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Application of post-consumer recycled high-impact polystyrene in the preparation of phase-inversion membranes for low-pressure membrane processes

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ABSTRACT

In this study, recycled plastic waste was successfully used in preparing low-pressure membranes by phase-inversion method. These membranes are considered as an alternative solution for economical and environmental concerns, namely: water reclamation as well as polymer recycling and reuse. Post-consumer recycled high-impact polystyrene and virgin commercial high-impact polystyrene were separately used to prepare membranes, which were thereafter compared in terms of their respective characteristics and performance. N,N-dimethylacetamide and deionised water were used as a solvent and coagulant, respectively. Membranes were characterised by microscopic observations, contact angle measurements, thermogravimetric analysis, and filtration experiments. The recycled polymeric membranes presented similar thermal properties as the membranes made from commercial high-impact polystyrene, which were used as control membranes. They also obtained similar asymmetric membrane structures, however with slightly higher porosity (from 47.54 ± 5.53% for control membranes to 52.31 ± 4.33% for recycled polymeric membranes). The presence of additives in the recycled polymeric structure was confirmed by EDX results. Such additives made the membranes to become more hydrophilic, reducing the water contact angle value from 81.78 ± 3.42° obtained for control membranes to 79.19 ± 4.15°. Moreover, irreversible fouling was satisfactorily minimised and humic acid rejection was very slightly enhanced (from 95.5 ± 0.2 to 96 ± 0.1%). This indicates that the more hydrophilic the membrane is, the better antifouling properties it possesses. Thus, the results of the post-consumer recycled high-impact polystyrene suggest that they can provide a sustainable and environmental alternative when implemented in low-pressure membrane processes.

1. Introduction

Water scarcity is a serious environmental concern that affects the natural environment, wildlife and mankind due to the fact that water (especially freshwater) is the most fundamental natural resource for the development and survival of living organisms in the world [1]. Nowadays, the increasing environmental problems related to both climate change and human socioeconomic development have irretrievably modified the dynamic water cycle, which led to the degradation of ground and surface waters (affecting both health and biodiversity of aquatic and terrestrial environments) and therefore brought about a dangerous imbalance between demand and limited availability of freshwater [1–3]. It is very important to keep in mind that water is an unalienable individual and collective right for every living organism [4]. Therefore, the enormity of such problems obliges researchers to search for solutions and to implement sustainable and "clean" technologies and resources, which is significant in the 21th century. Treatment, reclamation and reuse of wastewater in a cost-effective manner would render wastewater a sustainable water resource that could help to alleviate the water shortage [5].

Currently, there is a growing concern over the environmental impact of the ever increasing use of plastic and the associated generation of plastic waste, particularly non-biodegradable and toxic by-products, which also present disposal challenges at the landfill [6]. Polymers are produced using petroleum as their principal feedstock and are one of the most widely used materials for several applications for industrial, agricultural and household activities, mainly due to their good mechanical properties, versatility, low

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Nomenclature

Variables

A_m	effective area of the membrane (m^2)
C_f	solute concentration in the feed stream (mg/L)
C_p	solute concentration in the permeate stream (mg/L)
FRR	flux recovery ratio (%)
J	permeate flux during the filtration process (L/m^2 h)
J_f	permeate flux at the end of the humic acid filtration (L/m^2 h)
J_r	permeate flux during the rinsing process (L/m^2 h)
J_W	permeate water flux/deionised water flux (L/m^2 h)
K	water permeability (L/m^2 h bar)
N	number of points within the given area (dimensionless)
Q_W	water flow (m^3/s)
R	solute rejection index (%)
R_{irr}	membrane irreversible resistance (m^{-1})
r_m	average pore radius (m)
R_m	membrane intrinsic resistance (m^{-1})
R_{rev}	membrane reversible resistance (m^{-1})
R_T	membrane total resistance (m^{-1})
S_a	average roughness (nm)
T	temperature (°C)
V	total volume permeated during an experimental time interval (L)
W_D	weight of dry membranes (g)
W_W	weight of wet membranes (g)
Z	height values of the surface sample (nm)
Z_{avg}	average of the Z values of the sample (nm)
Z_i	Z value currently measured (nm)
ΔP	transmembrane pressure (bar)
Δt	filtration time (h)

Greek letters

ε	membrane porosity (%)
ζ	membrane thickness (m)
μ	dynamic water viscosity (Pa s)
ρ_P	density of the polymer (g cm^{-3})
ρ_W	density of pure water at operating conditions (g cm^{-3})

Abbreviations

AFM	atomic force microscopy
DMA	N,N-dimethylacetamide
EDX	energy dispersive X-ray spectroscopy
EWC	equilibrium water content
FTIR-ATR	Fourier transform infra-red spectroscopy with attenuated total reflectance
HA	humic acid
HATR	high attenuated total reflectance
HDPE	high-density polyethylene
HIPS	commercial high-impact polystyrene
HIPS-R	post-consumer recycled high-impact polystyrene
NIPS	non-solvent induced phase separation
NOM	natural organic matter
PET	polyethylene terephthalate
PP	polypropylene
PVC	polyvinyl chloride
SEM	scanning electron microscopy
TGA	thermogravimetric analysis
UF	ultrafiltration

density and ease of processing. Like freshwater and other natural resources, petroleum is becoming scarcer and more expensive. As a result, new alternative sources with less environmental impact as well as more clean technologies should be considered for plastic production. In this regard, feasible sources could be biomass and natural gas; however they are currently not economic alternatives. Among the different ways to deal with plastic waste (which include combustion and burying underground, which are unfriendly environmental processes due to the formation of toxic gases and fumes as well as the pollution of surface and ground waters), plastic recycling is therefore often the best environmental approach and could be considered as an area of particular interest, especially for reducing the need to produce new plastics as well as other polymer based products [6,7]. Among the different plastics that can be recycled include polyethylene terephthalate (PET), polyvinyl chloride (PVC), polypropylene (PP) or high-density polyethylene (HDPE), these plastics are having different identification codes and they have been used in a wide range of applications, such as packaging, appliances, automotive components, toys, and electrical and electronic equipment. High-impact polystyrene is a multiphase copolymer system which is formed by polybutadiene rubber particles dispersed in a matrix structure of polystyrene [8]. Its main advantages include good impact resistance, ease of moulding and processing, stability and low cost.

In this work, membranes were developed via phase-inversion method from post-consumer high-impact polystyrene. The aim was to assess the feasibility of using recycled plastic material to prepare membranes which could be applied in microfiltration and ultrafiltration processes. The novelty of this study lies in the use of post-consumer high-impact polystyrene for preparing membranes which could be used for different water applications such as water reclamation, thus promising to provide environmental and economic benefits in a way.

2. Experimental

2.1. Chemicals and materials

Commercial high-impact polystyrene (HIPS, Polystyrol 476L, supplied by BASF Co., Germany) and recycled high-impact polystyrene (HIPS-R, supplied by Acteco S.L., Spain) were used as base polymers and N,N-dimethylacetamide (DMA) was employed as a solvent. The non-woven support was commercial grade Viledon FO 2431 (Freudenberg, Germany). Humic acid (HA) solutions with concentration of 50 mg/L (at pH 7) were used as common model foulants to study the antifouling ability of the synthesised membranes due to the fact that HA can be considered as the main component of the natural organic matter (NOM) present in surface and ground waters. Both DMA and HA were purchased from Sigma-Aldrich (Germany). The pH of feed solutions was adjusted using 0.1 M NaOH (Panreac, Spain). Deionised water was used throughout this study. Solvents and chemicals were used without further purification.

2.2. Membrane preparation

Membranes were prepared from homogeneous polymeric solutions (from HIPS and HIPS-R, separately) in DMA by the non-solvent induced phase separation method (NIPS). The composition of both polystyrene/DMA solutions was 20/80 wt%. Such solutions