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Performance assessment and hydrodynamic analysis of a submerged membrane bioreactor for treating dairy industrial effluent

Praneeth K[a,b], Siddhartha Moulik[b], Pavani Vadthya[b], Suresh K. Bhargava[c], James Tardio[c], Sridhar S[b,*]

[a] *RMIT-IICT Joint Research Center, IICT, India*
[b] *Membrane Separations Group, Chemical Engineering Division, Indian Institute of Chemical Technology (CSIR-IICT), Hyderabad 500007, India*
[c] *Royal Melbourne Institute of Technology (RMIT), School of Applied Sciences, Melbourne, VIC 3001, Australia*

HIGHLIGHTS

- SMBR technology for successful treatment of dairy effluent developed.
- High impurity rejection achieved with PAN and PVDF hollow fiber membranes.
- Effect of TMP, air scouring and chemical cleaning on SMBR evaluated.
- Comprehensive CFD model proposed for prediction of hydrodynamics within membrane module.

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ABSTRACT

Submerged membrane bioreactor (SMBR) is a relatively advanced technology for waste water treatment that involves integrated aerobic and anaerobic biological processes with membrane filtration. In the present investigation, hydrophobic polyvinylidene fluoride (PVDF) and hydrophilic polyacrylonitrile (PAN) hollow fiber (HF) membranes were tested in an indigenously fabricated SMBR for dairy effluent treatment under aerobic conditions using mixed microbial consortia. Effect of operating parameters such as suction pressure, degree of aeration and trans-membrane pressure (TMP) on membrane performance in terms of flux, rejection of turbidity, BOD and COD besides fouling characteristics was investigated. The observed optimum permeabilities of PVDF and PAN HF membranes were approximately 108 and 115 LMH bar^{-1} with high extent of impurity removal. The rejection of COD was found to be 93% for PVDF and 91% for PAN HF membranes whereas corresponding rejection of BOD was observed to be 92% and 86%. A two-dimensional comprehensive model was developed to predict the hydrodynamic profile inside the module. Regression analysis revealed that the simulation results agreed well with experimental data.

1. Introduction

Dairy industries produce a variety of waste such as aqueous effluents and solid waste that contain significant quantities of biochemical oxygen demand (BOD) and chemical oxygen demand (COD), high levels of dissolved or suspended solids including fats, oils and grease, nutrients such as ammonia or minerals and phosphates [1]. The effluents that are produced require treatment before they are discharged into water bodies. This is usually done using conventional processes such as double stage activated sludge process, anoxic/oxic treatment, oxic-settling-anoxic treatment. To comply with more stringent permissible discharge standards, the aforementioned processes have however become increasingly expensive. The increased costs associated with conventional processes have led to interest in alternative technologies that can enable the effluent water to be reused [2–4]. One technology that has the potential for more efficient treatment of dairy effluent is membrane bioreactor (MBR) process.

MBR technology is a potentially viable, efficient and cost effective process with a wide range of applications in the areas of food, pharmaceutical, chemicals and biotechnology. Significant benefits of MBR over conventional filtration processes include complete retention of particulate matter, low discharge rate of total suspended solids (TSS), automated operation, good control

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* Corresponding author. Tel.: +91 040 27191394; fax: +91 040 27193626.
E-mail address: sridhar11in@yahoo.com (S. S).

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Nomenclature

$\vec{v}$	velocity of the fluid ($\mathrm{m\,s^{-1}}$)
G	external channel subdomain
R_i	internal channel subdomain
D	thickness of the fluid envelope (m)
K	intrinsic permeability ($\mathrm{m^2}$)
w	membrane or porous subdomain
P	pressure (bar)
R_{ext}	external radius (m)
R_{int}	internal radius (m)
ΔP	transmembrane pressure (Pa or bar)
γ	interfacial tension ($\mathrm{N\,m^{-1}}$)
r	radius of cylindrical pore (m)
φ	packing density
$\in$	porosity of the porous medium
μ_{eff}	effective viscosity (Pa s)
μ	dynamic fluid viscosity (Pa s)

of biological activity, high quality effluent free of bacteria and pathogens, smaller plant size, and higher organic loading rates [5–7]. MBR combines both biological treatment of effluent and clarification by submerged low pressure polymeric ultrafiltration (UF) membranes. A MBR can be classified based on the type of membrane separation process used: this can be done either by pressure-driven filtration in side-stream MBRs or with vacuum-driven membranes immersed directly into the bioreactor in submerged MBRs. Submerged or side-stream can be operated under aerobic or anaerobic conditions [8–10]. The reduced energy consumption is a major advantage that can be achieved using a submerged MBR compared to a side-stream MBR [9].

In recent years, MBR technology has gained unprecedented popularity in the field of wastewater treatment. However, one of the major obstacles for its widespread application is membrane fouling, which could cause severe loss of membrane permeability and thus an increase in energy consumption. Many researchers have focused on factors affecting the process performance which mostly include conventional factors such as biological and reactor kinetic parameters but very few on membrane performance parameters such as nature of membrane material (hydrophobic/hydrophilic), pore size and distribution, life span, water flux and impurity rejection [11,12].

Accordingly, it is necessary to use Computational Fluid Dynamics (CFD) approach for evaluating the hydrodynamics within the module. The few experimental and theoretical studies available in the literature visualize fluid flow phenomena within the membrane reactor to optimize process parameters for scale-up. Liu et al. [13] reported particle image velocimetry (PIV) technique to investigate hydrodynamic characteristics inside the membrane reactor. Chang et al. [14] experimentally investigated the effect of fiber diameter on filtration flux. Yoon et al. [15] optimized design parameters of vertically mounted submerged hollow fiber (HF) module. Nassehi et al. [16] coupled Navier–Stokes and Darcy equations together to illustrate the flow field in crossflow membrane filtration. Wang et al. [17] and Garakani et al. [18] reported CFD approach to simulate submerged and airlift MBRs.

In the present work, the performance of SMBR in treating dairy effluent was investigated using a laboratory-scale setup for a hydraulic retention time (HRT) of 10 h and a mixed liquor suspended solids (MLSS) concentration of approximately $5\,\mathrm{g\,L^{-1}}$. Experiments were conducted on this MBR containing 100 L feed sample and $0.07\,\mathrm{m^2}$ area of PVDF or PAN HF membrane modules. A study was conducted to compare the efficiency of hydrophobic PVDF and hydrophilic PAN membranes under aerobic conditions using mixed microbial consortia. The efficiency of COD and BOD removal, turbidity, TSS, pH was studied in order to investigate the system performance. The effect of different parameters such as suction pressure, air blowing rate and chemical cleaning on membrane fouling is discussed. A CFD based hydrodynamic simulation has been included in order to understand the operational performance of the module under different parametric conditions. The simulation study has been performed on a perfectly regular cylindrical unit cell using Happel's free surface model [19–22].

2. Materials and methods

2.1. Materials

Dimethyl formamide (DMF) and n-methyl-2-pyrrolidone (NMP) solvents, which are relatively environmentally benign, were procured from s.d. fine chemicals, Mumbai, India, polyvinylidene-fluoride (PVDF) and polyacrylonitrile (PAN) were supplied by Permionics Membranes Pvt. Ltd., Vadodara and Techno Orbital, Kanpur, India, respectively. Sigma–Aldrich grade polyethyleneglycol (PEG) and dextran were used for estimation of molecular weight cut-off (MWCO) of synthesized membranes. Deionized water for bore fluid was prepared in-house using the laboratory reverse osmosis (RO) system and tap water was used for gelation of HF membranes. Nutrient Broth, Nutrient Agar, Eosin Methylene Blue (EMB) Agar, McConkey Agar, Mannitol Agar were purchased from Hi-Media Chemicals, Mumbai, India. Soil sample, the source of inoculum was collected from Indian Institute of Chemical Technology (IICT), Hyderabad, India. Dairy effluent was collected from Vijaya Dairy Industries Pvt. Ltd., Hyderabad, India.

2.2. Hollow fiber spinning process

HF membranes were spun at room temperature (25–30 °C) by employing dry wet spinning technique. The spinning solutions were prepared separately from 18 wt% PVDF and PAN in DMF and NMP, respectively. The polymers were dissolved in respective solvents and stirred at approximately 60 °C for about 12–15 h to ensure complete dissolution of the polymer. It was ensured that the prepared polymer dopes were transparent and homogenous at room temperature (±25 °C) and the mixtures were then degassed overnight after charging into the reservoir and forced to the spinneret using pressurized nitrogen. The dope solution and the internal coagulant liquid were then forced through a tube-in-orifice spinneret; in such a manner that the polymer solution flowed through a ring nozzle while the coagulating fluid was fed through the inner tube [23]. Fig. 1 shows the process of the HF spinning method. The polymer solution was directly extruded into a coagulation bath at an air gap of 13 cm. Spinning conditions were kept constant as follows: the pressure applied on the spinning solution was about 3 bar and bore liquid flow rate was kept constant at $6.0\,\mathrm{mL\,min^{-1}}$. After spinning, HF was drawn out from the coagulation bath by a pulling motor at a speed of 30 revolutions per second (rps). The fibers were collected in a take-up drum and immersed in ethanol solution for about 24 h to replace water in membrane pores with ethanol that possesses a lower surface tension [24,25].

2.3. Fabrication of HF membrane module

The 'U' shaped twisted HF bundle made from hollow fibers possessing effective length of 60 cm each was introduced into the UPVC tube of 3.81 cm diameter and 30.48 cm length with one end potted by epoxy resin. A nylon rod was used for making end caps with provision for tube-side permeate flow through one end. The internal diameters of both PVDF and PAN HF membranes were 1.0 mm as