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Optimizing design parameters of an anaerobic baffled reactor for better performance: A review

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***Abstract*---**The review has summarized the currently available information about the basic configuration, advantages, applicability, modifications in the original structure, effect of modifications on improvement in the performance and finally, limitations of Anaerobic Baffled Reactors (ABRs). The comparison of the performance of four main types of the anaerobic reactor, including ABR, has proved the superiority of ABR in terms of chemical oxygen demand (COD)

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removal over other types of reactors. Many researchers have worked on improving the constructional details of the ABR to improve the performance. So, this review summarizes the modifications in the ABR design tried and tested by the researchers and concludes that design modifications indeed have encouraging effects concerning efficiency ABR.

***Keywords*---**design parameters, anaerobic baffled reactor, chemical oxygen demand.

Introduction

In many rural areas of developing countries, the primary reason for water pollution is the direct discharge of sewage without much treatment into the nearby water bodies (Gijzen, 2002; Grau, 1996). Domestic wastewater is the wastewater coming from toilets, showers, baths, sinks and kitchens (Van Lier et al., 1997). The availability of pollution-free freshwater is a basic need for any development of humans, but the availability of such clean, usable water is scarce. So, reusing the wastewater after treatment will help in reducing the demand for clear water (Hernandez Leal, 2007). Hence, many researchers have developed decentralized and sustainable wastewater treatment processes to reclaim the resources present in domestic wastewater (Kujawa-Roeleveld and Zeeman, 2006). Few of the expectations reported towards the sustainability of wastewater treatment processes include no or little use of mineral resources and energy, recovering resources or energy from wastewater, far-reaching applicability and easy construction, operation and maintenance (Lettinga, 2001).

The anaerobic wastewater treatment process is one of the sustainable methods of treating domestic wastewater compared to the aerobic treatment process (Lettinga, 1996; Lettinga et al., 2001; Raskin et al., 1994). The application of the anaerobic treatment process for sewage treatment has increased with high rate anaerobic reactors in the last two decades. They are characterized by low construction, operation, maintenance costs, reduced footprint, and higher capacity biogas production (Elmitwalli et al., 2002). Such anaerobic reactors are beneficial, attributed to their ability to separate the hydraulic and solid retention times. So, even with less hydraulic retention time, the concentration of biomass in the system is very high (Iza, 1991; Hickey, 1991), which ensures a significant reduction in pollutants from the wastewater such that at the temperatures above 200C, on an average, the reported decrease in the average total COD is around 70% (Kujawa-Roeleveld and Zeeman, 2006).

Anaerobic digestion (AD) consists of four stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis (Batstone et al., 2002). Out of these steps, if any of the steps is slow, it will affect the overall kinetics of the process. In the case of influents containing complex organic solids, hydrolysis will be a limiting step (Tomei et al., 2009). Hydrolysis, also known as liquefaction, is responsible for limiting the kinetics of the overall digestion process for influents consisting of lipids and a considerable amount of particulate matter (Khanal, 2008). The concentration of inoculums also impacts the rate of reaction kinematics involving numerous organic constituents in an influent. The rate of hydrolysis is found to be comparatively higher for a higher ratio of inoculums to the substrate (Fernandez et al., 2001; Chen and Hashimoto, 1996; Liu et al., 2009; Lopes et al., 2004).

The high rate reactors are developed to achieve more significant biomass accumulation within a reactor by using the phenomenon like settling or attachment to media or recirculation and improving the contact between the substrate and biomass (Iza, 1991). Due to high solid retention time, the microorganisms growing slowly are retained in the reactors for a longer duration. Hence, they allow higher organic loading rates even with smaller sizes of the reactors (Aiyuk et al., 2006). The high rate anaerobic reactors involve contact type, filter type, fixed-film type, fluidized bed type, expanded granular sludge bed, anaerobic baffled, up-flow anaerobic sludge bed, and hybrid reactor (Iza, 1991; Aiyuk et al., 2006). A few of these reactors are discussed below with requisite details.

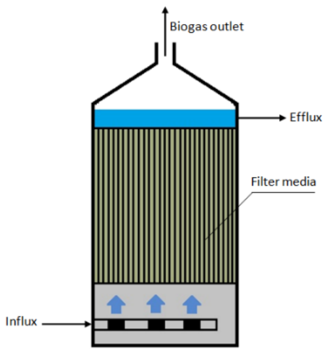


Fig. 1 – Anaerobic Filter

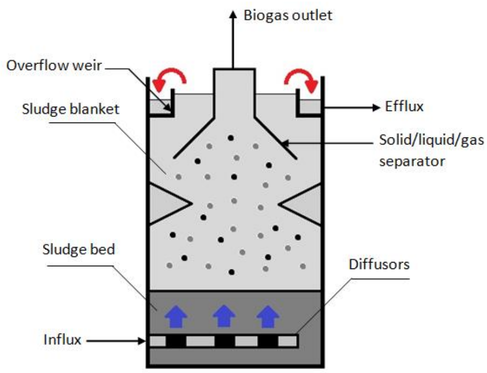


Fig. 2 – Up flow Anaerobic Sludge Blanket Reactor

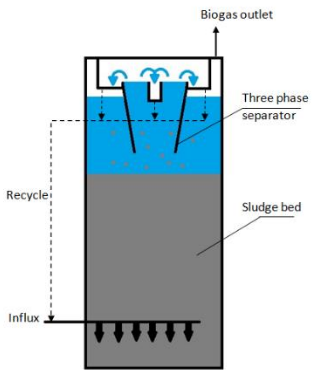


Fig. 3 – Expanded Granular

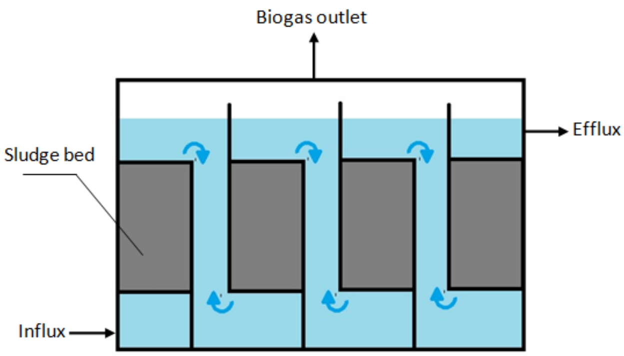


Fig. 4 – Anaerobic Baffled

Reactor

Sludge Bed reactor

a) Anaerobic Filter (AF)

As shown in Fig. 1, this reactor has filters arranged vertically. The filters are made up of inert media that act as a support for biomass to filter out the freely flowing flocks or biomass. Influent flows from bottom to top. During this flow, the wastewater comes in contact with biomass and gets treated (Young and McCarty, 1969).

b) Upflow Anaerobic Sludge Blanket Reactor (UASB):
The reactor shown in fig. 2 acts as a settling device and is fed upward (Lettinga et al., 1970). The suspended solids are retained in the reactor. This reactor doesn't contain packing materials. The sludge gets converted into granules. Hence, high biomass concentrations are maintained in the reactor (Bajpai, 2017; Gömec, 2010; Chernicharo et al., 2015; Seghezzo et al., 1998; Switzenbaum, 1983).

c) Expanded granular sludge bed (EGSB):
The reactor is shown in fig. 3 was developed to avoid problems such as hydraulic shortcuts, preferential flows and dead zones due to significant up-flow velocity to wastewater to be treated attributed to adequate height/diameter ratio and effluent recirculation (Bajpai, 2017; Gömec, 2010; Rinzema et al., 1993; Van Haandel et al., 2006).

d) Anaerobic baffled reactor (ABR):
The reactor shown in fig. 4 was developed by Mc-Carty and co-workers as a series of UASB reactors for wastewater treatment without clogging, providing sludge bed expansion. It is a reactor designed using baffles arranged alternately to allow the wastewater to flow up and down from one compartment to next which helps in maintaining the high concentration of biomass in upflow regions of each container (Bajpai, 2017; Barber and Stuckey, 1999; Manariotis and Grigoropoulos, 2002; Chinwetkitvanich and Ruchiraset, 2017).

Compared to the reactors mentioned above in COD removal and biogas production, 95% of COD reduction was obtained for ABR at T = 35 °C reactors with COD influent in order of 500 mg/L (Ghangrekar et al., 1996; Langenhoff and Stuckey, 2000). The biogas produced was about 49–0.55 Nm3 per kg of COD removed when an ABR was operated at hydraulic retention time (HRT) for 8 h, temperature ranging from 22 to 28°C, and COD value for influent varying between 505 and 914 mg/L (Nasr et al., 2009). Hence, the principal purpose of this review paper is to review the reported literature about ABRs such as basic configuration, advantages, applicability, improvements in the design, effects of such modifications in the betterment of the performance, and their limitations.

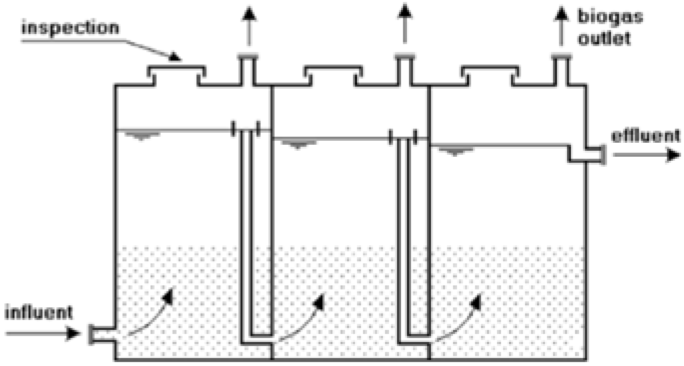


Fig. 5 –Schematic representation of ABR

As shown in fig. 5, the ABR is considered a series of UASB reactors divided into compartments with baffles stacking in it (Bachmann et al., 1985) which can work without granular sludge, unlike a UASB (Boopathyet al., 1988). Here, while moving from inlet to outlet of ABR, the wastewater also flows above and below the baffles. This compartmentalized design gives very effective separation of acidogenesis and methanogenesis microbes to convert the single-phase reactor into a two-phase reactor (E. J. Tomlinson and B. Chambers, 1979; G.K. Anderson et al., 1991; M. Asraf-Snir and V. Gitis, 2011) such that the process of acidogenesis takes place in the compartment close to inlet and methanogenesis takes place in the adjoining case (Barber and Stuckey, 1999; Uyanik et al., 2002; Plumb and Stuckey, 2001). This separation of microbes makes the reactor less susceptible to both hydraulic and organic shock loads (Nachaiyasit and Stuckey, 1997) and ensures smooth operation (Barber and Stuckey, 1999). Such a design enhances the intimacy between organic pollutants and biomass, reduces the reactor size, furthers the biomass retention and reduces the HRT independent of the solids retention time (SRT) (Barber, 2000). Moreover, the increased treatment efficiency gives high biogas yields and provides easy tapping (Bachmann et al., 1985, Barber and Stuckey, 1999, Hassan and Dahlan, 2013). The ABR finds use in treating various wastewaters, including domestic wastewater, as reported in the literature (Dama et al., 2002). Few of the limitations of ABR include disability of nutrient removal, low efficiency of pathogen removal, less effectiveness of removal of inert solids and requirement of post-treatment of effluent.

Reactor design modification

Since the invention of ABR, its design has been modified many times to enhance its efficiency by increasing the retention of biomass, reliability of the reactor, enhancing capacity for treating the wastewaters and cutting down the capital cost (Boopathy and Sievers, 1991; Orozco, 1997). As mentioned in the literature, the removal of COD and biochemical oxygen demand of 5 days (BOD5) from influent is influenced by some chambers (Sasse, 1998). Also, for the successful working of ABR, the up-flow velocity of wastewater (Cup, max) in the upcoming section of ABR needs to be up to 2 m per hr. Equation (1), expressed by the (Sasse, 1998), gives the relationship between Cup, max and the design tool input parameters, including the number of people (P) generating wastewaters, per head production of wastewater (Qp), duration of wastewater flow (tQ) and area of each ABR chamber (AABR). Generally, the period of wastewater flow for municipal applications is between 8 h and 12 h.

$$V_{up,max} = \frac{P * Q_p}{t_Q * A_{ABR}} \qquad (1)$$

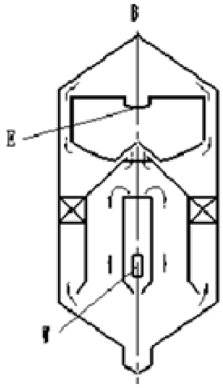


Fig. 6 –Anaerobic Sludge Bed reactor

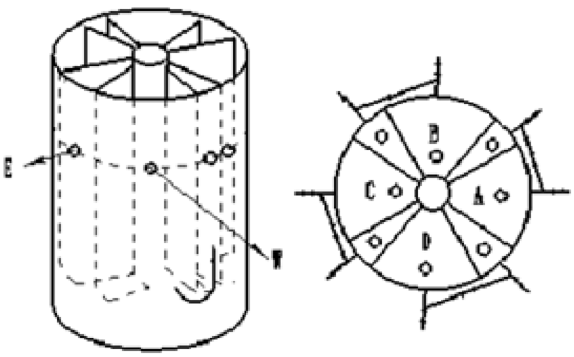


Fig. 7 –Periodic ABRwith vertical baffles

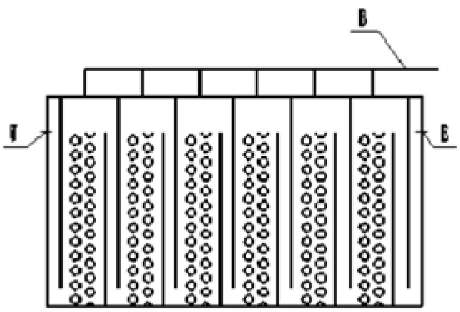


Fig. 8 – ABR with carrier medium

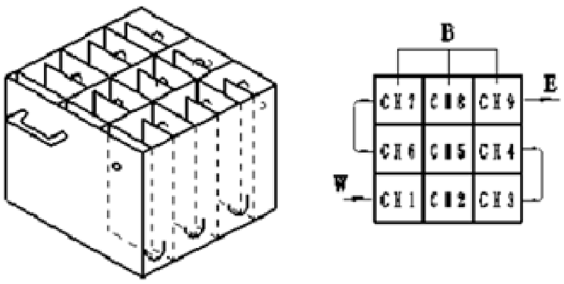
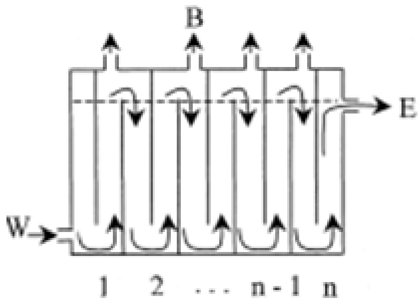


Fig. 9 – ABR with nine chambers

Fig. 6 shows the anaerobic sludge bed reactor in which vertical baffles are used to get the combined effect of UASB, contactor type anaerobic reactor and anaerobic filter. This type of reactor was used to treat distillery wastewater, the most hazardous one under high BOD and COD (Li et al., 2001). The fig. 7, named Periodic ABR, shows an ABR developed to get the best performance with the healthy working environment for the given parametric values of influent when operated periodically at different hours (Skiadas and Lyberatos, 1998). Fig 8 shows an ABR in which carrier medium was used to reduce the clogging loss of biomass and increase the intimacy between the bacteria and substrate to treat the wastewater at room temperature. This reactor is amenable to a decentralized wastewater treatment system (Faisal and Unno, 2001; Feng et al., 2008). Fig 9 shows an ABR modified by incorporating nine chambers. An investigation was undertaken on this reactor to evaluate the effect of variation in the design on the operational parameters by operating the reactor for 375 days. The reactor met the requirements of municipal wastewater treatment at the lowest HRT of 6 hrs (Bodkhe, 2009).



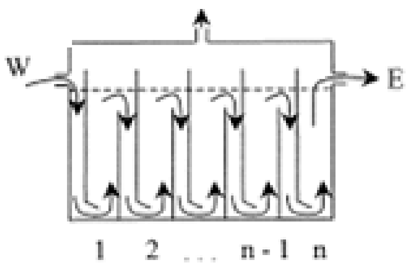


Fig. 10 –ABR with equal column widths; Fig. 11 – ABR with narrow down column

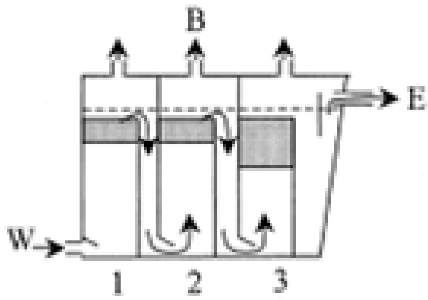


Fig. 12 –ABR with packing media

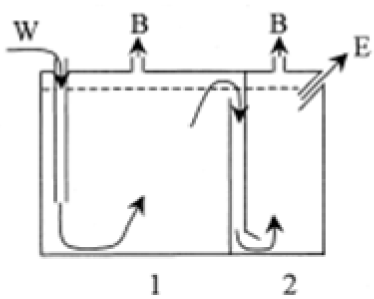


Fig. 13 –ABR with chambers having sizes in the ratio 2:1

Fig. 10 shows the ABR, which was obtained in 1981 by introducing the baffles vertically to a plug flow reactor to treat Seakelp slurry consisting of a high amount of solids to avoid the replacement of methanogens by incoming solids and to maintain the required amount of it (Fannin et al., 1981). ABR, as shown in fig. 11, was used to study the effect of narrowing down the column and bending the baffle bottom edges (Bachmann et al., 1983). Fig. 12 shows one of the hybrid ABR designs. Hybrid ABR consists of a solid settling chamber after the final compartment and a packing medium placed in each container (Tilche and Yang, 1987). Fig. 13 shows ABR consisting of 2 sections such that the first two are double in size than the second one. When compared with three chambers ABR of the same volume, the later one retained the biomass for a more extended period (Boopathy and Sievers, 1991).

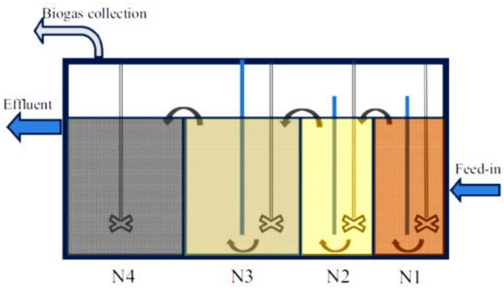


Fig. 14 – Multi-phased ABR

The fig. 14 shows the Multi Phased – Anaerobic Baffled reactor (MP-ABR). The baffles used in this reactor were adjustable to the widths of the compartments. The compartment's widths were increased in the direction of wastewater flow while each container was provided with a mixer (A. Ahamedet. Al., 2015). ABRs have been in use in combination with combined with other reactors to accrue benefits of both, e.g. ABR & aerobic biofilm membrane reactor (Bodik et al., 2003; Hu et al., 2009; Pillay et al., 2008), thoroughly agitated ABR used for treating the synthetically prepared wastewater with the efficiency of 94% for the Organic Loading Rate (OLR) of 2.1 kg COD/m3 day (Kuscu and Sponza, 2006).

Result and Discussion

The performance of an ABR is assessed in terms of Hydraulic Retention Time (HRT), OLR, nutrients, waste compositions, temperature, pH etc. are important for ABR. As discussed already, the basic design of ABR was modified from time to time to enhance its performance. The following table summarizes the effects of modifications in the ABR designs on the performance parameters.

Sr. No.	Description of modification done in basic configuration of ABR	Effects of modifications	References
1	By lowering the HRT, the effect of OLR fluctuation on MABR primary treatment were examined.	The MABR's excellent removal rate demonstrates that contaminants may be destroyed in anaerobic settings. In summary, the MABR might be an	Imran Ahemad 2020

		effective method for treating wastewater at a waste facility.	
2	Two additional anaerobic baffled bioreactors studied described after operation for further over 2400 occasions at a variety of effluent temperatures (11 to 24 °C).	76 percent of the chemical oxygen consumption eliminated was transformed to hydrocarbon biogas in numerous different anaerobic digesters (better power contents of 2.0 kW h kg1 COD eliminated).	Andrew Pfluger et. al. 2019
3	The comparing 24 h, 36 h, 48 h, and 72 h, a hemodynamic retention time (HRT) of 48 h was identified as the best HRT.	Under a 48-hour HRT, ABR performs well and has a lot of promise for practical use.	Xiao Zha et. al. 2019
4	Anaerobic Astonished Reactors (ABR) and a succession of azimuth and elevation chippings filters after a contaminant removal which was before.	The WWTP's overall proficiencies were 95 percent BOD5, 88 percent total COD, 95 percent TSS, 37 percent N-NH3, and 30 percent P, according to the metadata.	Ivette Echeverría et. al. 2019
5	Extrusion-made magnetic properties microporous packaging media subsequently employed, which were adjusted by adding appropriate quantities of heterogeneous catalyst and electromagnetic activation.	The impacts of putting active packing medium in diverse operational zones (hydrolysis or methanogenesis) on response parameter (organic material and nutrient removal, biogas generation) were investigated.	Marta Kisielewska et. al. 2018
6	The reaction is conducted at two distinct temperatures: regular water (25 degrees Celsius) and hot water (45 degrees Celsius).	As the temperature rose, so did the amount of dead space. Furthermore, increasing temperature of something like the reactor partitions resulted in less forming a layer.	Mehedi Hasan et. al. 2018
7	Draughty and shielded HABRs were run at heated temperature (18.6–37.6 C) utilizing various HRTs (30 h and 20 h).	It improves nutrient removal efficacy by 4% for TN, 8% for NH4-N, and 7% for NO3-N, but reduces PO4 3 clearance competence by 7%.	Md Khalekuzzaman et. al. 2018
8	Modified ABR with 7 chambers out of which first one was sedimentation chamber and last two chambers consisted of packing medium.	Hydraulic efficiency indicating the contact time of pollutant in the system and ability to break down the pollutants was best for all 5th onwards chambers.	Md Khalekuzzaman et. al., 2018
9	Laboratory-scale integration ABR with ultra-filtration membrane bioreactor separated into five compartments with four baffles. The mixed liquid	Complete removal of total suspended solids (TSS), elimination of chemical oxygen demand (COD) (93.3 3.8%), and removal of 53.6% nitrogen.	Hung-Nien Sung et al., 2017

	suspended solids (MLSS) from the membrane bioreactor are returned to the ABR.		
10	Laboratory-scale integration ABR with ultra-filtration membrane bioreactor separated into five compartments with four baffles. The mixed liquid suspended solids (MLSS) from the membrane bioreactor are returned to the ABR.	The maximum COD removal percentage of 99.7% was reached at an OLR of 0.258 kg COD/m3.d, whereas the COD removal percentage dropped to 39.5 at the highest OLR of 2.471 kg COD/m3.d.	Maizatul Asnie Mohd Aris et al., 2017
11	The 58-liter modified anaerobic hybrid baffled (MAHB) reactor was run at 35 degrees Celsius under microaerophilic conditions.	COD elimination is highest (87%), system pH is steady, and methanol concentration is highest (> 65%).	Siti Roshayu Hassan et. al. 2017
12	Addition of vertical baffles to a plug flow reactor	Methane concentration increased from 30 to 55% for OLR of 1.6 kg COD/m^3 per day	N. Reynaud and C. A. Buckley, 2016
13	Modified ABR with 4 compartments having the volume in the ratio of 3:1:5:5 and 120^0 angles are used as baffles	Continuously changed flow rate of wastewater between the baffles, so improved mixing.	Shengnan Li et. al., 2015
14	Increase in the number of compartments from 3 to 6.	Minimum dead space of 3% observed for 6^{th} compartment. For removal efficiency of 90%, the optimum number of compartments found to be within 4 to 6.	Ming Xu et. al., 2014
15	Combination of Sequential ABR and completely stirred tank reactor (CSTR)	Chemical oxygen demand (COD) removal efficiency increased up to 94% with the OLR of 2.1 kg COD/m^3 per day	Rongrong Liu et.al., 2010
16	Modified ABR with 9 chambers arranged in 3 rows of 3 chambers each	The efficacy of COD elimination was shown to be related to HRT. Cod removal efficacy was 91 percent for HRT > 1 day, but fell to 87 percent for HRT 0.25 day. The same pattern was seen for Biological Oxygen Demand (BOD) removal efficiency, with HRT exceeding 1 day removing 90% of BOD..	S. Y. Bodkhe, 2009
17	Dilution of incoming wastewater by effluent recycle	Negative phenomena such as the buildup of volatile fatty acids, a drop in pH, and the exposure of sensitive microorganisms to hazardous quantities of inorganic	Baloch et al., 2007

		and organic chemicals are all reduced.	
18	Modified ABR having 8 compartments with reducing height of standing baffles	COD reduction effectiveness was up to 85%, and it varied with HRT, with efficiency increasing from 60% to 90% when HRT was reduced from 60 hours to 20 hours.	P. Dama et. al., 2002
19	Adding carrier medium in ABR to build Hybrid ABR	Only 70% of the methane originated from the first compartment when the Volatile Suspended Solids (VSS) was 10%.	William P. Barber and David C. Stuckey, 1999
20	Comparing the performances of two hybrid ABRs with 3 and 2 compartments	SRT increased from 22 days to 25 days for 3 compartment reactor	Boopathy and Sievers, 1991
21	Multi phased ABR	COD removal efficiency of 55–93% when operated under HRT of 4.8–71 Hr at 35^0C with inlet COD of 8 g COD/L	Bachmann et al., 1985
22	The downflow chamber is narrowed, and the baffle edges are slanted.	The COD elimination effectiveness of 82 percent improved the rate of methane generation.	Bachmann et al., 1983

Conclusion

The literature review shows that the ABR can very well be used to treat wastewater with varying degrees of different contaminants over other reactors in use. Further, by combining, its performance efficiency can be improved considerably. Some notable modifications include narrowing the down column, increasing the number of compartments, slanting the hanging baffles at the end, etc. With such changes, the COD removal efficiency can be increased to almost 90-95%, which justifies the transformation in the configuration of ABR. Thus, ABR can be considered the most sought-after solution for futuristic technical challenges expected to face by researchers in wastewater treatment.

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