Membrane Bioreactor Applications in Wastewater Treatment

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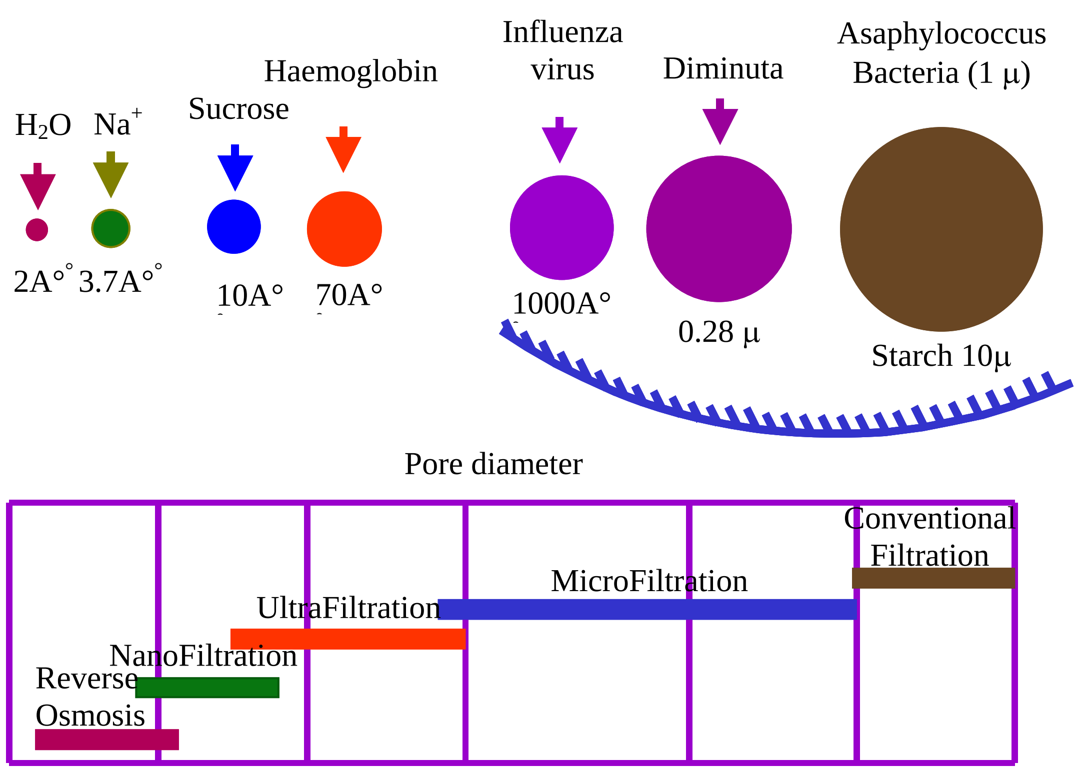
1. Introduction

A membrane is defined as a material that forms a thin wall capable of selectively resisting the transfer of different constituents of a fluid and thus effecting a separation, of the constituents. Thus, membranes should be produced with a material of reasonable mechanical strength that can maintain a high throughput of a desired permeate with a high degree of selectivity. The optimal physical structure of the membrane material is based on a thin layer of material with a narrow range of pore size and a high surface porosity. This concept is extended to include the separation of dissolved solutes in liquid streams and the separation of gas mixtures for membrane filtration.

Membranes can be classified by: 1) the driving force used for the separation of impurities, such as pressure, temperature, concentration gradient, partial pressure, electrical potential etc; 2) the structure and chemical composition, 3) the mechanism of separation and 4) the construction geometry of the membrane. Microfiltration (MF) and ultrafiltration (UF) are low pressure driven processes, where feed water is driven through a micro-porous synthetic membrane and divided into permeate, which passes through the membrane, and retenate or reject containing the non-permeating species. In wastewater treatment applications, these membranes process are more effective in removal of particles and microorganisms. Whereas, reverse osmosis (RO) is a high pressure driven process designed to remove salts and low molecular organic and inorganic pollutants. Nanofiltration (NF) operates at a pressure range in between RO & UF targeting removal of divalent ion impurities. Figure 1 illustrates the size range of various impurities and the application range of the membrane processes.

Figure 1. Membrane Filtration Spectrum.



2. Membrane Bioreactor Systems

Bioreactors are reactors that convert or produce materials using functions naturally endowed to living creatures. Reactors using immobilized enzymes, microorganisms, animal, or plant cells and those applying new methodologies such as genetic manipulation or cell fusion are typical bioreactors. Bioreactors differ from conventional reactors as living organisms present in the reactors operate under milder conditions of temperature and pressure. The ranges of operating conditions within bioreactors are usually determined by the biocatalyst (organism) and are usually small.

Membrane Bioreactor (MBR) systems essentially consists of combination of membrane and biological reactor systems. These systems are the emerging technologies, currently developed for a variety of advanced wastewater treatment processes. In general, MBR applications for wastewater treatment can be classified into four groups, namely:

1. Extractive Membrane Reactors
2. Bubble-less Aeration Membrane Bioreactors
3. Recycle Membrane Reactors
4. Membrane Separation Reactors

2.1 Extractive Membrane Bioreactors

Extractive membrane bioreactors (EMBR) enhance the performance capabilities of biological treatment of wastewater by exploiting the membrane’s ability to achieve a high degree of separation while allowing transport of components from one phase to another. This separation aids in maintaining optimal conditions within the bioreactor for the biological degradation of wastewater pollutants.

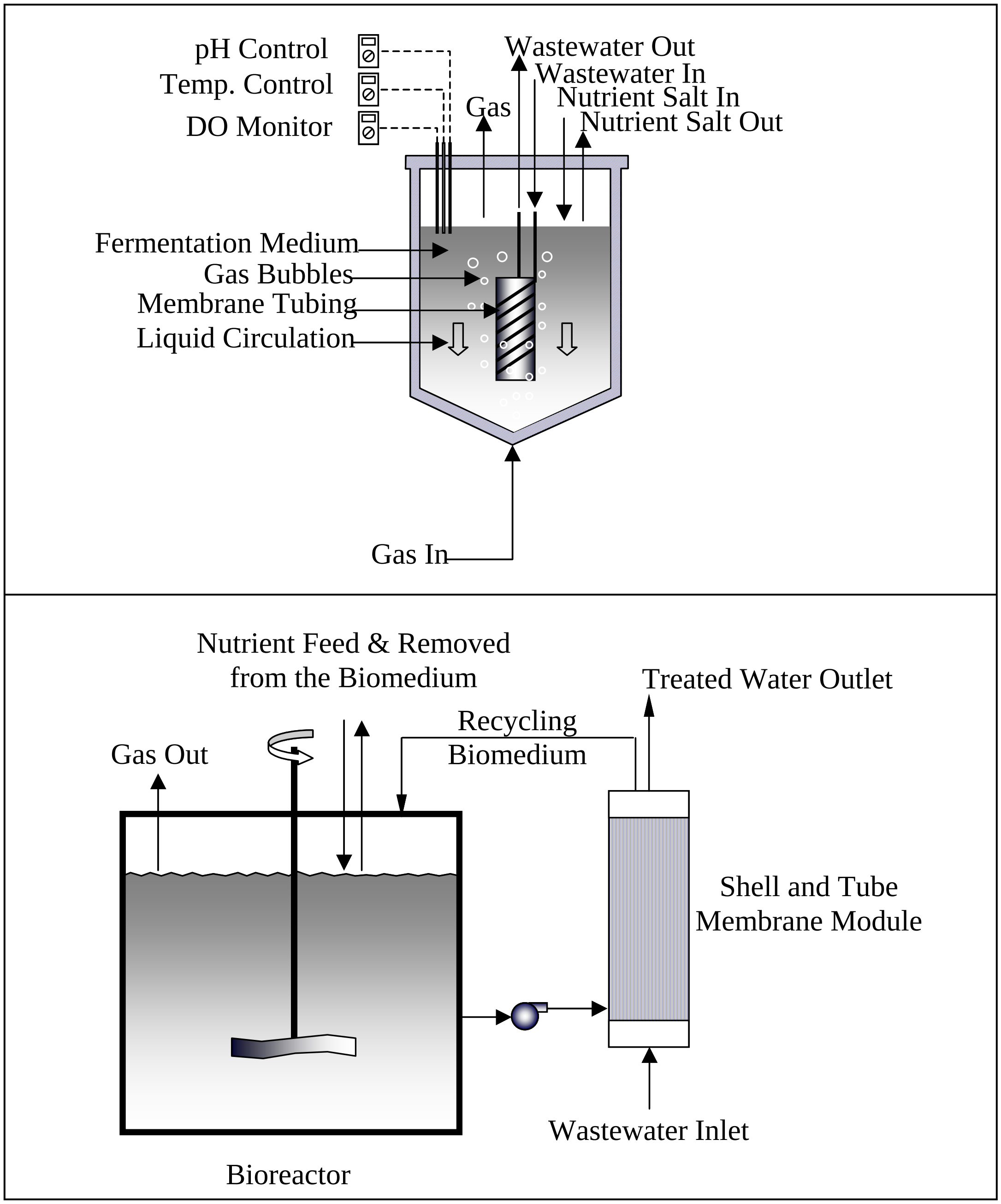
For example, degradable toxic organic pollutants from a wastewater could be transferred through a nonporous membrane, to a growth bio-medium for subsequent degradation. In this case the mass transfer of toxic compounds across the membrane takes place due to the presences of a concentration gradient, while the bio-medium functions as a sink.

The extractive membrane bioreactor can be operated in two modes as illustrated in Figure 2:

- Mode 1, where the membrane is immersed in the bio-medium tank. Here the toxic wastewater is circulated through the membranes, and due to the concentration gradient, the toxic compounds are selectively transported to the surrounding bio-medium. Specialised microbial cultures could be cultivated in the reactor, which could be easily optimised for the degradation of the pollutants.
- Mode 2, where the membrane forms an external circuit with the bio-medium tank. The wastewater containing toxic organic pollutants is circulated on the shell-side of the membrane modules. While the bio-medium liquid is pumped through the membrane lumens. Due to the presence of a concentration gradient, the toxic pollutant is transferred to the bio-medium. Within the bio-medium the toxic pollutant is continuously degraded by specialized microorganisms operated in optimum conditions in pH, temperatures, dissolved oxygen, nutrient concentration etc. Whereas the organic pollutant extracted wastewater is removed on the other end of the membrane shell.

In both systems, since the bioreactor is unaffected by the toxic wastewater within the membranes, the conditions within the bioreactor can be optimised to ensure efficient degradation of the toxic compounds. This technology has been successfully demonstrated for treatment of priority pollutants such as chloroethanes, chlorobenzenes, chloroanilines, toluene etc.

Figure 2. Two different operational modes of Extractive Membrane Bioreactors Systems.



2.2 Bubble-less Aeration Membrane Bioreactors

In a conventional aerobic wastewater treatment unit such as an activated sludge process, the process efficiency is controlled by the availability of air. Due to inefficient mode of air supply, 80-90% of the oxygen diffused as air in an activated sludge process is vented to the atmosphere.

Oxygenation with pure oxygen as opposed to air as an aeration medium would lead to an increase in the overall mass transfer and biodegradation rate. However, since conventional aeration devices have high power requirements due to the high rate of mixing, these devices cannot be used with biofilm processes. Biofilm processes are advantageous as they enable retention of high concentrations of active bacteria. The membrane aeration bioreactor (MABR) process use gas permeable membranes to directly supply high purity oxygen without bubble formation to a biofilm. Here the bubble free aeration is achieved by placing a synthetic polymer membrane between a gas phase and a liquid phase. This membrane is used to transfer large quantity of air/oxygen into the wastewater. As the gas is practically diffuse through the membrane, very high air transfer rate is attained. The membranes are generally configured in either a plate-and-frame or hollow fibre module. However, current research has focussed on the hollow fibre arrangement with gas on the lumen-side and wastewater on the shell-side. The hollow fibre modules are preferred since the membrane provides a high surface area for oxygen transfer while occupying a small volume within the reactor. Here the membrane also acts as a support medium for the biofilm formation, which reduces the potential for bubble formation and air transfer rate.

2.3 Recycle Membrane Bioreactors

The membrane recycle bioreactor consists of a reaction vessel operated as a stirred tank reactor and an externally attached membrane module. The substrate (feed wastewater) and biocatalyst are added to the reaction vessel in pre-determined concentrations. Thereafter the mixture is continuously pumped through the external membrane circuit. The smaller molecular compounds, the end products of the biodegradation reaction, are permeated through the membrane. While the large molecular size biocatalyst are rejected and recycled back into the reaction tank.

Traditionally batch processes are used in biotechnology applications. Due to this, the efficiency is lower than continuous processes with a batch-to-batch variation in product. In these processes, the microbial population would have to be separated out at the end of the run since the microbial species are attached to the membrane via adsorption, entrapment, micro encapsulation etc.

However, membrane recycle reactors are continuous processes that are being adopted for biotechnology applications. The advantages of adopting a continuous process are lower operating cost since the enzymes are more effectively utilized and the product is more uniform and consistent. Inhibitory end products are continuously removed from the system thus there is a reduced likelihood of biocatalyst poisoning. The disadvantages of membrane recycle process are the loss of activity of between 10 to 90 % due to enzyme substrate orientation and diffusional resistances. However, research efforts of late have been directed toward the effective adsorption of biocatalysts onto the membrane surface thereby maximizing the degradation potential of the recycle membrane reactor.

In industrial applications, the recycle membrane bioreactors are utilized essentially in two basic configurations, namely: tubular and beaker type. In the beaker type system, the feed wastewater together with the biocatalyst is placed in a beaker, which serves as the reaction vessel. U shaped bundle of fibres immersed into the beaker and product is continuously filtered through the membranes. Tubular configurations are preferred in large-scale industrial applications where the biocatalysts can be loaded or trapped either in the shell-side (annular space between the membrane fibres and the housing) or the tube side of a tubular membrane module. If the biocatalyst is trapped inside the membrane tube, the feed substrate is pumped through the shell side. The pumping rate has to be controlled to maintain a residence time within the membrane tubes for total biodegradation. This type of bioreactor has been tested on industrial scale for bioremediation activities, for the removal of aromatic pollutants and pesticides.

2.4 Membrane Separation Bioreactors

The activated sludge process is the most widely used aerobic wastewater treatment system to treat both municipal and industrial wastewater. Its operational reliability is one of the major reasons for the success for this technology. However, the quality of the final effluent from this treatment system is highly dependent on the hydrodynamic conditions in the sedimentation tank and the settling characteristics of the sludge. Consequently, large volume sedimentation tanks offering several hours of residence time are required to obtain adequate solid/liquid separation. At the same time, close control of the biological treatment unit is necessary to avoid conditions, which could lead to poor settleability and/or bulking of sludge.

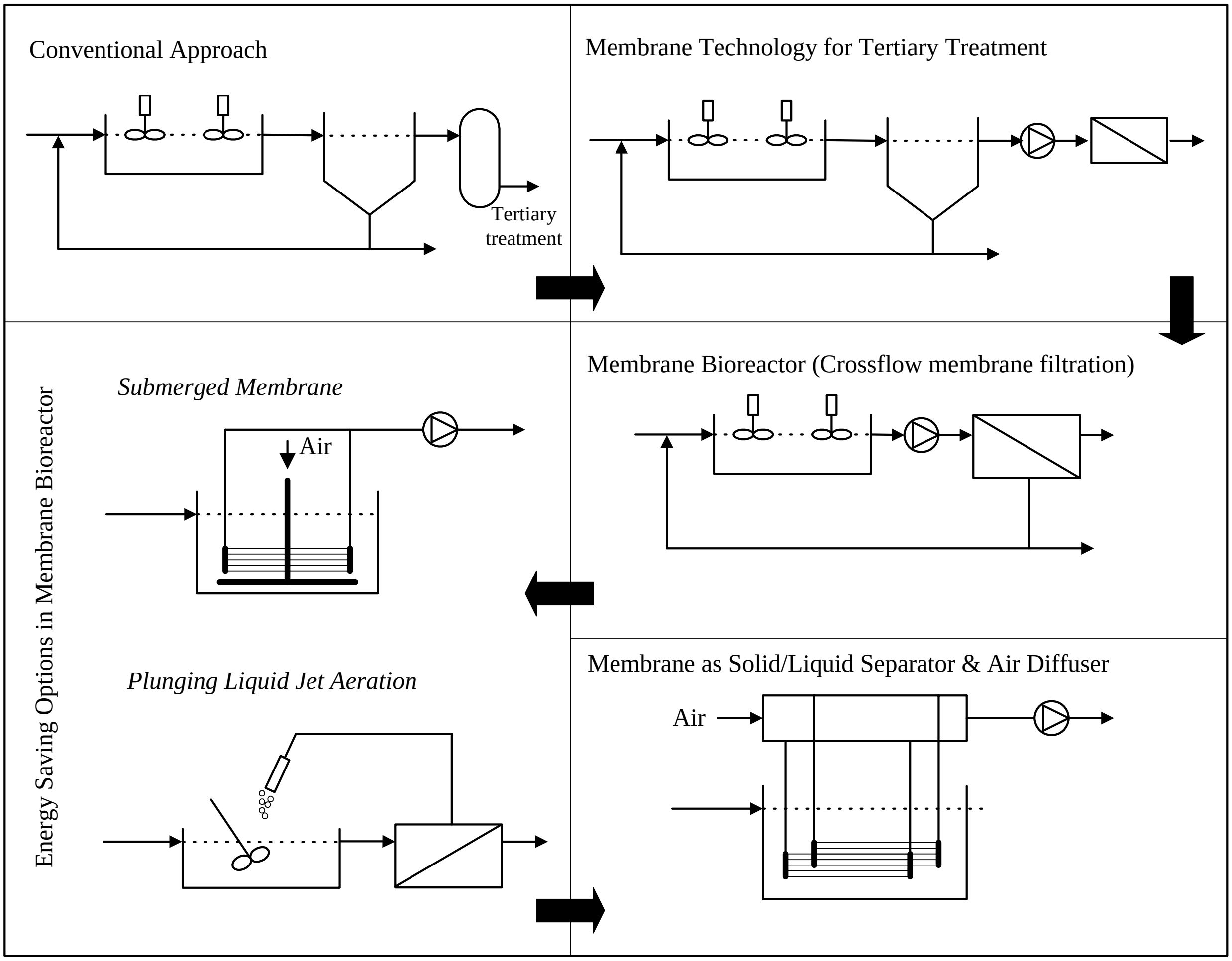
Application of membrane separation (micro or ultra filtration) techniques for biosolid separation in a conventional activated sludge process can overcome the disadvantages of the sedimentation and biological treatment steps. The membrane offers a complete barrier to suspended solids and yields higher quality effluent. Although the concept of an activated sludge process coupled with ultrafiltration was commercialised in the late 1960’s by Dorr-Oliver, the application has only recently started to attract serious attention with considerable development and application of membrane processes in combination with biological treatment over the last ten years.

This emerging technology of biomass separation bioreactor is a combination of suspended growth reactor for biodegradation of wastes and membrane filtration. In this system, the solid-liquid membrane separation bioreactor employs filtration modules as effective barriers. The membrane unit can be configured either external to or immersed in the bioreactor.

Figure 3 schematically represents the various stages of development of this MBR system, for biological wastewater treatment. The conventional approach to attain a reusable quality water from an activated sludge process is by applying tertiary treatment techniques such as multimedia filtration, carbon adsorption, etc., on biologically treated secondary effluents. As a first step, these tertiary treatment methods were replaced with membrane (ultra/micro) filtration, which ensures almost bacterial and viral free effluent in addition to colloids and solid removal without modifying existing treatment facilities. This type of coupling of membrane technology provides good quality effluent.

Later, in view of utilizing membrane technology more effectively, the secondary sedimentation tanks were replaced with cross-flow membrane filtration. Here membranes are placed in an external circuit, where the biomass is circulated at a higher velocity on the membrane surface. The higher energy cost to maintain the cross flow velocity led to the development of submerging externally skinned membranes in the reactor itself and withdrawing the treated water through the membranes. As a further attempt at energy saving in membrane coupled bioreactors, the possibility of using jet aeration in the bioreactor was introduced. The main feature of this bioreactor is that the membrane module is incorporated into the liquid circulation line for the formation of the liquid jet, thereby accomplishing both operations of aeration and membrane separation using only one pump. The jet aeration works on the principle that, a liquid jet after passing through a gas layer plunges into a liquid bath entraining considerable amounts of air. Recently, the invention of the air back-washing technique for membrane de-clogging led to the novel approach of using the membrane itself as a clarifier as well as an air diffuser.

Fig. 3. Developments in membrane separation bioreactors



The major advantages of the membrane separation bioreactors are:

- Since suspended solid are totally eliminated through membrane separation, the settleability of the sludge, which is a problem in conventional activated sludge, has absolutely no effect on the quality of the treated effluent. Consequently, the system is easy to operate and maintain.

- Sludge retention time (SRT) is independent of hydraulic retention time (HRT). Therefore a very long SRT can be maintained resulting in complete retention of slowly growing microorganisms, such as nitrifying bacteria, in the system.
- The overall activity level can be raised since it is possible to maintain high concentrations in bioreactors while keeping the microorganisms dispersed as long as desired and as a result, reactor volume will be reduced. In addition, the system requires neither sedimentation nor any post-treatment equipment to achieve reusable quality water, so the space saving is enormous.
- Treatment efficiency is also improved by preventing leakage of undecomposed polymer substances. If these polymer substances are biodegradable, there will be no endless accumulation of substances within the treatment process. On the other hand, dissolved organic substance with low molecular weights which cannot be eliminated by membrane separation alone can be taken up, broken down and gasified by microorganisms or converted into polymers as constituents of bacterial cells, thereby raising the quality of treated water.
- Removal of bacteria and viruses can be expected, so the disinfection process is ecologically sound.
- Compared to conventional activated sludge processes, maintaining low F/M (food/microorganisms) ratio will produce less excess sludge to be handled and treated.
- The fluctuations on volumetric loading have no effect on the system hence a high sludge capacity can be maintained.
- Since all the process equipments can be tightly closed no odour dispersion can occur.

Table 1, presents the overall performance of immersed type MBR systems in terms of influent and effluent concentrations. Considering the guidelines and criteria for reclaimed water use for various purpose in Japan, the effluent of MBR comply with every aspect of the reported values. In this pilot scale unit, it was also noted that the reactor performance was not affected at various operating conditions. This indicates that the improvement in membrane flux can result in an undisturbed water quality even at a hydraulic retention time of 3 hours, thus reducing the size of the treatment unit. The effectiveness of the process was proven since both effluent turbidity and pathogen removal was detected below drinking water standards. If necessary, a small dosage of chlorine could be added to maintain a residual chlorine concentration in the distribution system of the main water supply.

Table 1 Comparison of reclaimed water quality of the MBR with reuses guidelines

Parameters	Concentration		Criteria/Guidelines [a]		
	Influent	Effluent	Toilet Flush Water	Landscape Irrigation	Environmental Water
Total coliform/(Count/mL)	> 10^7	ND	≤ 10	ND	ND
Fecal coliform/(Count/mL)	> 10^5	ND	-	-	-
Chlorine residual combined/(mg/L)	-	-	TA	≤ 0.4	-
Appearance	NP	NU	NU	NU	NU
Turbidity /(NTU)	> 1000	< 0.3	-	-	≤ 10
Biological Oxygen Demand (BOD)/(mg/L)	295-375	< 4	-	-	≤ 10
Odor	NP	NU	NU	NU	NU
pH	7.6-8.5	7.3-8.4	5.8-8.6	5.8-8.6	5.8-8.6
Chemical Oxygen Demand (COD)/(mg/L)	530-625	< 25	-	-	-
Total Kjedahl Nitrogen (TKN)/(mg/L)	26-165	< 3	-	-	-
Total Nitrogen (TN)/(mg/L)	26-165	< 6	-	-	-
Total Phosphate (TP)/(mg/L)	2.2-9.0	0.2-4	-	-	-
Color/(Hazen color unit)	> 5000	<30	-	-	-

NP - Not pleasant ***NU - Not Unpleasant*** ***ND - Not Detected*** ***TA - Trace Amount***

[a] adopted from Japan Sewage Work Association, 1993.

3. Conclusion

The review of the membrane bioreactors for the application of wastewater treatment has proven that this emerging technology has developed a niche in the wastewater treatment sector. While, research efforts of late have been directed towards application of membrane separation bioreactors to various wastewaters, the next step in its development would be to develop a membrane bioreactor process that is both robust and efficient for various wastewater applications.

4. Suggested Reading

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