Bioresource Technology 185 (2015) 399–410

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

Review

The effect of activated carbon addition on membrane bioreactor processes for wastewater treatment and reclamation – A critical review

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HIGHLIGHTS

- AC addition to MBRs fortify adsorption, potentially enhancing biodegradation.
- AC-assisted MBRs more effectively remove resistant pollutants than usual MBRs.
- AC addition to MBRs can retard membrane fouling and improve membrane flux.
- For AC-assisted MBRs, AC dosage and retention time must be carefully controlled.
- Frequent but low-dose AC addition may facilitate timely replenishment of spent AC.

ARTICLE INFO

Article history:
Received 27 December 2014
Received in revised form 26 February 2015
Accepted 1 March 2015
Available online 6 March 2015

Keywords:
Wastewater treatment
Membrane bioreactors
Membrane fouling
Powdered activated carbon
Granular activated carbon

ABSTRACT

This review concentrates on the effect of activated carbon (AC) addition to membrane bioreactors (MBRs) treating wastewaters. Use of AC-assisted MBRs combines adsorption, biodegradation and membrane filtration. This can lead to advanced removal of recalcitrant pollutants and mitigation of membrane fouling. The relative contribution of adsorption and biodegradation to overall removal achieved by an AC-assisted MBR process can vary, and "biological AC" may not fully develop due to competition of target pollutants with bulk organics in wastewater. Thus periodic replenishment of spent AC is necessary. Sludge retention time (SRT) governs the frequency of spent AC withdrawal and addition of fresh AC, and is an important parameter that significantly influences the performance of AC-assisted MBRs. Of utmost importance is AC dosage because AC overdose may aggravate membrane fouling, increase sludge viscosity, impair mass transfer and reduce sludge dewaterability.

1. Introduction

Membrane bioreactor (MBR) technology integrates biodegradation by activated sludge with direct solid–liquid separation by membrane filtration. Nowadays, MBRs are considered an attractive alternative to conventional activated sludge process (CASP) for the treatment and reuse/recycle of industrial and municipal wastewaters (Judd, 2011; Jamal Khan et al., 2012; Hai et al., 2014). The application of MBR systems for wastewater treatment is favored over conventional treatment methods due to considerable advantages including excellent and stable effluent quality, less excess sludge production, operation at high volumetric loadings, and smaller footprint (Li et al., 2005; Ng et al., 2006). However, their widespread application is still restricted by a phenomenon called membrane fouling (Chang et al., 2002; Li et al., 2005; Ying and Ping, 2006). Uncontrolled membrane fouling leads to rapid reduction in membrane permeate flux (MPF) and/or increase in transmembrane pressure (TMP), resulting in high energy consumption and operating cost (Liu et al., 2007; Tian et al., 2010). A number of techniques have been explored for fouling control: these techniques either target at adopting suitable aeration strategies (*e.g.*, high-shear slug flow aeration in submerged configuration) or optimization of other operating conditions such as sub-critical flux operation, periodic air/permeate back-flushing and/or intermittent suction allowing a relaxation period for back diffusion of loosely attached foulants from membrane surface. A notable membrane fouling mitigation strategy is the addition of "membrane fouling reducers" (*e.g.*, flocculants or adsorbents) to MBRs (Chang et al., 2002; Li et al., 2005; Ng et al., 2006; Tian et al., 2010; Skouteris et al., 2012, 2014; Yang et al., 2012a).

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http://dx.doi.org/10.1016/j.biortech.2015.03.010
0960-8524/

The use of adsorbents such as activated carbon (AC) in conjunction with biological wastewater treatment processes such as CASPs or MBRs can be also beneficial in terms of stable treatment of recalcitrant wastewater. According to the available literature, potential advantages of dosing ACs such as powdered activated carbon (PAC) to CASPs include: (i) protection of autotrophic and heterotrophic microorganisms from peak loads of inhibiting compounds, (ii) biodegradation of refractory organic compounds, (iii) increase in AC adsorption capacity due to the presence of a biofilm, (iv) increase in sludge settleability and dewaterability, and finally, (v) bioregeneration of AC. Because the AC added into CASPs can be washed out along with the treated effluent, frequent replenishment of AC becomes necessary. This significant maintenance cost restricts their widespread use (Munz et al., 2007; Meng et al., 2009). Nevertheless, to date, ACs, in particular PAC, have been used in conjunction with CASPs to treat recalcitrant wastewater streams including industrial effluent (with inhibitory materials such as phenol, aniline or dye), landfill leachate, and high salinity oil-field brine (Ng et al., 2006).

Unlike CASPs, owing to the complete retention of sludge by the membrane, in MBRs, a decoupling of hydraulic retention time (HRT) and sludge retention time (SRT) is possible. This allows operation of MBRs at a longer SRT. The reduced frequency of sludge removal reduces loss of PAC, simultaneously reducing the maintenance cost. Thus MBRs appear more suitable than CASPs to couple with AC adsorption. Furthermore, AC dosing to MBRs can potentially reduce the operating cost for membrane cleaning and/or membrane replacement by about 25% (Yang et al., 2010). In this way the operating cost for PAC dosing can be potentially offset by the reduction in the cost for membrane maintenance, thus making the addition of ACs to MBRs highly attractive.

As noted above, the use of adsorbents in combination with MBR technology integrates adsorption and biodegradation of organic matter with membrane filtration (Fig. 1). It has been proven to be an alternative approach to modify the characteristics of the mixed-liquor in order to remove recalcitrant compounds from wastewater efficiently, enhance MPF and control membrane fouling (Li et al., 2005; Tsai et al., 2005; Iversen et al., 2009a). For example, Li et al. (2005) mentioned that the near critical-flux for an AC-assisted MBR was 32% higher than that of a conventional MBR. To date, the beneficial aspects of AC dosing to MBRs such as membrane fouling mitigation and efficient treatment of resistant wastewater have been separately and only briefly covered in relevant available reviews which focused either on membrane fouling (Le-Clech et al., 2006; Drews, 2010) or treatment of recalcitrant wastewater (Hai et al., 2014). However, a comprehensive understanding of the phenomena involved, particularly the interrelated impacts of AC on membrane performance and biodegradation, are yet to be critically analyzed. Thus this paper aims to provide an in-depth discussion on AC-assisted MBR systems. AC-assisted MBRs have also been tested in relation to drinking water treatment (Tian et al., 2009); however, this work will focus mainly on the effect of ACs on MBRs treating different kinds of wastewaters. A notable originality of this review paper is that it covers a critical assessment of integration of AC adsorption with both aerobic and anaerobic MBR (AnMBR) technology.

2. Coupling membrane technology with adsorption and biodegradation

2.1. Pollutant removal by activated carbon adsorption

Wastewater-borne pollutant removal takes place through their diffusion onto the surface and/or into the pores of the AC (Tsai et al., 2005; Vyrides et al., 2010). However, some organic pollutants show greater adsorption than others. For example, organics such as toluene and chlorinated organics that have a low solubility in waters can be adsorbed by ACs more easily than the organics that are polar (Vyrides et al., 2010).

ACs have been widely explored for the removal of a large number of pollutants including persistent xenobiotics and trace organic contaminants (TrOCs) such as pharmaceutically active compounds and endocrine disrupting compounds (EDCs), residual organic matter (ROM) and other refractory organics (Snyder et al., 2007; Nguyen et al., 2012; Whang et al., 2004) from different kinds of wastewaters (Ng et al., 2006; Munz et al., 2007; Liu et al., 2007; Remy et al., 2010; Lin et al., 2011). In general, they are successful in removing all compounds that can cause undesirable color, odor or taste in water – details can be found in Table 1. However, the contaminant removal efficiency of ACs is subject to, among other factors, their particle size. Vyrides et al. (2010) reported that small AC particles ($\leqslant$0.25 mm) adsorb better (98% COD removal) than larger particles ($\leqslant$0.75 mm) (50% COD removal) due to the fact that smaller particles have higher diffusion transfer and larger surface area. Also, Ng et al. (2013) showed that fine PAC particles can control membrane fouling better than coarser ones provided that the applied MPF does not induce severe PAC deposition on the membrane.

The efficiency of ACs in the removal of pollutants is also subject to the size of the molecules of the pollutants, with the addition of PAC achieving greater removal of high molecular weight compounds (Aquino et al., 2006). Large-molecular weight pollutants adsorbed in large AC pores reduce the effective pore diameter, so the rate of adsorption of smaller molecules, that have no option but to pass through these pores to reach smaller pores, is reduced. This unavoidably leads to a decrease in adsorption over time, particularly when there is a diversity of high-molecular weight

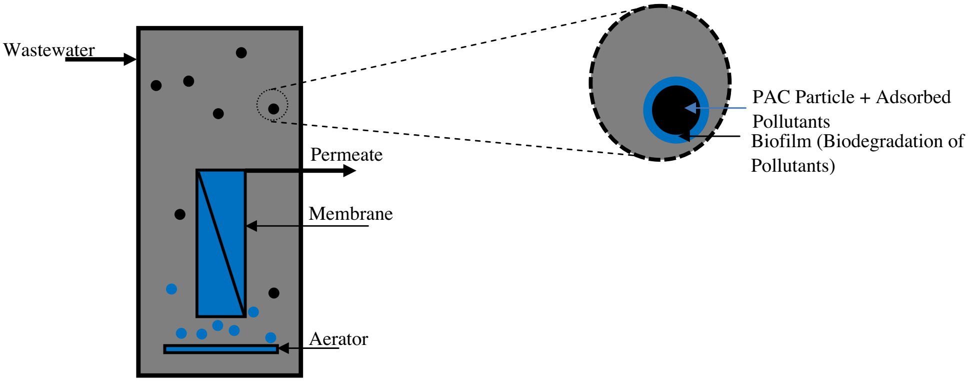

Fig. 1. Submerged PAC-amended MBR.