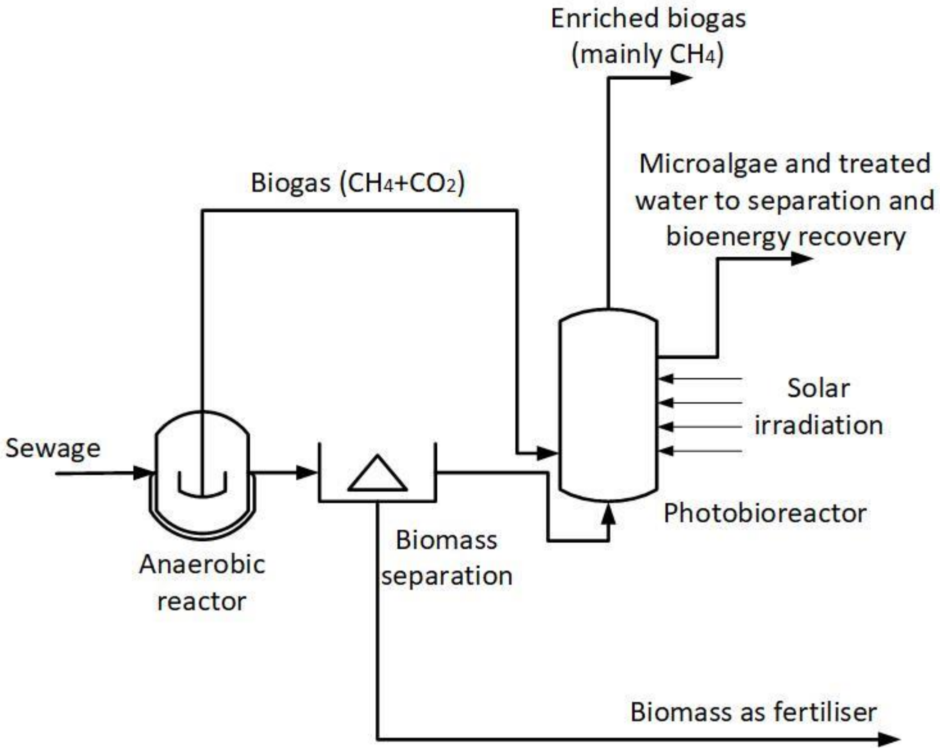
Table of Contents

1 Introduction

Adequate treatment of municipal and industrial wastewaters is essential to safeguard the environment and public health. The biodegradable COD in wastewaters is usually removed using aerobic biological processes, e.g. the activated sludge process and its variants. These processes, although significantly cheaper and more sustainable than chemical-physical processes are still energy intensive due to the large energy requirements for aeration. It is therefore important to minimize the energy costs of wastewater treatment processes and to consider processes with energy recovery from wastewaters. As an alternative to aerobic processes, anaerobic processes have been considered and are in some cases in use, especially for industrial wastewaters. Anaerobic processes have the advantage of not requiring aeration and of converting the biodegradable COD into methane, which can then be used for energy generation. As a further development, the combination of anaerobic processes with microalgae reactors has been proposed. In these processes, the CO_2 produced by the anaerobic reactor is used by microalgae for their growth in a photobioreactor. The produced microalgae can then be used, after separation and drying, for energy generation in various processes, e.g. they are converted to biodiesel or to bioethanol or can be combusted with air, maximizing the energy generation and CO2 removal from the wastewater. Overall, the shift from the conventional activated sludge process to the innovative process of anaerobic digestion followed by microalgae reactors (the two processes are compared in Fig. 1) can generate very significant energy savings.



(a)



(b)

Fig. 1: Schemes for wastewater treatment: (a) conventional aerobic activated sludge process; (b) Innovative anaerobic process followed by photo-bioreactor (PBR) for microalgae production, discussed in this paper.

The aims of the paper are to review the literature on energy consumption and municipal wastewater generation, with particular focus on the situation in India, and to critically analyze the proposed process of anaerobic digestion followed by microalgae growth, estimating the potential energy savings and energy recovery compared to conventional aerobic processes.

Section 2 summarizes the energy consumption and population growth on a global scale. Section 3 reviews the current generation of municipal wastewaters and the treatment capacity on the global scale and, more in detail, in India. Section 4 reviews wastewater treatment technologies, comparing anaerobic and aerobic processes and focusing on the promising technology of the anaerobic membrane bio-reactor (AnMBR). Finally, section 5 reviews the use of microalgae for CO_2 capture and energy generation, discussing the new proposed process of anaerobic digestion followed by microalgae growth, with a proposed flowsheet and mass balances showing the bioenergy generation potential of this process.

2 Wastewater generation and treatment scenarios

2.1 Global scale

On one hand, wastewater is a local issue – wastewater is generated by individual households and it is treated or disposed at the city level. On the other hand, it can also be considered a global issue because the effects are cumulative. It is therefore very important to analyze and understand the global scenario of its production, treatment, and disposal. Some of the world's strongest economies and advanced countries are the largest producers of wastewater in terms of volume. Fig.2 shows the wastewater production, treatment capacities and volume of treated wastewater for these countries.

Although these nations are technologically advanced, most of them cannot process and treat the amount of wastewater they produce with the United Kingdom being an exception. Though China has the largest population, wastewater production is maximum in the USA, thus it can be inferred that the population is not the only factor which affects wastewater production. The capacity of treatment facilities of Russia and the UK is more than the amount of wastewater they produce, thus making them ready for an increase in the population [1]. The USA is a highly advanced and developed country but cannot process and treat the amount of wastewater produced. None of these nations has utilized the installed capacity of their treatment plants fully. Population affects the wastewater production but it is not the only factor. It is clear from the Fig.3 that though the population trend follows Asia > Africa > America > Europe > Australia, the wastewater production does not follow any specific pattern, despite the factors like modernization and development affect wastewater production. Although Africa has the second highest population, the amount of wastewater produced is much less. This is due to the fact that most of the African nations are underdeveloped and have poor economic conditions. Though America is third in terms of population, it is the largest producer of wastewater in the world. Development and a modern lifestyle can be credited for this. All the continents except Australia treat only half of the wastewater they produce. Even continents like America and Europe, which are technologically most advanced, fail to treat the total wastewater they generate [1].

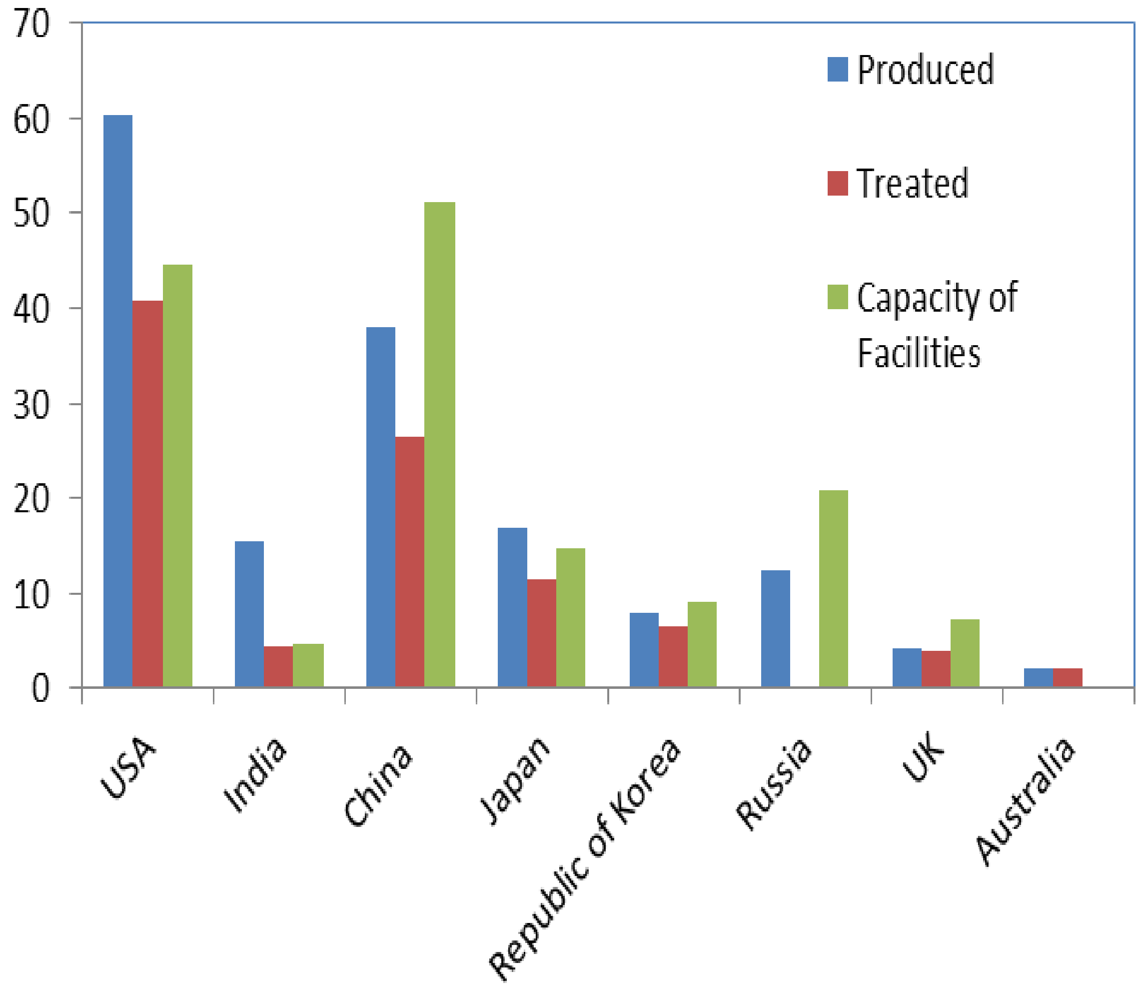


Fig. 2: Worldwide wastewater production, treatment, and capacity [1]

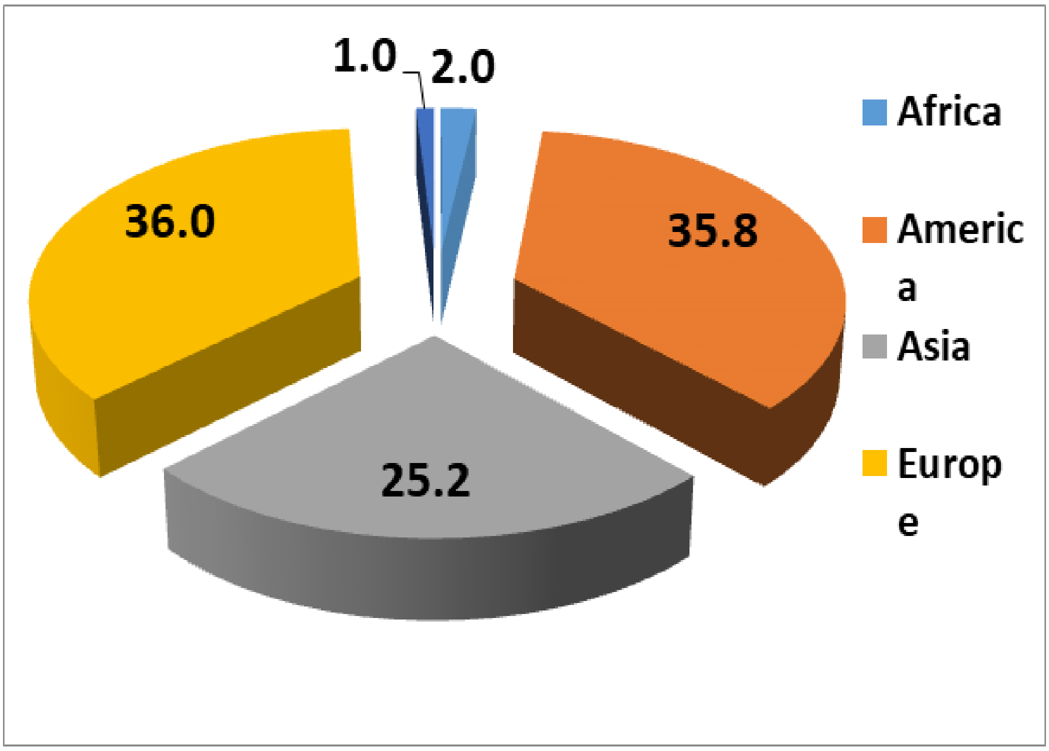


Fig.3: Distribution of wastewater in the continents

Fig.4 shows the wastewater production and its treatment facilities in the 5 continents. America and Europe have the largest number of wastewater treatment facilities. Asia also has a decent number of facilities while Africa and Australia have the least number of facilities. Though 36.1% population in Africa is much more than that of Australia and thus the wastewater generation is also more than Australia but the treatment facilities are much lower in Africa. This can be due to poverty and poor living standards. The average contribution of Asia, America, and Europe is roughly around 32% each, thus making more than 95% [1].

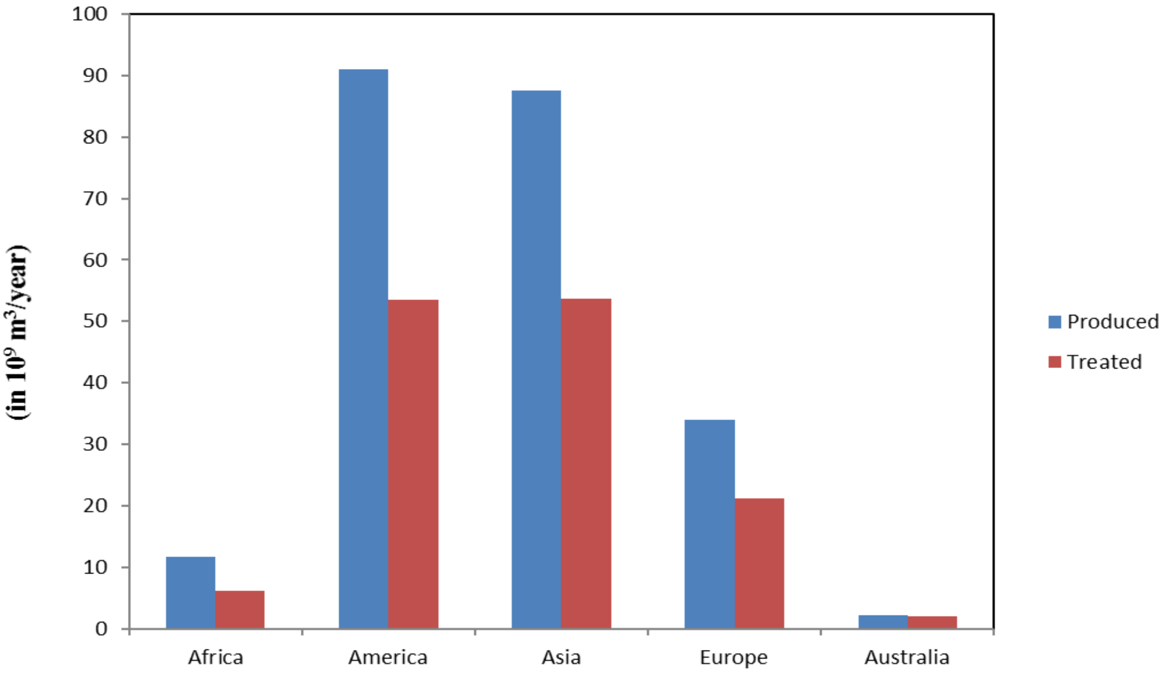


Fig. 4: Wastewater production and treatment facilities distributed in the continents

2.2 India scenario

2.2.1 Status of sewage generation & treatment in metropolitan cities

Fig.5 shows the sewage generated and treatment capacity in the states of India. There are 35 metropolitan cities with above 10 million populations in India. The sewage generation and treatment capacity of these cities are 1.56×10^4 million liters per day (MLD) and $8.04\text{x}10^3$ MLD respectively (Table 1), which implies that only 51% of the generated sewage water can be treated in these cities. Among these metropolitan cities, Delhi the capital of India has the highest capacity of sewage treatment of 2.33×10^3 MLD, which is 29% of the total treatment capacity of metropolitan cities. Mumbai occupies the second position with 2.13×10^3 MLD, which is 26% of total capacity in metropolitan cities [2]. Total sewage generation per capita of all the metropolitan cities is 4.02×10^3 Ld^{-1}. Delhi has the highest sewage generation per capita 233.1 Ld^{-1} while Allahabad with a population of 5.96 million has the sewage generation per capita of only 29.6 Ld^{-1}. For all the other metropolitan cities the sewage generation per capita is given in Table 1. As we can see with such a big population, an enormous amount of sewage is being generated per day but there are only some metropolitan cities that are able to provide proper sewage treatment.

Table 1: Per capita sewage generation in various Indian metropolitan cities

Sr. No.	Name of the cities	State	Sewage generation (MLD)	Population	Sewage generation per capita (Ld-^1)	Sewage treatment capacity (MLD)
1	Hyderabad	Telangana	426.21	77,50,000	55.0	593
2	Vishakhapatnam	Andhra Pradesh	134.99	9,82,904	137.3	-
3	Vijayawada	Andhra Pradesh	128.39	8,51,282	150.8	-
4	Patna	Bihar	279.14	16,80,000	166.1	105
5	Delhi	Delhi	3800	163,00,000	233.1	2330
6	Ahmedabad	Gujarat	472	63,00,000	74.9	488
7	Surat	Gujarat	432	46,00,000	93.9	202
8	Rajkot	Gujarat	108.8	12,00,000	90.7	44.5
9	Vadodara	Gujarat	180	22,00,000	81.8	206
10	Bengaluru	Karnataka	771.75	85,20,000	90.6	-
11	Indore	Madhya	204	32,76,697	62.3	78

		Pradesh				
12	Bhopal	Madhya Pradesh	334.75	23,71,061	141.2	22
13	Jabalpur	Madhya Pradesh	143.34	24,60,714	58.3	-
14	Mumbai	Maharashtra	2671	184,00,000	145.2	2130
15	Pune	Maharashtra	474	50,49,968	93.9	305
16	Nagpur	Maharashtra	380	24,05,421	158.0	100
17	Nasik	Maharashtra	227.84	18,62,769	122.3	107.5
18	Ludhiana	Punjab	235.2	16,93,653	138.9	311
19	Amritsar	Punjab	192	11,32,761	169.5	-
20	Jaipur	Rajasthan	451.71	66,60,000	67.8	54
21	Chennai	Tamil Nadu	158	46,81,087	33.8	264
22	Kanpur	Uttar Pradesh	417.35	47,67,031	87.6	171
23	Lucknow	Uttar Pradesh	363.81	29,01,475	125.4	42
24	Agra	Uttar Pradesh	260.36	17,46,467	149.1	88
25	Kolkata	West Bengal	705.86	44,96,694	157.0	172
26	Faridabad	Haryana	164	14,04,653	116.8	65
27	Jamshedpur	Jharkhand	199.43	13,37,331	149.1	-
28	Asansol	West Bengal	147	12,43,414	118.2	-
29	Coimbatore	Tamil Nadu	120	30,50,721	39.3	-
30	Madurai	Tamil Nadu	97.93	10,17,865	96.2	-
31	Meerut	Uttar Pradesh	177.05	13,09,023	135.3	-
32	Varanasi	Uttar Pradesh	230.17	10,92,000	210.8	102
33	Allahabad	Uttar Pradesh	176	59,54,391	29.6	60
34	Kochi	Kerala	188.4	22,77,620	82.7	-
35	Dhanbad	Jharkhand	192	11,95,298	160.6	-
	TOTAL		**15,644.5**	**1,341,72,300**		**8046**

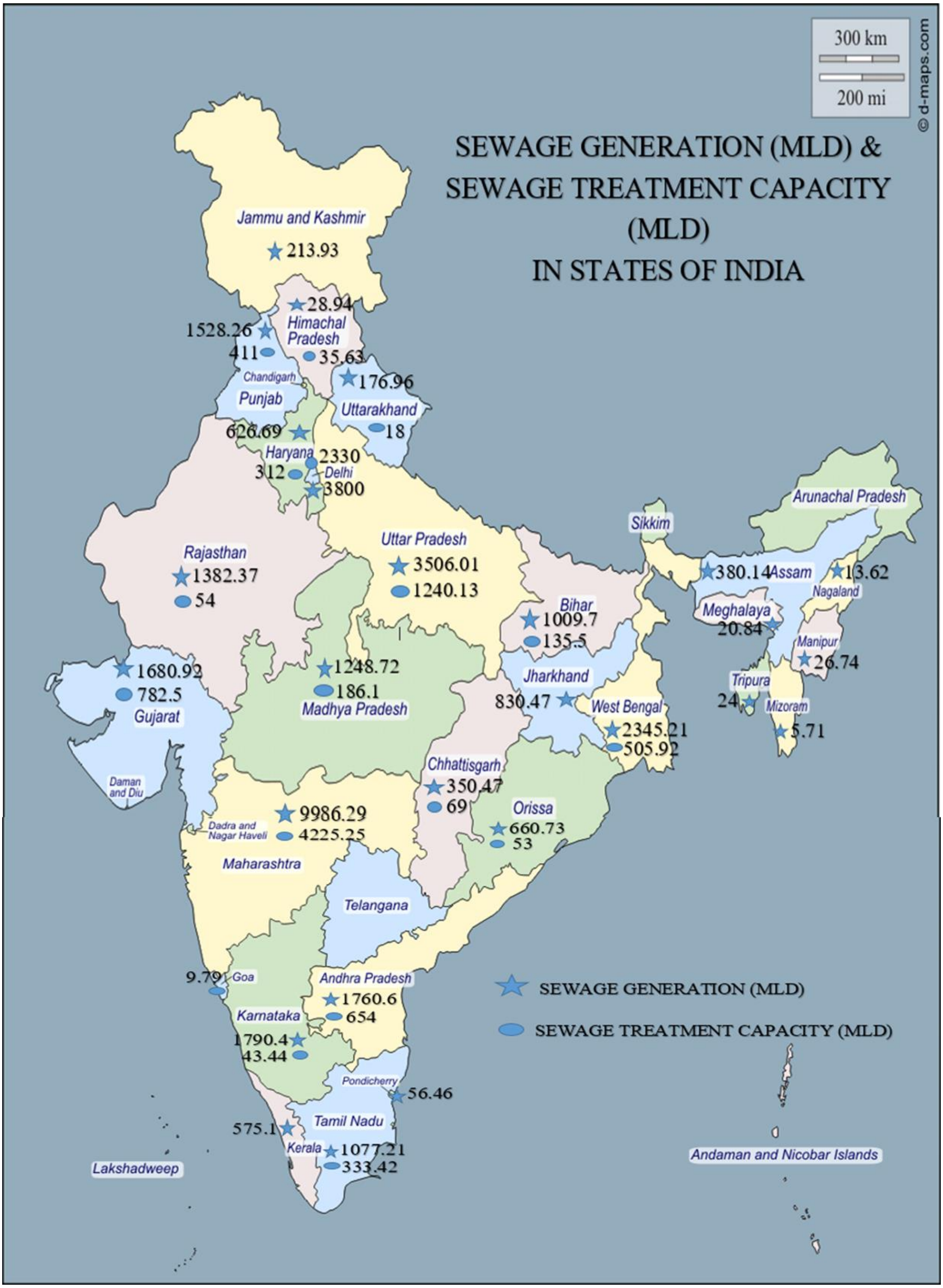


Fig. 5: Sewage generation and treatment capacity (MLD) in the states of India

3.2.1 2.2.2 Status of sewage generation & treatment in Class-I cities

According to census 2001, the Indian cities having a population of more than 100000 are classified as Class-I cities. There are 498 Class-I cities including metropolitan cities in India having above 100 million populations as per 2014 census. Around 52% of cities (260 out of 498) are located in five states viz. Andhra Pradesh, Tamil Nadu, Uttar Pradesh, West Bengal, and Maharashtra. Total sewage generated in these Class-I cities is estimated as 3.56×10^4 MLD [2]. In India, the share of Class-I cities is 93% of the total urban sewage generation. As can be seen from Fig. 6, the treatment capacity of these towns is 1.16×10^4 MLD, which is 32% of the total sewage generation.

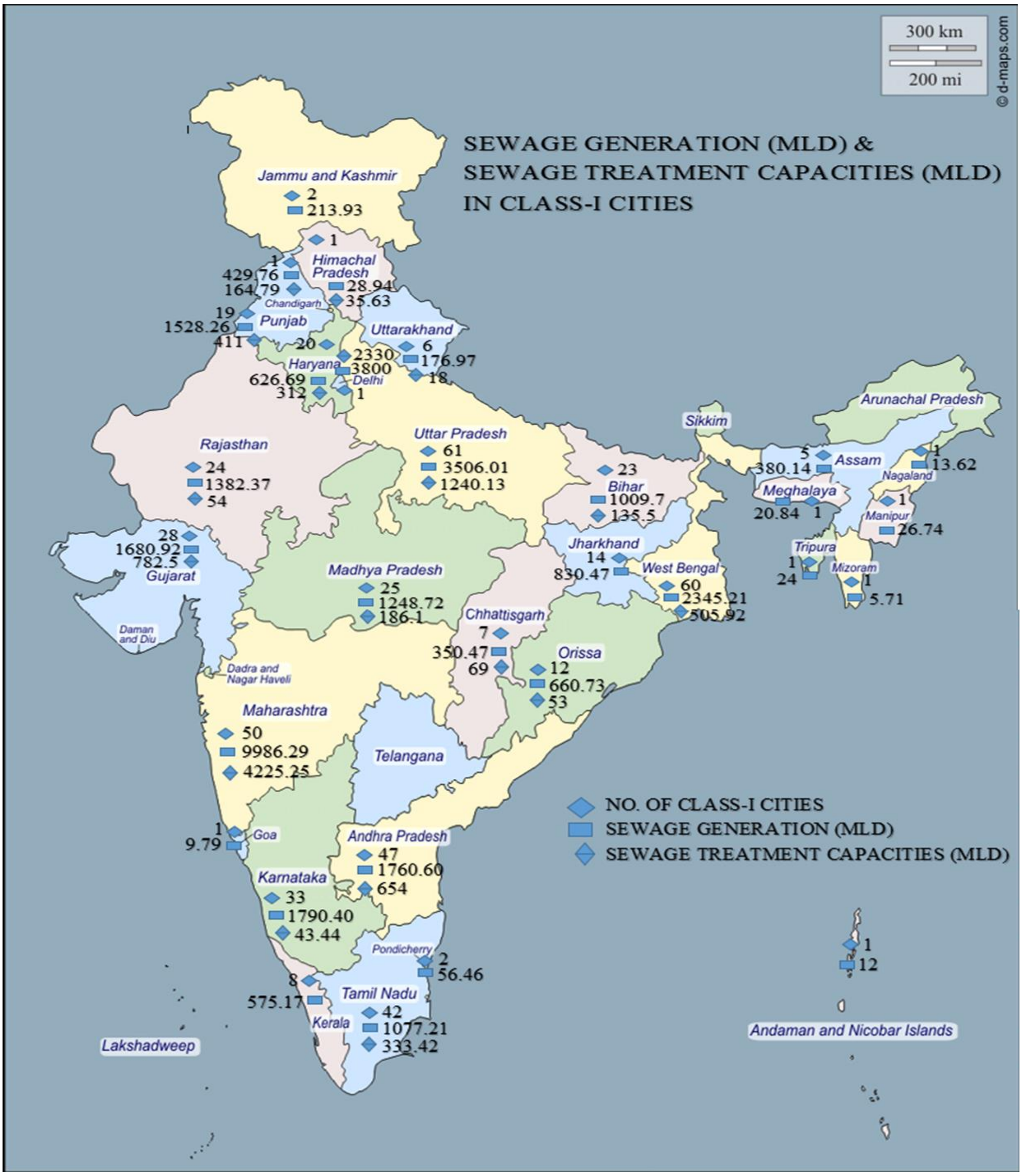


Fig. 6: Sewage generation and treatment capacity in Class-I cities of India

The total sewage generation per capita of Class-I cities is 4.35×10^3 Ld^{-1}. The highest number of Class-I cities are present in Uttar Pradesh and West Bengal (60 and 61 respectively) and their sewage generation per capita are 136.1 Ld^{-1} and 118.3 Ld^{-1}, while in case of Maharashtra, there are 50 Class-I cities but per capita is 248.1 Ld^{-1}. Delhi alone has sewage generation per capita of 255.7 Ld^{-1}. The status of sewage generation and sewage treatment capacity in all the states and union territories are shown in Fig. 6.

2.2.3 Status of sewage generation & treatment in Class-II cities

According to census 2001, the Indian cities having a population less than 100000 are classified as Class-II cities. There are 410 Class-II towns in India out of which, about 225 towns (more than 50% of the total number) exist in five states viz. Andhra Pradesh, Maharashtra, Uttar Pradesh, Gujrat and Tamil Nadu in India [2]. Total sewage generation in Class-II towns is 2.6×10^3 MLD (Table 2). As per the central pollution control board (CPCB) India report, 2013 total sewage treatment capacity in Class-II towns is 233.7 MLD which is only 8% of the total sewage generation. The total sewage generation per capita in Class-II towns is 6×10^3 Ld^{-1}. Maharashtra and Orissa have the highest sewage generation per capita values of 2.6×10^3 d^{-1} and 984.1 Ld^{-1} respectively. Andhra Pradesh and Gujrat come next in sewage generation and per capita. Most of the Class-II towns have no sewage treatment plant (STP) and only a small portion of the total sewage generation is treated in some of the towns.

Table 2: Per capita sewage generation in Class-II towns of states in India

Sr.No.	State/Union Territory	Population	No. of Class-II Towns	Sewage Generation (MLD)	Per Capita Sewage Generation (Ld^{-1})
1	Andhra Pradesh	5,73,290	52	217.59	379.5
2	Assam	11,13,800	8	6.46	5.8
3	Bihar	5,66,080	14	107.42	189.8
4	Chhattisgarh	1,72,850	7	40.82	236.2
5	Goa	21,80,590	2	13.89	6.4
6	Gujrat	5,44,040	31	227.55	418.3
7	Haryana	2,44,990	7	43.52	177.6
8	Jammu & Kashmir	8,26,300	4	27.86	33.7
9	Jharkhand	18,00,258	10	78.21	43.4

10	Karnataka	16,86,660	26	233.37	138.4
11	Kerala	17,45,050	26	231.32	132.6
12	Madhya Pradesh	25,03,080	23	130.9	52.3
13	Maharashtra	81,750	34	213.73	2,614.4
14	Meghalaya	1,26,520	1	11.25	88.9
15	Nagaland	9,04,510	1	1.36	1.5
16	Orissa	79,690	12	7.42	984.1
17	Pondicherry	11,09,670	1	7.984	7.2
18	Punjab	15,99,260	14	157.4	98.4
19	Rajasthan	735,30,000	21	147.79	2.0
20	Tamil Nadu	32,54,950	42	184.67	56.7
21	Uttar Pradesh	33,82,520	46	345.7	102.2
22	Uttarakhand	69,490	1	9.07	130.5
23	West Bengal	20,04,440	27	180.42	90.0
	TOTAL	**1,000,99,788**	**410**	**2625.70**	

2.2.4 State-wise distribution of STPs

The installed sewage treatment capacity of different states of India is shown in Fig.7. As we can see from Fig.7, Tamil Nadu (16.9%) and Uttar Pradesh (16.4%) come first followed by Andhra Pradesh (15%), Punjab (14%), West Bengal (10%). Then comes Haryana (7%), Maharashtra (6%), Gujrat (4.9%), Madhya Pradesh (3.6%), Bihar (3.4%) and Uttarakhand, Karnataka, Delhi, Goa is the states with less than 2% distribution [2]. According to the CPCB report, the Ministry of Environment & Forests funds 179 STPs under different schemes. The installed capacity of STP under national river conservation directorate (NRCD) schemes is 4.87×10^3 MLD out of which, only 64.26% i.e. 3.13×10^3 MLD of the installed capacity is actually utilized. Fig.8 shows the comparison of sewage generation, installed capacity and actual utilized treatment capacity among various states in India. It can be observed that in most states the installed capacity is only enough to treat a minor fraction of the generated wastewater. Furthermore, the utilisation of the STP capacity is also very variable, with a maximum in the states of Gujrat (97%), Punjab (74.68%), Haryana (79.97%) and Goa (96%), while in states like Tamil Nadu (49.31%), Uttarakhand (0%), Maharashtra (43.73%) less than 50% of the installed treatment capacity is utilised [2].

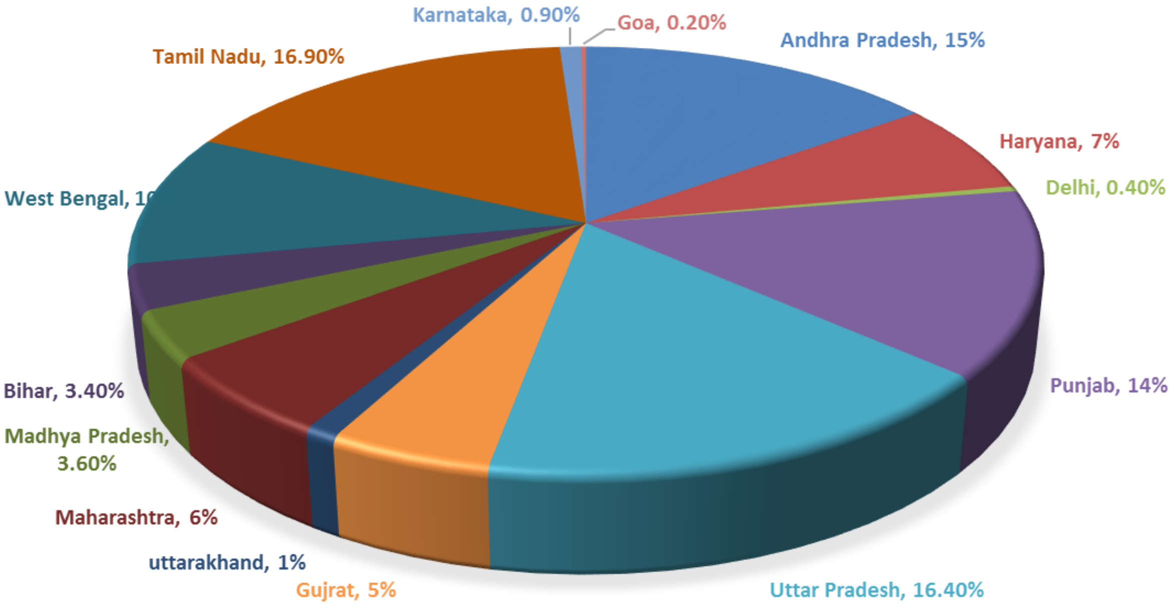


Fig. 7: State wise distribution of sewage treatment plants

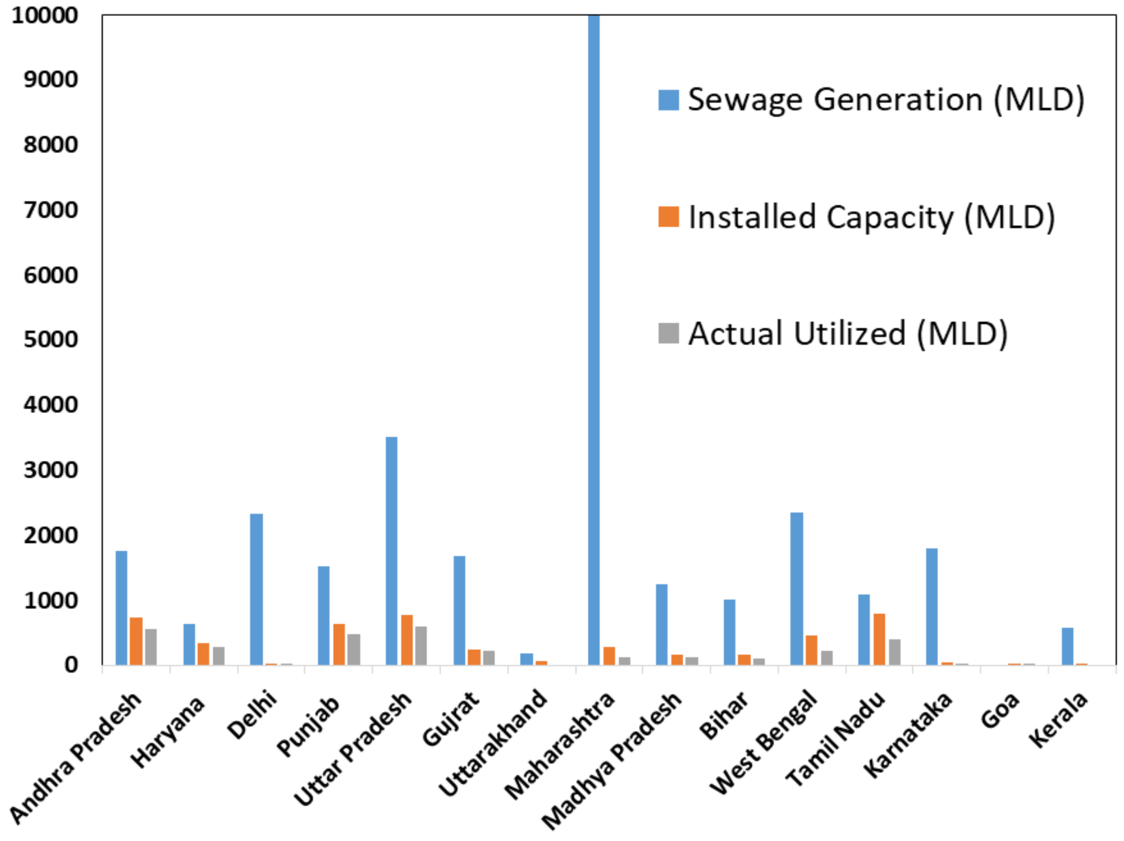


Fig. 8: Comparison of sewage generation, installed capacity and actual utilised treatment capacity

3 Energy demand and need for energy from wastewater

3.1 Population growth

The present world population is 7.3 billion which is expected to rise to 8.5 billion by the year 2035 (Fig.9) i.e. around 17% increment [3]. If the rate of population increase remains the same then the day is not far when our energy demands will outstrip the supply. India, China and few African countries like Nigeria will be the main responsible for the increase in energy demands since these countries have the highest population growth rate and are among the top developing nations. India has a population of 1.5 billion, which is estimated to rise by 40% by 2025, touching 2.1 billion. More population means more electricity requirements, more fuel for vehicles, more industrial energy requirements, thus an overall increase in energy consumption. Development leads to industrialization and improvement of living conditions, thus adding up to the energy needs.

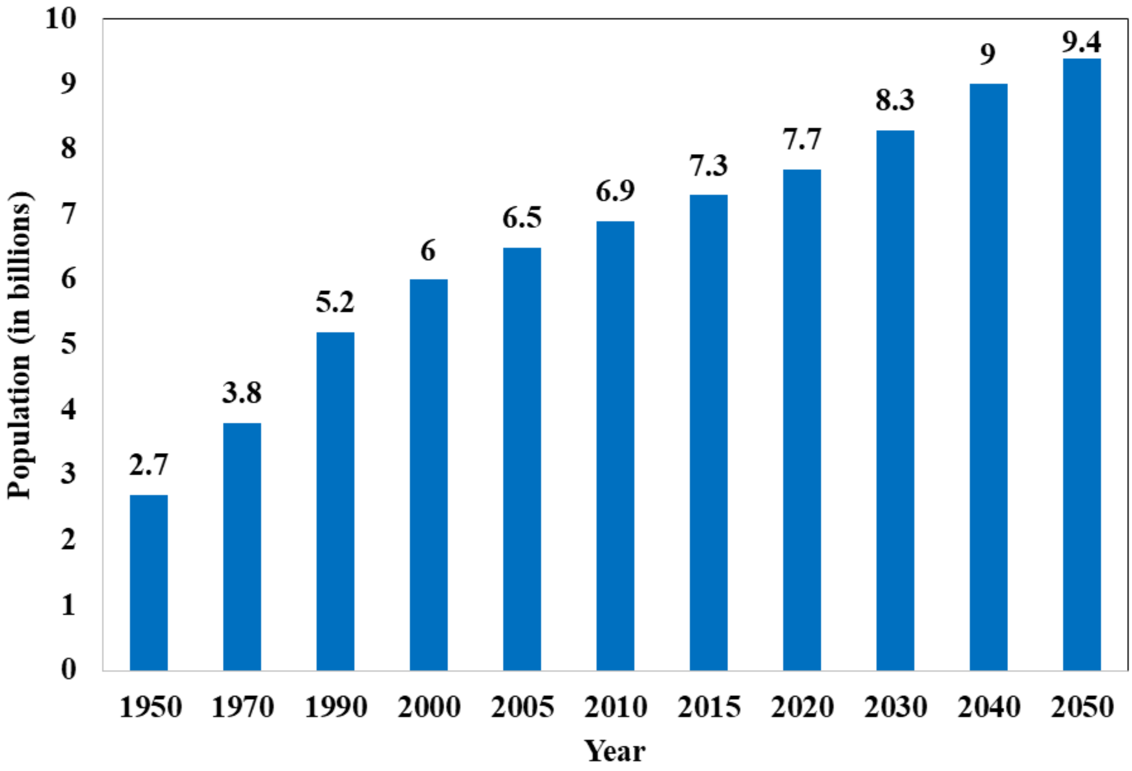


Fig. 9 Forecast of the population of the World [3]

3.2 Global energy demands and the need for alternative energy resources

World energy demand is going to increase significantly in the next 30 years. Fig.10 shows the energy consumption trend from various sources. Our planet, Earth, with more than seven billion population had a global energy consumption of more than 6 x 10^{20} J in 2011, which is expected to rise by 140% by 2040 with a changing composition of energy sources, with China and India driving the rate of increase far more than the rest of the world [4]. With 90%

of the world's oil reserves already discovered, there is a need to find new and more sustainable ways to make the energy to keep a match with the increasing energy demand.

Obtaining energy from municipal wastewaters is a way to generate renewable energy, which can contribute both to making the energy supply more sustainable and manage an unavoidable waste stream the generation of which increases as the population grows. The next section will examine the generation of municipal wastewaters on a global scale and in India in particular.

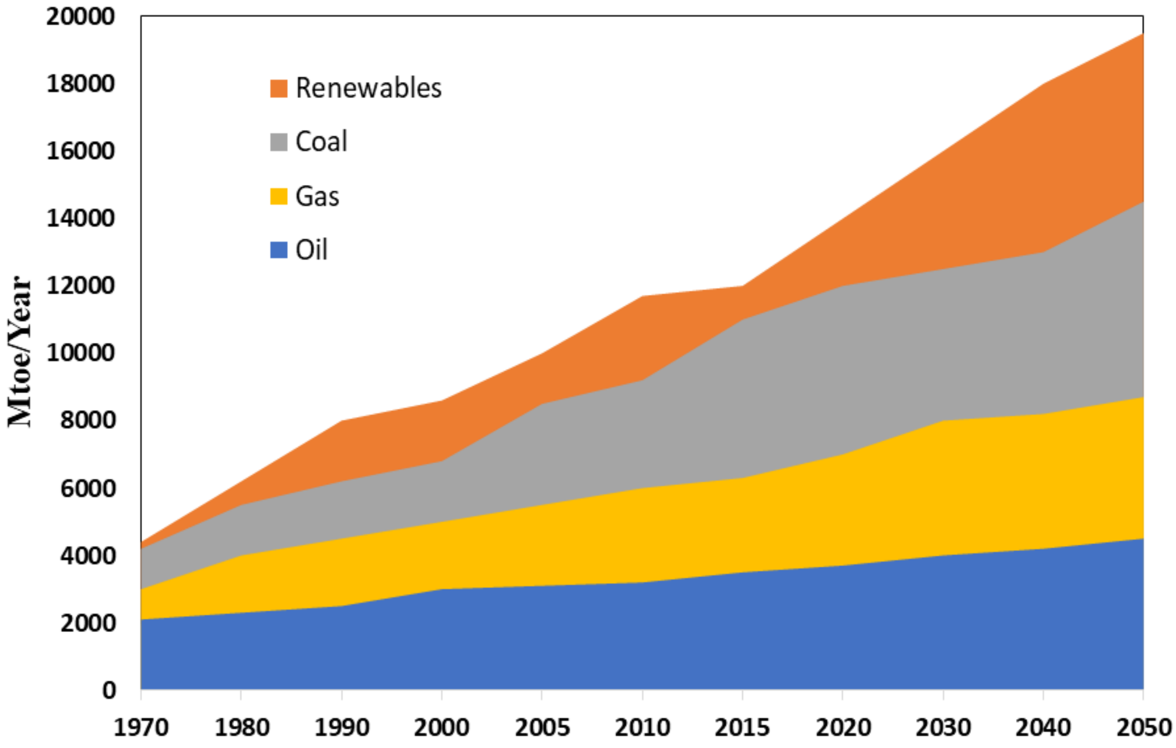


Fig. 10: Forecast of energy consumption [4]

4 Wastewater treatment technologies

The most common biological processes for wastewater treatment are based on the aerobic biodegradation of the biodegradable COD, for example, the activated sludge process. Aerobic processes have generally high biodegradation efficiency. However, they have typically large energy requirements due to the need for aeration. Anaerobic digestion processes have the important advantage of producing biogas (mostly CH_4 and CO_2), which can be used as a fuel, therefore converting the organic waste into renewable energy (up to 3516 kWh per 1000 kg of COD can be obtained). Another important advantage of anaerobic digestion is the absence of energy consumption which is due to aeration. Other advantages of anaerobic digestion are a reduction of produced biomass (5% to 20% of the aerobic process), less maintenance requirement, reduced endogenous decay during starvation [5]. The sludge produced from anaerobic digestion processes is rich in mineral elements and can be used as a fertiliser. However, anaerobic digestion has also significant drawbacks, as it is a slower process than aerobic digestion with lower COD removal efficiency. These limitations of anaerobic digestion can, however, be compensated to a good extent by using longer values of the solids residence time than aerobic processes. The detailed comparison between anaerobic and aerobic treatment process is given in Table 3. Since this study is focussed on energy generation from wastewaters, the rest of this study will only consider anaerobic digestion processes.

Table 3: Comparison of anaerobic and aerobic treatment, [6]

Parameter	**Anaerobic**	**Aerobic**
Energy requirement	Low	High
Degree of treatment	Moderate	High
Sludge	Low	High
Organic removal efficiency	High	High
Bioenergy and nutrient	Yes	No
Process stability	Low	High
Start-up time	2 to 4 months	2 to 4 weeks
Nutrient requirements	Low	High for certain industrial
Biogas production	Yes	Low

A comparison among various anaerobic digesters is summarised in Table 4. Although there are many configurations for decentralized anaerobic treatment units, septic tanks (anaerobic baffled reactors - ABR) and up-flow anaerobic sludge blanket (UASB) are most commonly found in the literature for real and laboratory scale applications. As discussed above, in spite of several advantages, anaerobic processes are not known to reach the acceptable quality level for immediate reuse and post-treatment is required to meet water quality standards for reclamation. However, by coupling an anaerobic bioreactor with a membrane filtration unit, effluent quality can be significantly improved without the need for aerobic post-treatment. Anaerobic Membrane Bioreactor (AnMBR), as the name suggests, is an integration of an anaerobic bioreactor with a low-pressure ultra/microfiltration membrane. This concentrates the substrate by filtering wastewater and retaining the volatile suspended solids (VSS). This provides compressed, biodegradable slurry for the microbes to decompose, thus helping reduce the reactor volume.

AnMBR can handle wastewater with very high COD concentration and total suspended solids, hence reducing the pre-treatment requirements, which are more in most other digesters. It can achieve around 94-99% COD removal and a CH_4 production of 0.25 to 0.35 m^3kg^{-1} COD [7]. It can be added to an existing anaerobic system with minimal complications, to increase loading capacity and/or improve performance and effluent quality. Using a membrane in an anaerobic digester can significantly increase the SRT and reduced the HRT and hence the size of the reactor. AnMBR has a high conversion per unit volume, with equally high productivity. Consequently, it occupies less volume as compared to the other digesters. AnMBR gives a very high-quality effluent water, which can be reused even for a few household purposes. The COD level of the water effluent from the AnMBR can be as low as 48 ppm. The acceptable levels of water used for industries are 250 ppm and it is 10 ppm for household purposes. For irrigation, we can use water with up to 100 ppm BOD. Table 5 shows the comparison of parameters for biogas production from different sources.

Table 4: Comparison between the types of anaerobic digesters [7]

Reactor	**Feed**	**COD** removal	**Organic Loading Rate (kg COD/(md)**	**Hydraulic Retention Time (d)**	**Methane Production (m^3/kg of COD**
Anaerobic Membrane Bioreactor	Brewery	99%	Above 30	2.5 to 4.2	0.28
	Distillery	97%	1.5	15	0.26
	Municipal Wastewater	94%	0.4-0.9	0.67-1.5	0.24
UASB Reactor	Wastewater	90% COD	2-3.6	3.91	0.22
Fixed Film Reactor	Domestic Wastewater	64-78 %	1.6	4-6	0.152
Hybrid Reactor	Vinasses	69% COD removal	17.05	7.5	0.263
Expanded Bed Reactor	Domestic Wastewater	89% COD removal	4.4		0.22

Table 5: Comparison of parameters for biogas production in AnMBRs from different sources

Wastewater	Brewery	Food industry	Kraft evaporator condensate	Sewage	Landfill	Coal industry	Distillery
COD (gL^{-1})	80-90	-	10	-	41	19.1	22.6
Temperature (^{o}C)	35-37	24-35	36-38	24-35	37	37	53-55
Organic loading rate (kg COD /(m^{3}d)	Above 30	0.4-11	22.5	0.4-11	6.27	Upto 25	1.5
HRT (day)	2.5-4.2		-	-	7	1.3	15
MLSS concentration (gL^{-1})	Up to 51	16-22	8-12	16-22	-	36	-
COD (removal)	99.00%	60-95%	93-99 %	60-95%	90.70%	96.80%	97%
Methane(m^3 /kg COD)	0.28	-	0.25	-	0.18	-	0.26
References	[8]	[8]	[9]	[10]	[11]	[10]	[12]

The synergistic effect of anaerobic reactors and membrane reduces the overall energy demand. A lot of reports also emphasize its advantages over the conventional aerobic methods for treating municipal wastewater [13]. According to studies conducted, PVDF microfiltration or ultrafiltration was found to be common with one exception where the flat-sheet dynamic membrane was employed [14]. Unlike the former, the performance of the latter was decided by shape, the molecular weight of the solution and its concentration. Due to the high packing density and cost factor, hollow fibers are preferred over flat-sheet membranes. Low packing density and higher dead volumes in tubular membrane modules make it difficult to use. Numerous studies reported full-scale aerobic MBR studies were reported [15]. However, till date, only one study is conducted in AnMBR where the wastewater was obtained from the food industry [16]. One of the strong points in employing AnMBRs is higher SRT as compared to conventional systems. Higher SRTs ensure higher COD removal and also aid microorganisms in adapting to different environments such as saline waters and pharmaceutical wastewaters [15].

The toxic effect of salt concentrations on non-adapted biomass serves as a hampering factor to the efficiency in anaerobic systems. Further, the decrease in COD removal with temperature. Since efficiencies are inversely proportional to the temperature, the majority of the studies were carried out in mesophilic conditions [17,18] However, one report at thermophilic conditions for treatment in the food industry [19]. One the other hand, ambient conditions were considered successful in low strength [20] and domestic wastewaters [21]. In the case of municipal wastewater, high temperatures can pose serious problems; as the wastewater is complex natured and consists of large particulate matters. Operating at psychrophilic conditions (below 20^0C) would be difficult in these situations but there are some reports under simulated conditions [20]. In another report, the same group conducted research 15, 12, 9, 6, and 3^0 C to achieve a significant reduction of COD [22] which was ascribed to higher activity in membrane biofilm. Furthermore, reusability of submerged AnMBR with forwarding osmosis was carried at psychrophilic conditions and results showed better performance of AnMBR over conventional AnMBR. A summary of the literature available on the use of AnMBR for the treatment of wastewater is provided in Table 6.

Table 6: literature on the use of AnMBRs to treat wastewater from different sources (L= Lab scale; P= Pilot scale; OLR= Organic loading rate)

Type of System/Module/ Configuration/ Membrane	**Membrane: Type/Material/Characteristic**	**Wastewater treated**	**Operating Condition**				**Influent COD (mg/L)**	**Effluent COD (mg/L)**	**Maximum COD removal (%)**	**Scale (L/P)**	**Ref.**
			HRT (h)	**SRT (d)**	**Temp (^{0}C)**	**OLR (Kg COD/m^3.d)**					
AnCMBRs/Submerged/Flat sheet	Ceramic membrane/Pore size = 80 nm/Area = 0.08 m^2	Domestic wastewater	5.8	60	25	10	417$\underline{+}$61	54	87	L	[23]
SAnMBR/Submerged/Flat-sheet	Polyethylene terephthalate/Pore size = 0.2 µm/Area = 0.116 m^2	Synthetic wastewater (alcohol ethoxylates)	42	-	25	6	1425	17.1	98.8	L	[24]
SAnMBR/Submerged/Flat-sheet	Ultrafiltration/Polyvinylidene fluoride/pore size=0.22 µm/Area=0.735 m^2	Domestic wastewater	5.8–4.8	50	35	0.43-0.9	400	40	90	L	[25]
AnMBR/External/Tubular	Ultrafiltration /Polyethersulfone/Pore size = 30 µm/Area= 0.11 m^2	Synthetic wastewater	6	126	25	2	530	52	92	L	[26]
AnMBR/External/Tubular	Ultrafiltration / polyvinylidene difluoride /Pore size = 30 µm/Area= 0.0038 m^2	Synthetic wastewater	6	126	25	2	530	42	92	L	[27]
AnMBR/External cross flow membrane/Tubular	Ceramic (ZrO_2–TiO_2)/Pore size = 0.2 µm/Area = 0.25 m^2	Industrial wastewater	1.7-5	120-450	35-37	2.5	4300	830	78	P	[28]]
SAMBR/Submerged/Flat sheet/and hollow fiber	Microfiltration/ Polipropilen-PP/Chlorinated polyethylene/ Pore size = 0.05 µm/ Area = 0.66 m^2	Synthetic industrial wastewater	390, 167, 168	-	35	0.3-0.54	20000-23000	-	85-90	L	[13]
Submerged anaerobic membrane	Microfiltration /Curtain-type/Pore size = 0.22 µm/Area =5.4 m^2	Synthetic	22	-	35	3	223-111	50-22	87	P	[29]
SAnMBR/Submerged/Hollow fiber	Microfiltration /Curtain-type/Pore size = 0.4 µm/Area = 0.040 m^2	Paper mill wastewater	35	40	21	7	11415	228.3	98	L	[30]

AnMBR/Hollow fiber	Ultrafiltration /Polyvinylidene fluoride /Pre size=-/ Area= 20 m^2	Synthetic anti-biotic solvent	48, 36, 24, 18	-	35	3.9-12.7	7892-21968	-	93.6-98.7	P	[31]
AnMBR/Hollow fiber/	Ultrafiltration/Polyvinylidene fluoride/Pore size = -/Area = 20 m^2	Synthetic anti-biotic solvent	48	-	37	3.79	15000-25000	-	96.5	P	[32]
AnMBR/Hollow fiber	Ultrafiltration /Polyvinylidene fluoride (PVDF)/Pore size = -/Area = 20 m^2	Synthetic anti-biotic solvent	48		35	10	1000-25000	-	95	P	[33]
AnMBR/Hollow fiber	Ultrafiltration /Pore size = 0.04 µm/Area = 0.047 m^2	Brewerywastewater	44	-	35	3.5-11.5	19100	171	99	L	[34]
AnMBR and B-AnMBR/Hollow fiber	Ultrafiltration/Polyvinylidene fluoride /Pore size = 0.02 µm/Area = 0.07 m^2	Bamboo wastwwater	72		32	6	17160	278.9	94.5	L	[34]
C-AnMBR and B-AnMBR Ultrafiltration /Hollow fiber	/Polyvinylidene fluoride/Pore size = 0.04 µm/Area = 0.047 m^2	Pharmaceutical wastewater	30.6	-	27	13-0.6	16249	8723	46.1	L	[35]
SAMBR/Submerged/ Flat sheet	Non-woven fibrous (chlorinated polyethylene)/Pore size = 0.2µm/Area = 0.116 m^2	wastewater (linear alkyl benzene sulfonate concentration)	24–12	-	25	3-6		23.5	97.07	L	[36]
SAMBR/Submerged/ Flat sheet	Microfiltration/Polymethyl methacrylate/Pore size = 0.2µm/Area = 0.116 m^2	Synthetic sewage	12, 8, 6, 4, 2	200	35	-	544	22	97	L	[37]
SMBR	Microfiltration /Polymethyl methacrylate/Pore size = 0.04 µm/Area = 0.047 m^2	Synthetic wastewater	8	140	18	1.77	-	-	98	L	[38]
AnOMBR/submerged	Cathode/Stainless steel mesh/Pore size = -/Area 1.5 m^2	Synthetic wastewater	-	-	35	-	2000	-	71.1	P	[39]

SAMBRs/Submerged/Flat sheet	Microfiltration /Non-woven fibrous (chlorinated polyethylene)/Pore size = 0.2 µm/Area = 0.116 m^2	Synthetic sewage	12-6	-	35	3-6	298	6.6	93	L	[40]
Integrated anaerobic fluidized bed membrane (IAFMBR) Hollow fiber	Microfiltration /Pore size = 0.4 µm/Area = 0.21 m^2	Synthetic benzothiazole wastewater	24	-	35	6.1	-	230	96	L	[41]
SAMBRs/Submerged/Flat sheet	Microfiltration/Chlorinated polyethylene/Pore size = 0.2 µm/Area = 0.116 m^2	Synthetic sewage	48, 24, 12, 6	-	25, 15, 10	-	-	134	94	L	[42]
AnMBRs/External /hollow fiber	Microfiltration/Polyvinylidene difluoride /Pore size = 0.22 m/Area = 0.06 m^2	Synthetic sewage	84		3.4	-	6752	663	96.7	L	[43]
EG-AnMBR and SG-AnMBR/ hollow fiber	Microfiltration/Polyvinylidene difluoride /Pore size = 0.22µm/Area = 0.06 m^2	Synthetic sewage	12	-	20	0.53-0.59	-	-	90	L	[44]
AnMBR/ Side-stream /Hollow Fiber	Ultrafiltration/polyvinylidene difluoride	Bamboo industry	2–10	–	28–30	8.0–14.0	21400	1500	85–90	L	[45]
AnMBR/ Submerged /Hollow Fiber; ZW-10	Ultrafiltration/ polyvinylidene difluoride	Slaughterhouse (side A)	2–7	50–1,000	37	26.1	5920	70	95	P	[18]
AnMBR/ Submerged /Hollow Fiber; ZW-10	Ultrafiltration/polyvinylidene difluoride	Slaughterhouse (side B)	4–7	50	37	17.0–40.2	10600	180	95	P	[18]
AnMBR/ Submerged /Flat sheet	Ultrafiltration/Chlorinated polyethylene	Molasses	26	1,535	34	18.7	110900	10700	94	L	[17]
AnMBR/Submerged /Flat sheet	Ultrafiltration/Chlorinated polyethylene	Molasses	5.3	1,535	34	10	14500	500	93	L	[17]

AnMBR/ Side-stream /Tubular	Ultrafiltration/polyvinylidene difluoride	Liquid dairy manure	19 (10–35)	19 (10–35)	Room	54	53700	–	41	P	[46]
AnMBR/ Side-stream /Tubular	Ultrafiltration/polyvinylidene difluoride	Liquid dairy manure	12	24	Room	28	41800	–	42	P	[46]
AnMBR/ Submerged	Dynamic//–	Landfill leachate	2.5	125	37	16.9	13000	4910	62	L	[14]
AnMBR/ Side-stream /Hollow Fiber	Ultrafiltration/polyvinylidene difluoride	Pharmaceutical industry	21.3–42.6	700	27	6.0–8.4	15400	8770	43	L	[20]
AnMBR/ Side-stream /Hollow Fiber	Ultrafiltration/polyvinylidene difluoride	Pharmaceutical industry	21.3–42.6	700	27	1.2–2.1 + 11.0	15400	8230	47	L	[20]
AnMBR/ Side-stream /Hollow fiber	Ultrafiltration/polyvinylidene difluoride	Debris leachate	15.5	–	23	6.0–7.0	-	-	80	L	[47]
AnMBR/ Side-stream /Tubular	Ultrafiltration/polyvinylidene difluoride	Lipid rich corn-to-ethanol thin stillage	10.1	20; 30; 50	37	15.2–24.9	72200	470	>99	L	[48]
AnMBR/ Submerged /Hollow Fiber	Microfiltration/polyvinylidene difluoride	Food industry (oil and grease	–	–	36	11.4	7900-22800	180–300	97	P	[49]
AnMBR/ Submerged /Flat sheet	Microfiltration/–	Food industry (salad dressings)	–	–	33	20.0–45.0	3900	210	99	F	[50]
AnMBR/ Submerged /Flat sheet	Microfiltration/Chlorinated polyethylene	Food industry	20–70	20–100	57	75	–	2000	67	L	[19]
AnMBR/ Submerged /Hollow Fiber	Microfiltration/ Polyetherimide	Food industry(sugarcan	–	–	19–27	20	17700	708	96	L	[51]
AnMBR/ Submerged /Hollow Fiber	Ultrafiltration/ polyvinylidene difluoride	Food industry (snacks)	–	–	30–36	18	11000	2750	75	P	[52]
AnMBR/ Submerged /Flat sheet	Ultrafiltration/polysulfone	Municipal wastewater	–	–	35/20	15.0–20.0	400	80	90	P	[21]

4.1 Pre-treatment methods for wastewater

The amount of organic matter in wastewater that is digested primarily depends on its solubility. With increasingly soluble COD, the more organic matter is digested and more CH_4 and CO_2 is produced. The main aim of pre-treatments is, therefore, to solubilise the suspended organic matter in the wastewater. There are several different methods for pre-treating the wastewater before it is fed to the anaerobic digester. Mechanical, chemical and thermal pre-treatment methods are discussed in the following sections. Mechanical pre-treatment is carried out by mills, which results in size reduction breaking of cellular structure and increase in specific surface area. In addition to increasing the rate of enzymatic degradation, particle size reduction can also reduce viscosity in digesters to aid the mixing. Chemical pre-treatment constitutes the use of a range of chemicals, mainly acids and bases to dissolve the substrate particles. Lignocellulosic materials are highly complex, stable, and resistant to hydrolysis. Alkali, acid and oxidative pre-treatment results in swelling of lignocelluloses and partial lignin solubilisation. In thermal pre-treatment of sludge, the sludge is raised to a particular temperature to facilitate removal of the pathogen to improve dewater-ability and reduce the viscosity of the digested sludge [53,54]. The study of thermal pre-treatment effects is done in two regimes- low temperatures and high temperatures. The carbohydrate solubilization increased with temperature. Pre-treating the substrate at low temperature i.e. 60°C, 80°C, 100°C for 30 mins, increases the soluble protein from 2% to 12%, 20%, 18% of the total protein, respectively [55]. Pre-treatment at high temperatures i.e. between 120 °C to 170 °C results in substrate solubilization and protein exposure are increased leading to higher biodegradability. There are numerous literature suggesting that biogas production increases with the temperature of the thermal pre-treatment. Since for proteins solubility is directly proportional to temperature, the soluble COD increases with an increase in temperature from 60^0C-170^0C [56]. The soluble carbohydrate concentration increases until 130^0C and then decreases on further increase in temperature [56]. Haug *et al.*, (1978) [57] state that pre-treatment at 175 ^{0}C for 30 min results in increased biogas production by 60%-70%. Perez-Elvira et al. (2010) [58] show that thermal treatment at 170^0C for 30 min results in enhancement of biogas production by 40%, compared to the conventional digester.

4.2 Fouling in AnMBRs

The characteristic component of the AnMBR is its filtering medium or the biological membrane. The configuration of these membranes aims at maintaining a large membrane area to bulk volume ratio, high turbulence on the feed side, lowering the energy requirements and ensuring accessibility for simple cleaning. The membrane fouling is a major factor limiting the efficiency of the AnMBR. The various mechanisms by which fouling takes place are biofouling, organic and inorganic fouling [59]. Biofouling has three distinct mechanisms: pore clogging, sludge cake formation and adsorption of extracellular polymeric substances (EPS) [60]. Pore clogging is also caused by cell debris and colloidal particles [61]. The deposition of organic compounds and bio-polymeric substances like polysaccharides and proteins leads to organic fouling [59]. Fouling due to EPS can also be considered a particular type of organic fouling. Generally, higher organic loading rates cause higher residual CODs and lower membrane fluxes [62]. It has been found that cases of inorganic fouling are dealt with less effectively than organic or biofouling [59]. The most common inorganic fouling agents are struvite ($MgNH_4PO_4 \cdot 6H_2O$) [57] found in urinary wastes, $K_2NH_4PO_4$, $CaCO_3$ [63]. A few compounds with Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, etc. ions also contribute to fouling. Operating the reactor at higher SRT to minimize the COD concentration exposed to the membrane helps decrease the rate of organic fouling [64]. Occasionally, powdered activated carbon and zeolites are introduced into AnMBRs to adsorb soluble organic compounds which helps reduce organic. The fouling rate can be reduced by operating a membrane below the critical flux and by maintaining a high shear across the membrane surface. This can be achieved either by maintaining a high-velocity gradient or by gas sparging. It often becomes difficult to change the process parameters like maintaining high flow rates. Thus, bubbling gas through the membrane is a convenient option to reduce fouling.

5 Coupling anaerobic processes with microalgae cultivation

The effluent treated water from the anaerobic-membrane process is rich in nutrients, with a high amount of dissolved CO_2 and some soluble biodegradable particles. We need to ensure the productive disposal of this effluent water. A solution to this problem can be found in the use of a microalgae cultivation setup which follows the digestion process. Microalgae are unicellular photoautotrophic/photoheterotrophic microorganisms, like simple plants with no root and leaves that grow through the process of photosynthesis. They capture CO_2 in the course of photosynthesis and produce biomass, which can be used as food, fertilizer, a source of medicine and biodiesel [65]. Since the requirements for microalgae growth are merely the nutrients and CO_2 available in treated water and the abundant sunlight, they can be grown on this effluent water [66,67]. This will help providing energy in addition to solving the problem of water disposal. In addition, microalgae have an enormously high biofuel yield (80,000 L/acre/year) compared to many other plant sources [68].

There are two commercial methods for cultivating microalgae- open system (open pond cultivation) and closed system (photo-bioreactor cultivation). The various types of open ponds include shallow big ponds, tanks, circular ponds and raceway ponds. Though open ponds are easy, natural ways of cultivating microalgae and easier to construct and operate, they have certain drawbacks which limit their use. They exhibit poor light utilization by the cells, evaporative losses, diffusion of CO_2 to the atmosphere, and requirement of large areas of land. Photo-bioreactors (PBRs), instead, have excellent space utilization characteristics and have many advantages over the conventional open pond systems.

- The growth parameters (e.g. temperature, illumination, pH, CO_2 input) can be better controlled;
- They exhibit high surface to volume ratios, which allows attainability of high volumetric productivities and cell concentration
- The closed system not only prevents evaporation of the water maintained inside but also its contamination.
- They ensure maximum CO_2 utilization to minimize its release to the environment
- Besides having the flexibility of constructing in indoors as well as outdoors, space can be saved if constructed vertically.

Hence, most commercial firms prefer the use of PBRs.

5.1 Photo-bioreactors

Photo-bioreactor (PBR) is a biological reactor that cultivates phototrophic microorganisms using a light source (solar or artificial) and nutrients. They are used for accurate phototropic cultivation of algae and cyanobacteria. Various factors affect the production of microalgae in PBR. The algal yield depends upon the availability of light, nutrients, CO_2, the pattern and degree of mixing of the nutrients and CO_2, the culture density, the operating conditions of the PBR- temperature, pH and flow rate of inlet water. The PBRs mainly find application in cultivating algae or producing biomass. PBRs offers a unique combination of the cultivator and a monitoring device. One can easily control the frequency of light, power, spectral composition, the temperature and the aeration gas composition. Even the cultivation conditions can be dynamically modified to suit the user requirements.

The tubular system is designed to ensure uniform illumination over the whole volume of cultivated culture. There are various PBRs based on their ability to homogenize illumination, their light absorbing characteristics, yields of algal strains, etc. The main types of PBRs are the vertical column PBR, the flat plate PBR, the tubular PBR, the bubble column PBR [69] and the airlift column PBR [70]. The advantages and limitations of each type of PBR are explained in Table 7. The tubular PBR is the most widely used reactor, owing to its large illumination surface area and high yield of biomass from the reactor [71,72]. It results in the healthy growth of algal culture with very low risk of contamination compared to open ponds [73], which in turn results in higher productivity and more efficient use of land. The tubular PBRs have peculiar characteristics making them very effective. They have a large surface area available for solar irradiation. They are even suitable for outdoor cultures with fairly high productivity. They have a long working life and are relatively cheaper than the raceway ponds, but still, have 13 times the productivity of raceway ponds [72]. The Undular Row Tubular PBR has the highest microalgae productivity of algal strains (2.70 $gL^{-1}d^{-1}$) as compared to other types of PBRs. A challenge with this cultivation system is the production of O_2 during the photosynthesis process. The oxygen will build-up in the closed system, inhibit algal growth and may even poison them. Thus, the culture must be regularly passed through the degassing zone to cut down the excess oxygen levels. Another problem is depletion of CO_2 in the closed system, which may cause CO_2 starvation of the microalgae. It has to be ensured that there is a continuous supply of CO_2 to the system, also considering the need to maintain the workable pH. The maintenance of the desired temperature is ensured by employing heat exchangers in the system or in the degassing zone [73]. The bubble column and airlift type PBRs are used as artificially illuminated, lab-scale PBRs. The comparison of productivity and operating parameters for different types of PBRs are summarised in Table 8.

Table 7: Advantages and limitations of types of PBRs [67]

PBR type	Advantages	Limitations
Tubular	1. Large illumination surface area 2. Suitable for outdoor cultures 3. Good biomass productivities 4. Relatively Economical	1. Requires large land area 2. Some degree of wall growth 3. Gradients of pH throughout 4. Fouling
Flat Plate	1. Good for immobilization of algae 2. Easy to clean up 3. Large illumination surface area 4. Suitable for outdoor cultures 5. Good Light path	1. Scale up requires support materials and many compartments 2. Problems controlling culture temperature3. The possibility of hydrodynamic stress 4. Some degree of wall growth
Vertical	1. High mass transfer	1. Small illumination surface area

Column	2. Good mixing with low shear stress 3. Reduced photo inhibition & oxidation 4. Readily tempered	2. Construction requires sophisticated materials 3. Shear stress build up to algal cultures

Table 8: Comparison of productivity and operating parameters for different types of PBRs

PBRs	Volume (L)	Photosynthetic strain	Productivity (gL^{-1}d^{-1})	Reference
Airlift tubular	200	*Porphyridium cruentum*	1.50	[73]
Airlift tubular	200	*Phaeodactylum tricornutum*	1.20	[74]
Airlift tubular	200	*Phaeodactylum tricornutum*	1.90	[73]
Inclined tubular	6.0	*Chlorella sorokiniana*	1.47	[75]
Undular row tubular	11	*Arthrospira platensis*	2.70	[76]
Outdoor helical tubular	75	*Phaeodactylum tricornutum*	1.40	[77]
Parallel tubular (AGM)	25,000	*Haematococcus pluvialis*	0.05	[78]
Bubble-column	55	*Haematococcus pluvialis*	0.06	[79]
Flat plate	440	*Nannochloropsis sp.*	0.27	[67]
Tubular	5.5	*Spirulina platensis*	0.42	[80]
Tubular	146	*Arthrospira*	1.15	[81]

5.2 Proposed flowsheet for optimal biofuel production

The idea discussed in this paper is to design a completely integrated process to couple tubular PBR in adjunction with AnMBR. Fig.11 shows the proposed process flowsheet for the integrated AnMBR and PBR system. The municipal wastewater is pre-treated thermally to de-agglomerate the lumps of soluble substrate particles and consequently increase the amount of soluble COD in the feed water. This also helps with a reduction in viscosity of the wastewater, thus easing out the pumping process. Pre-treatment at 160-170 ^{0}C for 30 min will result in 60%-70% increased biogas production [57]. In the digester, the solids residence time will be in the order of 100-120 d in order to maximise biogas production. The biogas comprises methane, carbon dioxide and trace amounts of H_2S, moisture, and siloxanes. The

H_2S produced is removed from the system by scrubbing in a packed bed absorption tower. The biogas is now concentrated to about 60% methane and 40% carbon dioxide. The effluent water from the digester has reduced COD levels (about 94% COD removal). The sludge formed during digestion is evacuated from the bottom. Some part is sent to final processing for fertiliser production and the rest is recycled back to the digester.

However, this water still contains some soluble particles, not metabolized in the digester. Hence, it is sent to the clarifier where it is filtered through a side stream membrane, which acts as a clarifier-settler. However, filtration of this water stream may lead to the eventual fouling of the membrane. The remedy to this problem is scouring the membrane with the biogas from the digester. The gas bubbles cause stress at the membrane surface, loosening out the fouling and retaining the membrane effectiveness for long [82]. Another advantage is that we get enriched biogas, with more concentrated CH_4 (about 82%), since CO_2 is more soluble in water than CH_4.

The next step is the cultivation of microalgae in PBRs using effluent water. The treated effluent from the anaerobic digestion and membrane process, rich in CO_2 and NPK nutrients, is fed to the Tubular PBR. The requirements of the PBR are well provided- sunlight, warmth, nutrients, and CO_2. Of these, CO_2 is the limiting factor and hence is used up completely in the process, thus cutting down its emissions to the environment. All other factors necessary for microalgae growth are present in excess. The tubular PBR gives productivity of 0.55 kg microalgae per kg of CO_2 [67]. This procedure ensures nearly pure methane gas at the outlet. The cultivated microalgae will subsequently be used, after separation and drying, for energy generation, for example, to extract biofuels or combustion. Thus, the considered process converts the organic matter of the municipal wastewater to biofuels and methane gas. The microalgae thus cultivated can be used as sensible energy in three ways:

- Conversion to biofuels: this method calls for high-end machinery to efficiently convert the microalgae to biofuels, and hence is expensive. Further study needs to be done to reduce the cost of this method:
- Recycling back to AnMBR: this is a cheap, easily implementable method to recycle the microalgae back to AnMBR, where it will be served as a nutrient for the anaerobic bacteria. This makes the system self-sufficient:
- Co-firing with coal/coke: the microalgae can be co-fired or burnt along with coal/coke in the existing industries. In this way, the search for infrastructure to use up microalgae need not be done. Also, the calorific value (HHV) of the total fuel mixture increases, thus enriching the combustion process.

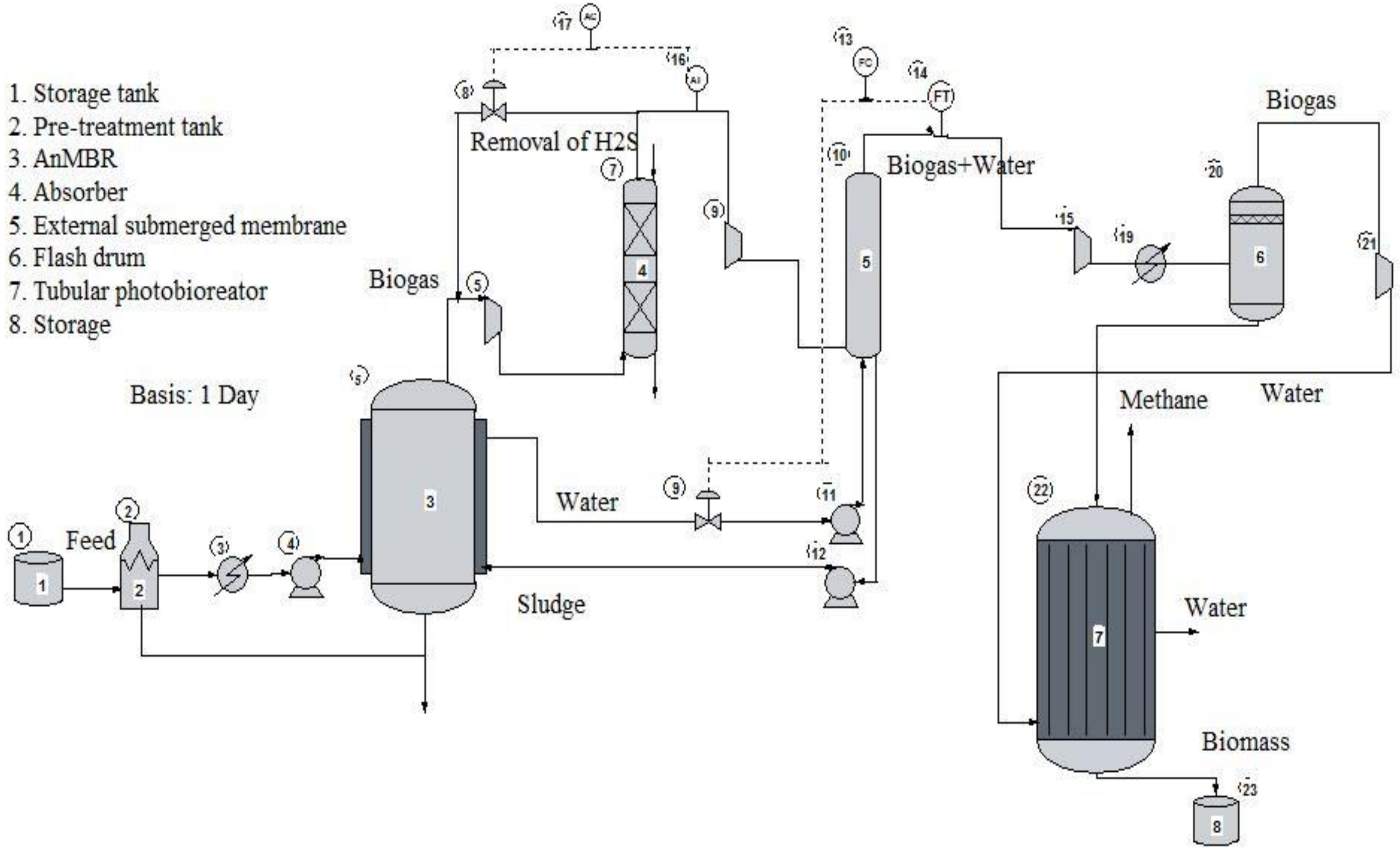


Fig. 11: The proposed flowsheet for the integrated AnMBR and PBR system

5.3 Biofuels potential from sewage in India

Fig.12 shows the proposed flowsheet with brief calculations for India’s Class-I (including metropolitan cities) and Class-II cities combined. The calculations prove that biofuels are a potentially valuable resource in the coming future. The total consumption of petroleum products in India for the year 2014-15 is 1.63×10^{8} tons, which corresponds to energy content of 5.71×10^{9} kWhd^{-1} Considering the recent scenario, the biogas production capacity for India comes out to be 3.21×10^{6} m^{3}d^{-1} and the equivalent fuel calorific value (HHV) is 36.4 MJm^{-3}. The biomass production from the PBR is calculated out to be 2.02×10^{6} kgd^{-1} Fig.13 shows the proposed flowsheet with the brief calculation based on the prediction sewage generated throughout India. From the educated predictions of the near future stats, the potential of biogas production can be calculated as 1.12×10^{7} m^{3}d^{-1} and the biomass generation is 7.07×10^{6} kgd^{-1}. The total equivalent energy from the combined biofuels (methane from anaerobic digestion and energy from microalgae) is predicted to be 1.69×10^{8} kWhd^{-1}. This has the potential to replace approximately 3 % of the recent total petroleum product consumption. The energy generation potential from the sewage water generated in India is summarised in Table 9. The calculations shown in this section refer to the treatment of the total volumes of municipal wastewater generated in India. However, as shown in the previous sections, currently only a minor fraction of the generated wastewaters in India is actually treated. This indicates that a significant expansion in the treatment capacity and utilisation in India will be needed in order to achieve the full potential of bioenergy generation from wastewaters calculated in this study. Based on the available data and suitable assumptions, the world’s total energy generation potential from wastewater is also calculated and depicted in Table 9. The total energy that can be generated from the wastewater around the world is found to be 5.54×10^{8} kWhd^{-1}**.** The wastewater generation data is available for a few countries across the world. The energy potential can increase by four to five fold if the actual wastewater generated in the world is considered for the calculation.

Table 9: Summary of the calculations for generation of energy from wastewater

Parameters	For Class-I and II cities	For whole India (both	For the World
Wastewater generated (MLD)	4.23×10^{4}	1.89×10^{5}	6.2×10^{5}
COD(kgd^{-1})	1.15×10^{7}	4.01×10^{7}	13.16×10^{7}
Microalgae (kg d^{-1})	2.02×10^{6}	7.07×10^{6}	23.19×10^{6}
Biogas (m^{3} d^{-1})	3.21×10^{6}	1.12×10^{7}	3.68×10^{7}
Equivalent energy from Biogas (kWhd^{-1})	3.25×10^{7}	1.14×10^{8}	3.74×10^{8}
Equivalent energy from Microalgae (kWhd^{-1})	1.57×10^{7}	5.5×10^{7}	18.04×10^{7}

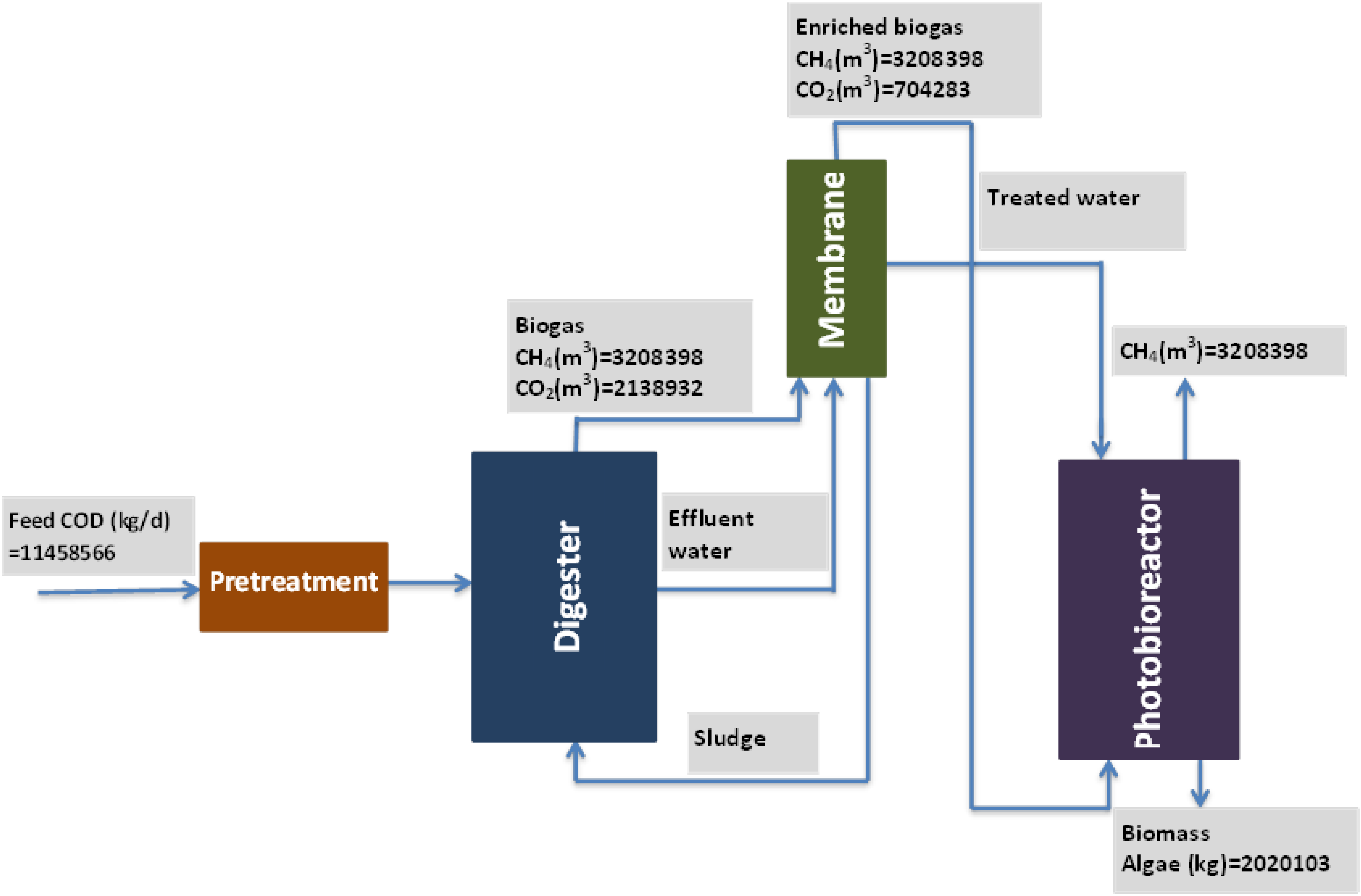


Fig. 12: Proposed flowsheet with brief calculations for Class-I (including metropolitan cities) and Class-II cities in India

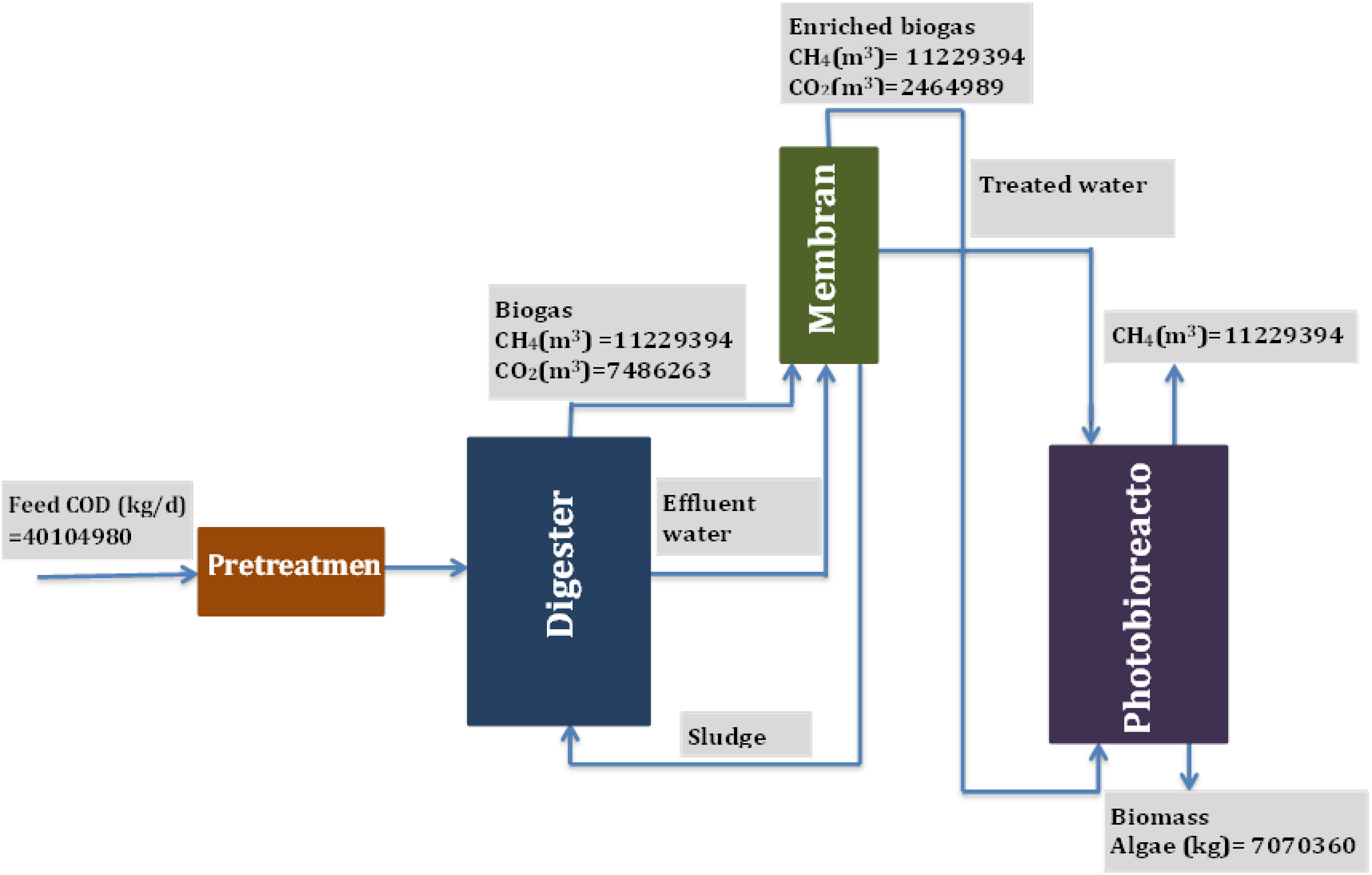


Fig. 13: Proposed flowsheet with the brief calculation for whole India (both rural and urban)

6 Conclusion

The idea of building an integrated system of an AnMBR in conjunction with a PBR will help addressing the important problems of wastewater treatment and energy generation. The conventional anaerobic digestion process typically produces 0.25 kg methane and 0.46 kg CO_2 per kg of COD in wastewater. The primary products of anaerobic digestion, CH_4, and CO_2 are concentrated in the membrane screening process, thus making CH_4 readily usable as a combustion fuel. CO_2 can be the feedstock for the PBR to produce micro-algae, leaving no CO_2 emissions. Microalgae can then be converted to biofuels or bioenergy. The process as a whole converts the organic matter in the wastewater into biofuel and biogas, with low NO_x or SO_x emissions from combustion, thus making the process environmentally sustainable. The algal biomass has a calorific value (HHV) of 28,000 $kJkg^{-1}$, which is higher than 27,000 $kJkg^{-1}$ of coal. If applied to all the sewage generated in India, the process could theoretically produce 1.12×10^7 m^3d^{-1} of biogas and 7.07×10^7 kgd^{-1} of biomass per year. This could replace approximately 3% of the total petroleum product consumption. The world energy generation potential from wastewater is also calculated based on the reported data, and this can significantly increase if data is available for all the country across the world. The results show that, the renewable energy from wastewater can greatly contribute to the world's energy demand and reduce the pollution load from non-renewable energy sources. The system aims to convert all the carbon in the wastewater into energy, thus complying with the aims of zero discharge of wastewater and CO_2 into the environment. The major limitations in its practical applicability lie in the high costs to set up PBRs and in maintaining the desired operating conditions. Further research on decreasing the costs of the microalgae cultivation process will add an invaluable contribution to this field. The process flowsheet considered in this study can be extended to the treatment of other types of waste, in addition to municipal sewage. For example, concentrated industrial wastewaters and organic solid waste could be a potential feedstock for the anaerobic/microalgae process. The use of these feedstocks could greatly enhance the bioenergy generation potential of the process.

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