A Review on Internal Design Modifications in Activated Sludge Process: Status, Impact and Recommendations

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With water crisis getting severe each year all over the world, development in waste water recycling techniques has gained momentum to meet strict environmental norms and to take advantage of the recyclability of water. Biological treatment methods predominate over other recycling methods as they are less expensive and do not generate secondary pollutants. Challenges faced in using these methods such as low oxygen solubility in water or insufficiency in maintaining booming environment for microorganisms and sludge water separation issues restrain their full fledge utilization, thus hampering expenditure control and the final effluent quality which can be achieved otherwise. The developments made so far to overcome drawbacks of conventional activated sludge process revolves around modifications in suspended, attached growth process and improvements via integration of both systems. Further process refinement includes modifications in aeration and sludge separation systems but lacks the cost analysis for scale up. This paper critically reviews various internal design modifications made in aerobic treatment of wastewater by several researchers on lab and pilot scale to overcome the problem faced while operation. This paper also gives guidelines to meet the design objectives for a commercial scale wastewater treatment plant from process efficiency and economy aspects.

Introduction

India, as per the UN data for the midyear 2019, has a population of approximately 1.366 billion which accounts for around 17% of the world's total population. With availability of only 4% of world's total freshwater resources [**1**], it's even distribution and management is quite a challenge. One of the ways to curb the water scarcity issue is to explore the wastewater recycling and reuse techniques. Most of the Indian states, with conventional treatment facilities such as activated sludge process, tricking bed reactor etc., present with municipal wastewater systems are capable of treating only up to 40% of the total wastewater generated, owing to low installed capacity. In Indian scenario, the bioreactor for wastewater is fabricated by keeping a mechanistic point of view with a focus on design for quantity of air flow, without considering its even distribution which increases the cost of aeration and process but does not increases the efficiency. Low dissolved oxygen (DO) levels, shock loading, poor settle-ability of the sludge and separation of treated water from sludge are the major problems associated with high chemical oxygen demand (COD) municipal and industrial wastewater. For the process to give desired results, several modifications have been made in conventional aerobic methods:

(a) To have a proper distribution of microorganism and carbon source offering a complete mixed state modifications in attached growth, suspended growth and integration of both,
(b) To maintain the DO levels in water– modifications in aeration systems,
(c) The way in which all the three come in contact with each other thus defining the process configuration of the system,
(d) And developments in the effluent water and sludge separation systems.

Attached growth systems, better known for their less space requirements, on the basis of the way media is employed can be classified into non-submerged (trickling beds), submerged (bio filters), and combined arrangements (rotating biological contactors (RBC)) etc. Fixed media suffer from clogging issues, thus a modification in conventional biofilm processes such as moving bed biofilm reactors (MBBR), invented in 1980s, so as to have a good contact between substrate and microorganisms has resulted into improved treatment capacity and increased sludge settle ability [**2**]. Inability to handle high organic loading rates, thus requiring greater retention time and oxygen diffusion limiting conditions in attached growth system is often compensated by using suspended growth pattern of microorganisms. Use of biofilm growth media, in a suspended system promotes growth of biofilm over it and also keeps them immobilised. Use of an inert media such as silica sand with a few millimetre diameters in a fluidised bed biofilm reactor gives more specific surface area as compared to trickling filters and RBC and gives more biomass concentration and process loading rates than conventional activated sludge process [**3**].

Oxygen helps in bacterial metabolic activities involving redox reactions, through which the energy is stored by acting as a terminal electron acceptor. This energy, stored in the form of adenosine triphosphate (ATP) is used by microorganism to survive and multiply. To maintain the essential oxygen concentration in wastewater several types of aeration systems have been investigated and applied. A balance between aeration cost and desired effluent quality marks the efficiency of the process. Surface aeration technique involves expelling water in to the air which when falling back under the effect of gravity traps the oxygen molecule. Centrifugal surface aerators, paddle wheel and horizontal rotors give aeration efficiency in the range of 1.3 to 2.3 Kg O_2/ KWh [**4**].Whereas, subsurface aeration systems, installed at the bottom of the tank are common for tanks with great depths. Size of the bubble generated gives the difference in the area for the mass transfer of oxygen from liquid phase to the cell wall of the microorganisms. Separation of sludge and treated effluent water serves as an example of two phase separation system. Filtration using membranes have emerged as a solution but need of trained labours and maintenance requirement to manage its shelf life leads to upsurge in cost. The aim of this paper is to review various internal design modifications made in aerobic treatment of wastewater to overcome the problems faced during application of these modifications from lab scale experiments to pilot plant. The author also presents a guideline for the configuration of reactor, the media which should be used in the reactor and best possible way to enhance the air distribution to promote the COD removal rate. However, for choosing any technology, care should be taken with respect to the design capacity or volume of the technology being used as efficiency may differ depending on the size.

Status on modifications and their effects

Distribution of substrate and biomass

Suspended growth system

With increasing water pollution problems in industrializing England, Dr. Fowler initiated activated sludge experiments in 1912 later modified by Arden and Lockett in the year 1913-1914 leading to development of a revolutionary treatment method all over the world. Since then, several modifications in the process have been made but the original method still finds significance in various wastewater treatment stations due to its low cost as only suspended microorganisms are required as catalyst for treating wastewater under the presence of sufficient dissolved oxygen. However wastewater with substances which have inhibitory activity to microorganism's enzymatic activities makes the technique insufficient.

Li and his co-workers [**5**] in an experiment treated wastewater containing antibiotics with concentration up to 100μg/l. To remove eleven target antibiotics with six different classes, biodegradation and adsorption in activated sludge were chosen as treatment techniques. Instability of β-lactam ring led to its breakdown by enzymatic action of microorganisms. However, not all classes of β-lactams could be removed due to different structures and thus needs adsorption as removal mechanism. Sulfonamides could not be removed to significant levels by adsorption due to its solubility, only upto 53.4% as maximum limit by biodegradation. Fluoroquinolones were observed to be removed by adsorption up to 90% within 15 minutes of operation in freshwater sewage system and no biodegradation was observed to take place, whereas in saline sewage water, both biodegradation and adsorption played significant role but needed high hydraulic retention time. Tetracyclines removal was 90% by adsorption only. Macrolides and trimethoprin showed very low removal rates. Therefore, to treat a wastewater containing even low concentration of antibiotics, suspended growth process can't be considered a good option. To overcome various disadvantages associated with suspended growth system such as high volume of reactor required and operational costs involved Moghanloo *et al.* [**6**], used biofilm airlift suspension reactor as a modified version offering high surface area to oxidise hydrogen sulphide using basalt as media. Air was sparged at a rate of 1.7 l/min from bottom, creating pressure difference in riser and down comer of reactor and thus internally circulating the carrier with diameter and settling velocity of 0.3mm and 50m/h respectively. Effect of shock loading was tested by varying concentration of hydrogen sulphide from 0 to 12.2 mol/s^{2}m^{3}h mixed with 0.5g/l of glucose and at all loading rates 100% removal rate was observed. The result indicated as most of the biomass was attached to media, drawbacks of a suspended growth system such as wash away of biomass could be prevented. Use of such a reactor can efficiently help in post treatment of gases generated from anaerobic treatment of wastewater.

A little modification such as an integration of a rotating biological reactor (RBR) with conventional activated sludge process is found to be capable of decreasing the operation cost as process can be carried out at greater organic loading rate without hampering the effluent quality. Hassard and his co-workers [**7**] in a modified version of activated sludge process placed RBR downstream of return activated sludge and influent wastewater.

The biological reactor containing porous polyvinyl chloride plate with 95% porosity led to 1.3 times greater loading rates in biological reactor than conventional activated sludge tank and greater COD removal rate. Total COD removal rates were found to be directly related to the extracellular enzymatic activity (EEA), responsible for hydrolysing polymers into smaller parts such that they can enter the cell wall. EEA, in turn is related to biomass growth rate. EEA was greater for rotating biological reactor as the microbial density in the system was high as compared to conventional process and corresponding nutrition requirements for growth were also high. Also, with presence of anoxic zones in the modified version ammonium nitrogen removal was observed to be 42% greater than conventional process.

With nano-materials finding prominence in commercial products, water bodies have not remained out of grasp of such entities. Park *et al.* [**8**] worked on removal of gold, titanium dioxide and silicon oxide nanoparticles suspended in artificial sewage water with COD of about 200 mg/l, using activated sludge process and found that extracellular polymeric substances present in sludge tended to retain the nanoparticles and were later removed via sedimentation whereas in absence of EEA, adsorption on microorganism's surface was considered to be the removal mechanism. And thus, activated sludge process can't be considered as a choice for removal of inorganic compounds or metals, as they do not act as a food source to microorganism. Clearly, the data obtained from the work of above researchers prove that use of a media, promoting the favourable growth condition to biomass should be given a priority than using a suspended growth system alone.

Attached growth system

Non-submerged fixed-bed reactors

Presence of active biofilms on media such as sand, pebbles, activated charcoal, foams, metals or any medium with physical and chemical characteristics promoting the growth of biomass act as packing for a non-submerged fixed bed bioreactor and the efficiency of the process is affected by the media used. With continuous down flow movement of influent wastewater, these biofilm act as catalyst for removing COD, fixing high nitrogen, phosphorous and other trace metal contents. Removal of refractory chemicals such as phenol on pilot scale using a packed bed bioreactor with gravel packing was reported by Tziotzios *et al.* [**9**], using a combination of *Alcaligenes* and *Acinetobacter* bacteria with phenol concentration of 1.8 g/l in both, batch as well as continuous operating mode. Batch mode, apparently was found to give better COD removal rate of 92.432% than continuous operating mode. The hydraulic retention time required to achieve this efficiency was reported to be 5.5 hrs. Dey *et al.* [**10**], in a similar finding used glass beads as packing material with organic loading rate (OLR) ranging from 0.72-4.32 g/l with and without phenol. The HLR was varied between 4.27 m^3/m^2day and 9.96 m^3/m^2day. For OLR exceeding 4.32 m^3/m^2day, the COD removal efficiency dropped from 100% to 54% without influence of phenol and 100% to 40% in its presence in a 24 hour operation. Microorganisms used are often food selective in nature and need suitable temperature and pH conditions to result the degradation. Thus selection of microorganisms and their combination thereof is also a governing factor in organic pollutant removal efficiency of the process. The combination of appropriate inoculum and low cost gravel packing can serve as a good selection for treating large volume of wastewater as less retention time requirement will save the cost.

Dyes are often difficult to be degraded due to their complex structure and this difficulty increases as effluents from industries are generally an amalgamation of such various compounds. Aerobic and anaerobic processes in combination have been in practice along with various physicochemical processes like adsorption, coagulation, membrane filtration etc. [**11**]. Various fungal strains possess exceptional capabilities to degrade azo and anthraquinonic dyes as described by Singh [**12**]. In an another experiment, Kornaros *et al.* [**13**] for determination of effectiveness of trickling bed filter treating wastewater from an organic dye and varnishes manufacturing plant comprising of aniline oil, methyl-oxitol, isopropanol and methanol, used silica gravel packing. For influent COD of 9.7 g/l, 60-70% efficiency was reported for hydraulic loading rate (HLR) of 1.1m^3/m^2day. The efficiency was found to increase up to 80-85% with decreased HLR of 0.6m^3/m^2day. But since the time required to reach the obtained results was essentially greater than 24 hours, the entire process would involve higher operational cost. Novotny *et al.* [**14**] used a combination of fungal and bacterial treatment for treating textile wastewater in a two-step process. Fungus does decolourization and detoxification by lignin degradation and avoids formation of toxic aromatic amines, whereas bacteria in second step degrade the secondary products. For designing such a system, polyurethane foam media was used. In a batch experiment with 0.150 g/l of influent COD concentration, 95-98% removal rate was observed requiring a retention time of 7 days.

Rock lava with 60% porosity was used to treat dairy wastewater on pilot scale at low temperatures, with natural aeration and variable hydraulic retention time (HRT) by Mehrdadi *et al.* [**15**]. Influent COD of wastewater was measured to be in the range of 2.580 g/l to 2.680g/l. With HRT of 7 hours, and hydraulic loading rate increasing from 0.33 to 9.95 m^3/m^2day, COD removal percentage of 96.98 to 96.88% was obtained. Also total Kjeldahl nitrogen (TKN) removal obtained was reported to be greater than 75% due to well porous nature of lava rocks, providing both aerobic and anoxic conditions to the reactor. Rock lava obtained from nearby volcanic craters served as an inexpensive media, but their chemical inertness and porosity for extensive use should be considered. Tabla *et al.* [**16**], in a comparison between activated carbon and polyurethane foam as packing material in trickling filter for removal of organic pollutants, found foam to give better organic material removal efficiency of 63% than activated carbon which gave efficiency of 51%. Though activated carbon provided greater surface area but better porosity of foam played a significant role in the growth of microorganisms.

The feeding strategy used in non-submerged bed bioreactors is percolation, which often imparts limitations on system such as low organic loading rates or less hydraulic retention time and rate limiting diffusion related problems corresponding to biofilm layers, decreasing the treatment capacity of a bioreactor. For such systems rock lava media, naturally available to regions with volcanic activity, proves to give best results with maximum COD removal efficiency and minimum HRT, thereby allowing the process to be operated at greater capacity per day and reduces cost. In absence of such a media, gravel can serve the purpose well giving flexibility over influent COD.

Submerged fixed-bed reactors

Such a configuration is characterised by a media bed with biofilms covered over it, submerged into a mixed liquor of carbon source, giving more flexibility in terms of HLR and therefore finds extensive use on pilot plant scale operation.

Though the study using coarse gravel to peaty soil as a media was carried out by Frankland *et al.* [**17**] in the year 1868, it was till 1920's that there existed a confusion about mechanism of activated sludge process, if it was physicochemical or biological in nature. Later that year, Buswell and Long verified it to be reliant on metabolism of aerobic microorganisms [**18**]. Relation between loading rates and flow distribution over the packing varied with the media used are still the areas of study for designing submerged fixed bed reactors.

Enhancement in coverage area owing to the media used has shown to bring better nitrogen removal rates. Use of rope like Ringlace® media as seen in **Fig. 1**, with step aeration by Randall *et al.* [**19**], provided coverage length as high as 30,000 m within a volume of 475m^3 of bioreactor, displacing less than 1% of the total integrated fixed-film activated sludge (IFAS) section volume, resulting into increased nitrification rate per unit volume to 225% than without the use of any media. The challenge was to upgrade the removal rate of nitrogen within short HRT but without increasing the area, which would have otherwise caused an increase in expenditure. With such a modification, constructional cost was brought down up to 61.66% and HRT required was only 3.33 to 6 hours even though the plant was operated at high influent of 19,000m^3/day to 34,000m^3/day, thereby also decreasing the operational cost. Optimum site to place ring-lace rope media was found to be at the middle of the bioreactor which formed 50% of the aerobic zone. For obtaining better nitrification rates, Ringlace® media proves to provide robust environment. Hamoda and his co-workers [**20**] used a combination of suspended and attached growth systems by applying a series of ceramic plates as media with diffused aeration with a varied influent HLR between0.08 to0.32 m^3/m^{2}day.

Attached growth media was found to make system robust against shock loading by organic substrate. Biological oxygen demand (BOD) removal rate obtained from effluent was found to be above 94% at all flow rates, whereas COD removal rates ranged from 65.7% to 76% with very minor effect of HRT. Short HRT increased the activity of suspended biomass and an increase in volatile suspended fraction, whereas long HRT tended to promote attached biomass and an increase in nitrification rates and low sludge production. But, the system is found to be inefficient against increase in loading rates.

Fig. 1. A Ringlace® installation at Annapolis water reclamation facility [**21**].

A comparison between various media in submerged packed bed was drawn by Nacheva and his co-workers [**22**] to use them as a packing for treatment of domestic wastewater with variable organic loading ranging from 0.8 to 6 g COD/ m^2 day. HRT was varied from 0.8 to 6 hours. **Table 1** gives comparison of characteristic features of packing, COD removal rates and the amount of biofilm developed.

Table 1. COD removal efficiency of various packing materials [**22**]

Packing material	Source	Packing characteristic	COD % removal
Ceramic spheres	Natural	High particle density(t/m^3)	78-80%
Crushed tezontle	Natural (Volcanic stones)	High particle density(t/m^3)	90%
High density polyethylene (HDPE)	Synthetic	High bed pore volume (ml/g)	78-80%
Low density polyethylene (LDPE)	Synthetic	High bed pore volume (ml/g)	92-93%
Polypropylene	Synthetic	High bed pore volume(ml/g)	78-80%
Polyurethane cubes(PU)	Synthetic	Maximum bed media void age%	90%
Polyethylene tape	Synthetic	Maximum bed media void age%, highest biomass concentration.	92-93%

The COD removal rate obtained was same up to 2 g COD /m^2 day organic loading after which the decrease in the performance for all the packing materials was observed at all OLR. Polyethylene tape or Sessil® gave maximum COD, nitrogen and turbidity removal. LDPE and PU foam can serve as an alternative when working in the OLR range of 0.8 to 6 g COD/m2 day.

The COD removal rate of sessil® was further investigated with an increased OLR of 4-17 g COD/m^2 day and decreasing the HRT to 0.2-1.1 hours by Nacheva *et al.* [**23**], as seen in **Fig. 2**, and obtained the efficiency between 85% to 78%.

Fig.2. Polyethylene tape used by Nacheva *et al.* [**23**] as packing material.

Erosion of media in a packed bed reactor was addressed by Morgan *et al.* [**24**], when he quantified it in terms of reduction in packing height for about 1% per month, resulting into an increase in suspended solids and colour change in effluent. Though the tracer studies carried out using bromo-cresol green indicated absence of dead zone, volcanic scoria or tezontle does not proves to be a cost effective media when compared to Sessil or PU foam.

Riahi *et al.* [**25**] used a rectangular mesh of surface fibres obtained from tree trunk of date palm as a media for filtration in domestic wastewater treatment to remove turbidity, COD, phosphorus and helminth eggs, which is a parasite. Media with lowest diameter of 0.2 to 1.2 mm gave maximum COD removal of 80.6% at a filter depth of 0.36 m and influent flow rate of 0.288 l/ hr. Further investigation on behaviour of date palm fibre at higher HLR is required for its commercial scale application and thus its efficiency for such systems remains ambiguous.

When dealing with high organic load, low penetration of oxygen and substrate through water to reach aerobic bacteria creates problems thus media with high porosity and rough surface can attribute to increased biomass growth and good penetration of oxygen as well as carbon and nutrients. Biological Filtration and Oxygenated Reactor (BIOFOR), an attached growth technology patented by Degremont was studied by Sharma *et al.* [**26**]. BIOLITE, the media, as seen in **Fig. 3**, provided greater surface area for biomass growth as well as filtration, which helped in treating influent with high organic loads up to maximum installation capacity of 110 MGD. Increase in oxygen transfer rate was observed due to upflow aeration and flow of influent wastewater from the bottom instead of sprinkling from top as is observed more commonly. Average COD removal efficiency reported was 93.4%, but the system was not found much efficient in removing the faecal coliform in effluent.

A general constraint associated with the use of packed bed is change in its bed porosity due to biomass attachment.With reduction in porosity, the bioreactor will result into water logging at higher flow rate of influent water and at low flow rate will result into channeling and formation of dead zones.

Fig. 3. BIOLITE media used by Sharma *et al.* [**26**]

Combined (Attached + suspended) bioreactor

Moving beds provide liberty to bring the carbon source and microorganisms together as the moving bed with attached biomass over it circulates throughout the bioreactor due to aeration. The media is essentially porous and light in density, nearly equal to density of water. Moving bed tends to resolve the issue of clogging as well as inefficiency in process due to dead zones. Such a configuration also helps in reduction of reactor size requirements and thus the cost associated with land. Separation of biomass from treated water is quite easy with such modification. Less washing out of biofilms also helps in early recovery from shock loads.

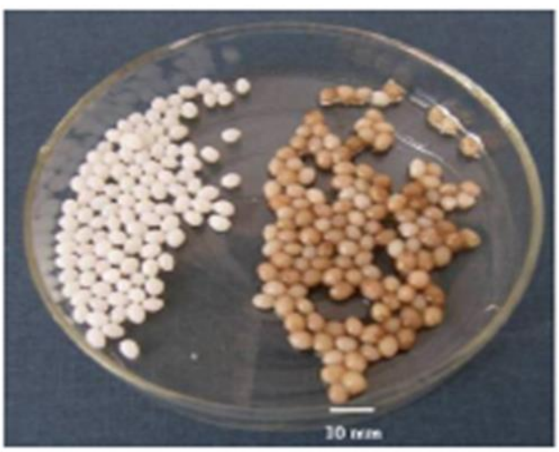
In a comparative study Loukidou *et al.* [**27**] compared COD removal efficiency of polyurethane cubes (PU) and granular activated carbon (GAC) for treatment of leachate, which is water containing dissolved solids into it, generated from municipal solid waste. Leachates have been known for their high COD values of about 10,000 to 60,000 mg/l, mostly have contamination by refractory organic compounds and thus are difficult to be treated by biological means. Maintaining the proper pH for microorganisms to grow is another challenge when treating such water. Operation was carried out in sequencing batch reactor with 5g/l of influent COD for 20 days and with BOD/COD ratio only 0.2. With PU, COD removal efficiency was 65% and with GAC 81% was obtained, whereas, BOD removal rate of 90% was observed for both the media. Activated carbon known for its good adsorption characteristic was found to give better results due to its physico-chemical effects as well as high active surface area for growth of microorganisms but involved cost. On the other hand, PU, which was waste packaging material, involved no purchase cost. Another disadvantage associated with GAC was the losses owing to the attrition between the particles and resulting into increased turbidity in the final effluent. Therefore, PU emerged as a better selection.

The effect of filling ratio of media in a suspended plus attached system revealed that better COD removal is obtained when system contain both suspended as well as attached biomass owing to less media filling ratio, whereas better ammonium removal is obtained when large amount of media is used, allowing slow growing nitrifying bacteria to work efficiently. In a study by Trapani *et al.* [**28**] 35% and 66% filling ratio was used to treat OLR of

1.2 Kg COD/m^3 day. At this rate, 90% total COD removal efficiency was obtained with 35% filling ratio and 89% with 66% filling ratio. During the biofilm detachment period, due to improper penetration of nutrients to the lowest layer of biofilm, the efficiency of both the filling ratio was same. It is obvious that cost for 35% media filling ratio will be less and better removal rates are obtained, therefore it should be preferred for COD removal.

Chu *et al.* [**29**] used biodegradable polycaprolactone (PCL), as seen in **Fig. 4**, as a media as well as carbon source for nitrogen removal from wastewater with an idea that as PCL is insoluble in water it can act as media and with biodegradability it can be used for treating wastewater with low COD /N ratio. With the filling ratio of 11.3%, PCL with diameter of 3.5mm and specific surface area of about 0.376 m^2/g was used in a reactor of 6 litre volume.

(a)



(b)

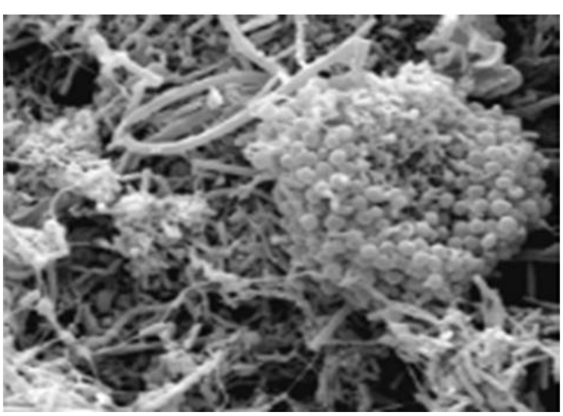


Fig. 4. (a) Image of fresh and used PCL by Chu *et al.* **[29]** (b) Scanning electron microscope image of biofilm on PCL media used by Chu *et al.* **[29].**

A comparison for total nitrogen removal efficiency between PCL media and glucose acting as a carbon source up to 100 mg/l revealed PCL was 74.6% efficient, whereas glucose was 34.3%, indicating simultaneous nitrification and denitrification process requires a slow degrading carbon source. Consumption of polymer for per gram of total nitrogen (TN) removal was 1.27g PCL per gram of nitrogen. Results reported indicate that porous media provide both aerobic and anoxic environment required for conversion of ammonium-nitrogen to nitrate first and then to nitrogen gas or nitrogen oxides. Cationic charges present on media carrier due to its chemical structure help to bond with the negative charged bacterial cells leading to faster attachment of biofilms. Chu *et al.* [**30**] modified polyurethane (PU) form bearing a net positive charge to treat wastewater with low organic loading rates. A contact angle of 66^o between the surface of media and water indicated its hydrophilic nature leading to media immersion in water. 80-88% of COD removal was obtained which is common with the use of PU. Not much difference between the porosity of polyurethane form and the modified one was observed. Such a modification can help in faster growth of biofilm over media which generally take 5-7 days of continuous operation.

Merging the strength of non-porous carriers and high specific surface area of porous media served as an advantage when Chen *et al.* [**31**] coated a hard polyethylene ring with polyurethane sponge on the inner and outer surface with varied sponge thickness and number of pores per inch of sponge This suspended carrier when compared with a commercially available biofilm carrier BioM® to treat synthetic wastewater with COD of 250 mg/l gave better COD removal efficiency on all 7 days of operation. Media with 4 mm thickness and 45 pores per inch gave best results as rough surface favoured biofilm attachment and can be used in a system with increased organic loading rates thus decreasing equipment volume. Oxygen uptake rates for COD removal were greater for sponge with 4mm thickness and 45 pores per inch than commercial BioM®, indicating good microbial growth and complete oxidation, whereas specific oxygen uptake rate defined as bacterial activity per gram of attached biomass, was found to be very less showing insufficiency of inner layers of biomass to oxidise resulting from very less nutrient availability. Similar results were obtained for ammonium-nitrogen removal. Such a combination of properties for a media holds great capability to replace any commercially available media.

Effect of carrier configuration and distribution pattern of biomass, studied by Bassin *et al.* [**32**] using two different media namely, Kaldnes ®K1 with diameter of 5 to 8mm and Mutag Biochip™ carrier with diameter of 30 mm, both made from polyethylene indicated significance of active biofilm surface area over amount of biomass attached. Kaldnes ®K1 with cylindrical shape entrapped more biomass but led to clogging at high organic loading rates, whereas Mutag Biochip™, due to its parabolic shape was more vulnerable to detachment of biofilms due to attrition which led to development of thin layers on both side of carrier and performed better at higher loading rates. Nitrification rates were reported to be severely affected at high loading rates as autotrophic nitrifiers grow slowly and at high influent COD are competed for oxygen and nutrients by heterotrophic microorganisms, feeding on organic carbon. The high growth rate of heterotrophic microbes helps them to overgrow nitrifiers, thus limiting the conditions for autotrophs. However, at low Hydraulic retention time, nitrification rates reported were better for Kaldnes® K1 than Mutag Biochip™. Thus, for a faster degradation mechanism as in case of removal of COD Mutag Biochip™ should be favoured, whereas for slow process such as nitrification Kaldnes® K1media should be given a preference.

Aeration modification

Low solubility of oxygen in water leading to low volumetric mass transfer coefficient is often compensated by using aerators. Surface aeration involves bringing the water in contact with the air present immediately above the water surface and drawing it in by expelling the water. Subsurface aeration, on the other hand involves using a diffuser below the surface of water which releases bubbles rising gradually through the bulk water. A lot of research work carried out on subsurface aerators proved the high aeration efficiency of porous diffusers than the non-porous aerators which produce large bubbles. Coarser bubbles generated due to large pores and high air flow rate have high velocity, thus rise quickly to the surface of water and escape into the atmosphere. In contrast to this fine bubbles, having greater residence time in water provide contact sites for food and microorganism. However, porous diffusers come with their own set of limitations.

Rosso *et al.* [**33**] through a study, summarised pros and cons of fine pore diffusers, coarse bubble diffusers and surface aerators and discussed relation of aeration efficiency with MCRT which is the average time a microorganism cell spends in a bioreactor. Higher MCRT provides early removal of organics, but also tend to increase the oxygen requirement. Though fine pore diffusers were found to have high aeration efficiency, fouling and clogging of pores, imparting back pressure was a common problem with such aerators and required frequent cleaning to restore functioning. Coarse bubble diffusers with low clogging required more energy. Thus choice could be made between the two on the basis of requirement of either high oxygen transfer rates or low aeration cost. Systems with greater mean cell retention time (MCRT) possess greater deviation from oxygen transfer efficiency (OTE) in clean water as more cells in work mean more oxygen requirement. Correlations between Reynolds number and α factor which is defined as ratio of volumetric mass transfer coefficient in process water to that of clean water, indicated that with increase in Reynolds number, greater mixing profiles were achieved and thus mass transfer increases and α factor decreases. In an attempt to understand the durability of a fine pore diffuser, Liu *et al.* [**34**] used hydrophilic porous glass membrane with small mean pore size of 517nm, for micro-bubble aeration and studied the fouling effects such as change in its structure before and after applying some cleaning methods and compared it to a completely new membrane. Fibres, tied to rope at equal distance, vertically at the centre of the reactor were used as a media for carrying biofilm for the treatment of synthetic wastewater with organic loading rate of 0.29 kg/ m^3.day and hydraulic retention time of 24h. Inorganic substance deposition was seen on the inner and outer side of membrane and was found to be acid soluble, also on the outer surface fouling layers showed presence of large amount of biofilm. Methods used to treat the membrane included mechanical scrapping and ultrasound treatment which could not remove fouling. With acid treatment, a part of the fouling got removed whereas with acid and thermal treatment combined together, all fouling got removed and morphology and pore distribution obtained by scanning electron microscope were quite similar to those of new membrane indicating no change. After acidic and thermal cleaning porosity, pore size, volume and area were observed to increase than the new membranes, not due to fouling but due to pressurised aeration. Also with fouling effects, larger size bubbles were generated, depleting the DO concentration as the residence time of bubble decreases, but after cleaning smaller bubble size generation was restored. With proper treatment, fine pore diffuser can be used over a longer time period and better OTE too can be achieved.

Al Ahmady *et al.* [**35**] determined oxygen transfer performance of sub surface aeration system and variations observed in aeration efficiency by changing depth of diffuser in tank and coverage area of diffusers by carrying out tests on potable water. Coverage was measured in terms of f/b ratios where **f** represented total width of diffuser band and **b** represented width of the tank. At constant air flow rates OTE were proportional to submergence with minimum OTE equal to 18-34 g O_2/m^3.h at a depth of 0.5m and maximum up to 160 g O_2/m^3.h at 4.6m depth. At low depth f/b ratios were not observed to play significant role as the curves obtained by plotting OTE verses f/b ratio is almost horizontal with depth equal to 0.4m. With submergence equal to 4.6m, maximum OTE of over 160g O_2/ m^3 h of water was obtained at f/b ratio equal to 1. As the depth is more, residence time of bubble in the water is more and better absorption of oxygen is achieved. Thus greater f/b ratios, so as to have maximum coverage and installation of diffuser at maximum depth promote OTE.

In an another experiment determining relation of oxygen mass transfer coefficients with variation in shape of air diffusers and with variation in air flow rate, Cheng *et al.* [**36**] worked with i-shape, e-shape, s- shape and disk shape air diffusers. Increasing water depths always gave increment in oxygen transfer rate as the bubble residence time increased and I-shape was observed to always give increment than the other shapes used. But, variation in air flow rates did not seem to affect the efficiency for any of the shapes. C shape and disk- shape diffusers gave moderate efficiency whereas s-shape performed the worse.

Sludge - water separation techniques

High maintenance cost and energy consumption are the two major problems which limit the explicit use of membrane bioreactors (MBRs), though they give good effluent quality in a wastewater treatment facility.

Ren *et al.* [**37**] in an experiment to reduce the installation as well as maintenance cost, coupled MBR with a nonwoven polyester fabric filter bag having 100µm pore size for treatment of domestic wastewater. The wastewater and culture were bought into contact inside the bag and the sludge produced was supposed to act as an effluent filter operating under gravity. Within 20 minutes of filtration, turbidity and suspended solid removal up to 53.8% and 73% respectively, was obtained. This removal increased with time and turbidity removal of 88% and suspended solid removal of 96.2% was observed resulting from cake layer formation. COD removal efficiency increased from 85.5% to 89.3%, whereas BOD removal efficiency up to 96.7 - 97.9% was observed. Total nitrogen removal was observed to be up to 37.8% and ideal conditions for denitrification were self-maintained and no alkali supplement was additionally required. Specific resistance of the filter was observed to increase with decreasing hydraulic retention time. Also, with low food to microorganism ratio excess sludge production was diminished. Scanning electron microscopy results indicated decrement in pore size due to clogging of fabric filter.

Aeration is required to help microorganism growth and in case of MBR, to prevent clogging and fouling of membrane which add up to the total electric energy consumption. In a study by Krzeminski *et al.* [**38**] energy consumption of MBR for treating sewage water was analysed. Treatment plant facilities with flat sheet membrane and hollow fibre membrane, submerged in separate filtration tank along with plant equipped with side stream, externally placed tubular membrane were analysed. Submerged configuration was found to be less costly due to its low operational energy demands than side stream configuration but need greater capital investment. As side stream have higher flux, less number of membranes is required per module requiring low capital investment. Performance of various installed MBRs, measured in terms of effluent concentration, removal efficiency and energy consumed per volume of treated wastewater revealed COD, BOD, and total nitrogen removal up to 92-96%, 99% and 96-98% respectively. However, specific energy consumption for aeration of hollow fibre membrane was observed to be lesser than flat sheet membrane and typically varied between 1.1KWh/m^3.MBRs with larger capacity were found to be more energy efficient. In some cases, aeration requirement to prevent clogging and membrane fouling added to the biological aeration cost, pumping and internal recirculation cost. Total cost was also observed to be dependent upon volume of flow treated and on weather conditions. In dry months, the cost was observed to be increased as the pumps and blowers were not being used up to their design flow capacity.

The effect of flocs size on membrane fouling was studied by Shen *et al.* [**39**] using a submerged membrane bioreactor. The properties of sludge such as its size and adhesion characteristics were found to be the reason behind binding of sludge to the membrane and its fouling. A poly vinylidene fluoride membrane, having an effective filtration area of 0.1m^2 and pore size of 0.3µm was used to treat synthetic wastewater for a hydraulic retention time of 5.5 hours. To study the effect of membrane material on cake resistance, a comparison was drawn between the actual generated sludge and by replacing its supernatant with sodium chloride solution and then passing it through filter to undergo caking. The presence of negatively charged biopolymer in the supernatant were neutralised by counter ions in sludge suspension, but only up to the electrostatic interaction range. Thus there is a reduction in the chemical potential of water in cake layer resulting into development of osmotic pressure induced resistance which accounts for a major part of cake resistance, which further increases with reduction in flocs size. Most of the sludge formed was of the size range of greater than 1µm, preventing membrane fouling due to pore clogging as none could penetrate the 0.3µm membrane pore. Also, due to the presence of energy barrier, there exist some repulsion between membrane surface and sludge which did not allowed it to adhere and thus sludge caking occurs.

In an attempt to reduce the maintenance cost and improving wastewater treatment efficiency, Son *et al.* [**40**] developed a tube type ceramic microfiltration membrane by extrusion using poly methyl methacrylate and α-alumina powder and blending in cellulose and then recoating it by α-alumina slurry. Membrane module with three membranes was put after clarifier with each membrane having area of about 72.2 cm^{2}for removal of total carbon and nitrogen. Synthetic wastewater with COD and TKN of 135-230 mg/l and 24.6-36.4 mg/l respectively were treated with and without membrane in the treatment unit. Without membrane treatment effluent with COD, TKN of 4-28 mg/l and 0-2.24 mg/l respectively was obtained whereas with membrane, presence of 0-6.7 mg/l COD and 0-0.84 mg/l of TKN was detected. Back flushing to remove fouling was carried out with water and took just 10 minutes, flux and trans-membrane pressure were recovered after every wash, justifying membrane's durability. Developing easier membrane fouling prevention methods and reduction of cost are two main challenges underlying with this process.

Conclusion & future prospective

Biological process neither works for wastewater containing antibiotics nor for removal of inorganic compounds and metals. Requirement of huge reactor volume, insufficient COD removal and easy wash away of biomass makes the suspended growth process out dated.

Attached growth systems provide better performance anytime as compared to suspended growth system. For non-submerged fixed bed reactor, rock lava, gravel packing and silica gravel packing give good COD removal rate but only at low OLR thus can't be used for commercial level water treatment facilities.

A media merging both porous (sites for microbial attachment) and non-porous (strength) structure with improved surface chemistry so as to fasten the growth of microorganism over media can replace any commercially available media. A filling ratio of 35-40% can save cost without affecting COD removal efficiency.

Submerged fixed bed reactors provide greater flexibility of HLR over non- submerged fixed bed reactor, but alteration in bed porosity may lead to clogging. Some of the media have excellent removal characteristics as described in the **Table 2** below.

Table 2. Recommended packing media for submerged fixed bed reactor.

Media	Advantages	Dis-advantages	Comment
Ringlace® rope media	Excellent nitrification rate, displaces less than 1% of reactor volume, requires low HRT.	Technology bear patent cost.	Suggested for nitrification in systems with high influent rates.
Sessil® media	Requires low HRT, Efficient at high OLR.	Technology bear patent cost.	Suggested for COD removal.
BIOLITE® media	BIOFOR process is good for continuous operation, saves 75% cost and 40% space than CASP.	Technology bear patent cost.	Suggested for COD removal.

Fine pore membrane diffusers are capable of providing better OTE and are durable with proper maintenance. For maximum oxygenation, all the aeration facilities must be installed at the maximum depth in tank while maintaining maximum coverage area.

Hollow fibre membrane should be preferred than flat sheet membrane. For both submerged and side stream having same shelf life but different operational and capital cost, one with lower operational cost must be chosen. Sludge with larger flocs size is preferable as it does not clog pores of membrane and forms cake layer, enhancing filtration.

The work done by several researchers provides abundant data for lab and pilot scale plants but the relevance of these data for up gradation to commercial scale is limited. Therefore, future work by the author aims for modification in conventional design and particularly in aeration system, focussing upon the shapes of aerators, which can be used for even distribution of air and better COD removal.

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Conflicts of interest

The authors declare no conflict of interest.

Keywords

Chemical oxygen demand (COD), aeration modifications, biological treatment, aerobic, biofilm media.

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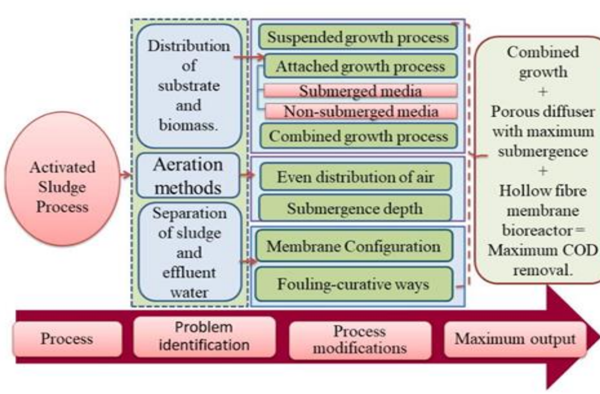
Graphical abstract

The authors review problems encountered in conventional activated sludge process and various design modifications used by different researchers to increase the efficiency of the process. Through this review, authors give guidelines for the best design which can be implemented commercially to obtain maximum Chemical Oxygen demand removal.



SUPPORTING INFORMATION

Table III: A comparison of modifications in activated Sludge process

Technology used	Type of wastewater	Influent COD (mg/l)	Hydraulic retention time, (hours)	COD Removal efficiency	Reference
Activated sludge process with suspended biomass	Freshwater and saline sewage with antibiotics and caffeine	0.2	10-17	No biodegradation	[5]
Activated sludge process with nanoparticles	Synthetic wastewater	200	8	No biodegradation	[8]
Comparison between activated sludge and attached growth (mineral media)	Synthetic wastewater+ phenol	100 - 2700	2-300	92.432% with attached growth	[9]
Aerobic packed bed biofilm reactor (glass beads media)	Synthetic wastewater with and without phenol	100-400	-	Without phenol=52%, With phenol=40%	[10]
Biological trickling filter (continuous +batch mode)	Dye wastewater	36,000	24	60%	[13]
Activated sludge process with Combination of fungal and bacterial treatment	Textile wastewater	100-500	120- 168	90-99%	[14]
Bio-trickling filter packed bed reactor(lava rock media)	Dairy wastewater	2750	7	96.43%	[15]
Aerobic baffled bioreactor (activate carbon (AC) and polyurethane foam (PF) media)	Synthetic wastewater	3248.80	24-72	With AC = 51%, With PF = 63%	[16]
Hybrid aerated submerged fixed film reactor (HASFF)	Municipal wastewater	319-293	2-8	65.7-76%	[20]
Bioreactor with submerged packing bed (polyethylene tape)	Domestic wastewater	90-564	0.23 -1.1	90%	[23]
Aerobic submerged filter packed bed reactor (volcanic scoria media)	Sewage + synthetic wastewater	28-3230	3.96-8.31	80%	[24]
Activated sludge process with packed bed reactor (date-palm fibres media)	Domestic wastewater	105	36	80.6%	[25]
Advanced aerobic biological filtration and oxygenated reactor (BIOFOR) process with BIOLITE media	Domestic wastewater	475	-	93.4%	[26]
Moving bed biofilm reactor (polyurethane media (PU) and granular activated carbon (AC))	Landfill leachate	5000	576	With PU= 65% With AC=81%	[27]
Hybrid moving bed biofilm reactor (HMBBR) with 35% and 66% filling ratio	Municipal wastewater	437	-	With 35% filling ratio = 90%, With 66% filling ratio= 89%.	[28]
Moving bed biofilm reactor (polyurethane sponge coated with polyethylene ring media)	Synthetic wastewater	250	6	99.5%	[31]
Moving bed biofilm reactor (Kaldnes K1 and Mutag Biochip media)	Synthetic wastewater	400-1600	3-12	>90%	[32]