



## A Review on the Separation of Volatile Organic Compounds from Wastewater by Pervaporation Processes

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### HIGHLIGHTS

- Pervaporation process (PV) is one of the membrane separation methods.
- The pervaporation process is part of a chain of water treatment processes.
- Various types of membranes were developed by adding different materials to improve membrane performance.
- Benzene and toluene were removed from the water via the pervaporation process.

### ARTICLE INFO

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### ABSTRACT

Pervaporation (PV) is one of the distinctive membrane separation processes harnessed for volatile organic compounds (VOCs) removal from water. The process is characterized by low cost, ease of installation, lack of chemicals, and operation at moderate temperatures. PV is part of a chain of water treatment processes and has eminent efficiency for pollutant removal, drying processes, and many others. The presence of benzene, toluene and their compounds at high concentrations in water are problematic due to their harmful effects on humans and the environment as many carcinogenic diseases may induce. The present review will investigate the efficiency of the PV process for separating VOCs from water such as benzene and toluene and the troublesome associated with the entire separation process. Besides, reviewing the recent advances in various membrane processes and membrane modification routes targeted to optimizing the process performance along with optimized operational conditions. Besides, reviewing the recent advances in various membrane processes and membrane modification routes targeted to optimizing the process performance along with optimized operational conditions.

## 1. Introduction

By 2050, the global population will already have multiplied by 40-50 percent. In parallel, there is a keen interest in water treatment processes in order to accommodate the increasing demand for drinking water [1]. The presence of VOC contaminants in any river water poses a serious threat to the ecosystem and must be tackled urgently. The removal of benzene, toluene, and their components poses a troublesome to water treatment scientists. Some chemicals, such as styrene, phenol, cyclohexane, aniline, and polyester resins, were prepared using a benzene compound. It is often used in the manufacture of drugs, dyes, insecticides, and plastics. Besides which, it is produced by refinery operations and mixes with the water used in these operations, where its concentration could indeed reach 16 ppm. Toluene, on the other hand, is a common solvent used in paints, glues, and printing ink. Toluene is produced during refinery operations and mixes with the water used in these operations, reaching concentration levels of up to 55 ppm. These benzene and toluene fractions are considered high and very dangerous to humans and the environment, having caused many carcinogenic diseases. Undoubtedly, these contaminants must be taken down mostly using advanced, efficient, and cost-effective methodologies. To produce items like refrigerants, plastics, adhesives, paints, and petroleum products, many industrial applications nowadays require organic solvents in their technological processes. [2-7]. Substantial quantities of VOC-contaminated water are generated often by various industrial processes, which are toxic to the environment and humans [7-10]. PV used to consider removing organic components from water can indeed be categorized into two types: hydrophilic pervaporation and organophilic pervaporation. There also is target organic pervaporation, which is used to separate organic matter from each other. VOC solubility in water is frequently very low, implying low concentration in water. Particularly, it does not make sense to use large and expensive processes to remove

these compounds, such as distillation, oxidation, biological treatment, and adsorption [11]. Where it is commonly used, regardless of high energy demand or azeotrope formation [10,12-17]. In comparison to certain other treatment methods, the distinguished advances of PV are considered a promising technology in treating diluted VOCs aqueous effluents of many industries. PV, in particular, is distinguished by the absence of emission issues, the absence of expensive regeneration steps, and low costs [18-20], as well as compact/modular designs and the potential of reusing recovered VOCs solvents [11].

This review focuses on recent advances in the PV process, the mechanisms that enable it, and other common hybrid separation processes. A state-of-the-art review was furnished for research dealing with PV technology applications targeting the removal of volatile organic compounds (VOCs), precisely benzene and toluene. Nonetheless, the potential for improving the specifications and characteristics of the separation membranes is harnessed in such processes.

### 1.1 Hydrophilic pervaporation

This technique involves separating water from an aqueous-organic mixture by passing it preferentially through a membrane where there is an affinity between the water and the membrane. For example, azeotrope breaking in binary mixtures [21-31], multi-component mixture dehydration (continuous and batch), and batch-wise dehydration in discontinuous processes.

### 1.2 Organophilic pervaporation

It is also renowned as hydrophobic pervaporation, and it takes place once hydrocarbon compounds are separated from an aqueous-organic mixture owing to the hydrocarbons' attraction to the membrane, where there is an affinity between the organic substance and the membrane. For example, wastewater treatment [32], separating organic material from ground and drinking water, separating alcohol from beer and wine, disposal of aromatic compounds in feed technology[33-35], removal of compounds from a fermentation broth in biotechnology, purification of 1-butanol from aqueous solution [36], and decarboxylation of beverages [37, 38].

### 1.3 Target organic pervaporation

This procedure entails the separation of organic matter from each other. For example, benzene separation from cyclohexane [32, 39], ethanol separation from ethyl-tert-butyl ether (ETBE) [40], xylene isomer separation [41], and toluene and heptane separation [42]. The results of the pervaporation processes at varying conditions and membranes can be seen in Table 1. VOCs can indeed be separated from water using multiple techniques such as adsorption, oxidation, and biological treatment [11]. Most conventional processes have drawbacks when it comes to separating VOCs. For example, in air stripping, water pollution could turn into air pollution. In adsorption, activated carbon must be generated which is a costly process. while advanced oxidation is only efficient for specific compounds and is very expensive and may form harmful byproducts while biological treatment needs to long time [2,13].The results for the pervaporation processes at different conditions and different membranes.

**Table 1:** The results for the pervaporation processes at different conditions and different membranes

Membrane	VOCs	T (°C)	Con.	Pressure	Flux (g/m <sup>2</sup> .h)	S.F	Ref.
(polydimethylsiloxane)PDM S +Lotus leave powder	Ethanol	45-60	6% wt	300 pa	1108	7.6	[43]
PDVB(polydivinylbenzene) coated PDMS	Ethanol	45-60	6% wt	300 pa	1423	10	
	Toluene				675 786	29 24	
polydimethylsiloxane membrane (PDMS)	Ethanol	40	5-25%wt	9-10 mbar	344 386	19 14	[44]
	Propanol				338 383	21 18	
		45	0.1%wt 0.7%wt	20 mbar	180 610	91 63	
Polyvinyl chloride	propyl acetate	35 65	0.3	20 mbar	210 710	98 32	[45]
		45	0.3	2 mbar 65 mbar	120 1570	11 158	
PDMS				@	11	10	
PDMS_plasma_C8 membrane (PDMS).-NaCl				@	8	7	
PDMS_Al <sub>2</sub> O <sub>3</sub> _nat		30	5%wt	@	13	11	
PDMS_Al <sub>2</sub> O <sub>3</sub> _mod_C8				@	10	10	[46]
PDMS/PVDF				@	21	11	
Pervap™4060	Ethanol			@	8	9	
				@	201	9	

Table 1: Continued

Membrane	VOCs	T (°C)	Conc.	Pressure	Flux (g/m <sup>2</sup> .h)	S.F	Ref.
Polydimethylsiloxane- 3-aminopropyltriethoxysilane (APTS) and 3-triethoxysilylpropyl)ethylenediamine (TSED)		40	10%wt	20 kpa	234	12	[47]
PDMS	acetonitrile	40	5913 ppm	4-15 mbar	31.56	28.2	[48]
PDMS	phenol	40	0.5%wt	200 pa	4	15	[49]
PDMS + oleyl alcohol (5%)		70			7	3	
					3	3.5	
					11	6.5	
ZSM-5 zeolite filled polydimethylsiloxane (PDMS) composite membranes with Nylon micro-filtration membrane as the support layer	Acetaldehyde	25	8 %wt	@	2333.3	35	[50]
PDMS	Styrene	30	20ppm 300ppm	1mmHg	3 12	493 812	[51]
PEBA ( polyamide and polyether)	MTBE	30	4 %wt 8 %wt	0.3 mbar	300 900	66 63	[52]
Pervap® 4060	Acetone	30 60	0.5 %wt 10 %wt	5.5 kpa	2.7 9	41 37	[53]
B-ZSM-5	Ethanol	60	5%wt	@	243	31	[54]
Ge-ZSM-5	Ethanol	30	5%wt	@	317	47	[55]
Silicalite-1	Ethanol	30	10 %wt	@	133	31	[56]

Conc. (Concentration); @ (unknown); S.F. (Separation Factor)

This review research focuses on the pervaporation process for separating VOCs such as benzene and toluene from water, including the different types of membranes used for this purpose and different working conditions such as temperature, pressure, flow rate, and concentration.

## 2. Hybrid processes

Pervaporation is a membrane technology that can be exploited in a wide range of industries. However, it is typically used as an integrative process to improve process efficiency. Three industrial examples of integrated systems requiring pervaporation are organic dehydration, organic removal from aqueous solutions, and organic-organic separations. Dehydration of organic materials The use of a hydrophilic membrane was the first practical application of pervaporation to dehydrate organic solvents. This is still the most widely applied application for pervaporation. In the chemical and petrochemical industries, for example, integrating distillation and pervaporation is the perfect way to perform dehydration or debottleneck challenging separations. A bioreactor or reactor can also be equipped with hydrophilic membranes to remove byproduct water [57-61]. Other researchers focused on combining PV and molecular sieves to continue improving the ethanol drying process [62].

The extraction of organics from aqueous solutions is a more recent application of pervaporation than the extraction of organic species with low solubility in water. Examples encompass integrated fermentation-pervaporation systems for bioalcohol recovery. Most researchers have examined combining fermentation with separation technologies such as distillation, a common but often inefficient strategy, solvent extraction, gas stripping, adsorption, and pervaporation. Pervaporation has several advantages, including clear product separation and no heat, chemical, or mechanical stress on microorganisms. Combining fermentation with environmentally and economically advantageous membrane methods for alcohol removal [63] Pervaporation is thus recognized as a powerful method for the on-site separation, concentration, and purification of bioreaction products in modern industrial-scale biotechnology [64]. Figure (1) depicts a combined fermentation-pervaporation system [65].

To recover alcohols in fermentation-pervaporation systems, a variety of hydrophobic membranes were used, including ceramic membranes, polytetrafluoroethylene, polyvinyl alcohol (PVA), polypropylene, and (PDMS) [66].

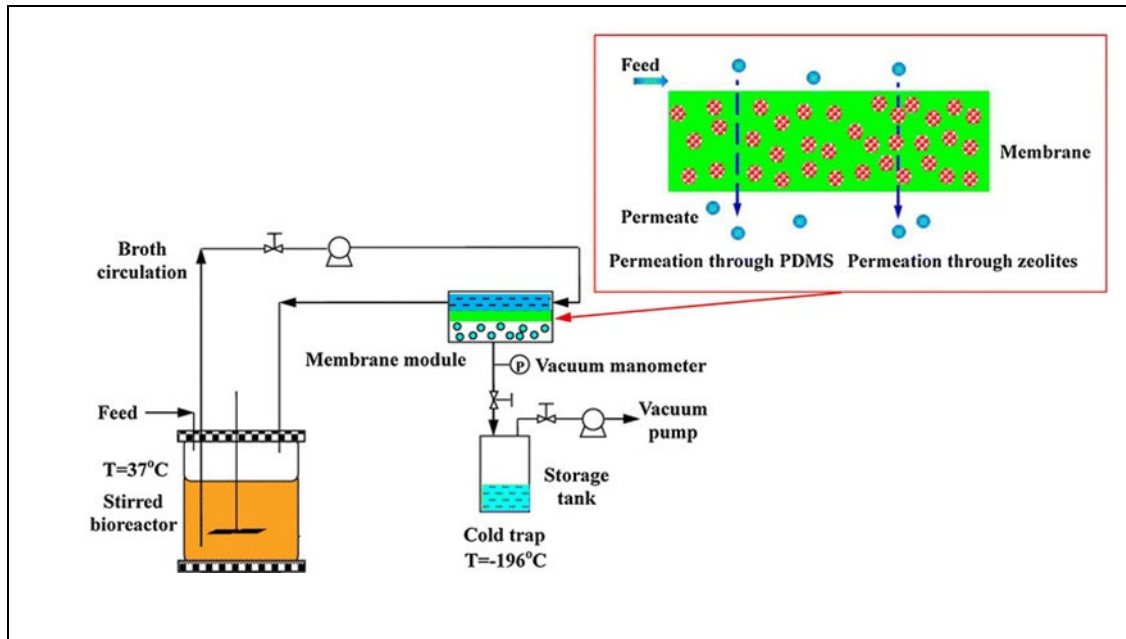


Figure 1: Integrated fermentation-pervaporation system [65]

Sosa and Espinosa [60] employed a hybrid distillation-pervaporation approach to perform a techno-economic feasibility study on isopropanol recovery from a stream comprising 95.64 weight percent isopropanol and 4.36 weight percent water. To accomplish this, a commercial hydrophilic membrane is used to pervaporate the feed stream, resulting in a 99.7 percent pure alcohol retentate stream. To compensate for isopropanol losses in the permeate stream, a distillation procedure is used. Szitkai et al. [67] propose yet another hybrid distillation-pervaporation procedure for ethanol separation. It includes a pervaporation unit for producing pure ethanol after a distillation column near the ethanol/water azeotrope is used for preliminary separation. As a matter of fact, the integration of distillation and pervaporation processes can be used in two scenarios: first, pervaporation-distillation to reduce ethanol loss, and second, distillation-pervaporation to achieve high product purity. The proposed integrated system's layout is depicted in Figure (2).

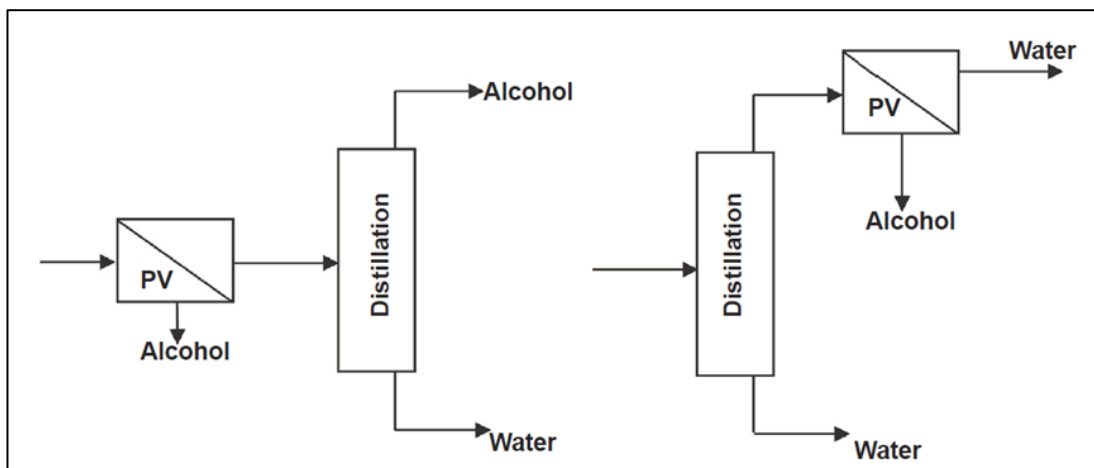


Figure 2: Integrated distillation-pervaporation system configurations [66]

Haelssig et al. [68-69] proposed membrane dephlegmation, a hybrid pervaporation-distillation method that strengthens the recovery of ethanol produced by fermentation. They combined the two procedures into a single system, substituting a dehydration membrane device for the rectifying column. Commercial tubular NaA zeolite membranes with a selective layer inside the tubes were used to provide a workable shape for the technique. Figure 1 depicts a schematic representation of the ethanol separation process (3). This study investigated the effectiveness of separation concerning feeding flow rate, feed concentration, permeate pressure, reflux ratio, membrane length, and membrane diameter. A mathematical model was used to explain the transport processes that occur in the hybrid process.

For wastewater treatment and environmental protection, many integrated distillation-pervaporation-adsorption systems and integrated photocatalyst-pervaporation systems were used [5, 70-73]. Camera-Roda et al. [73] used titanium dioxide ( $\text{TiO}_2$ ) powder in a photocatalyst-pervaporation hybrid process to remove 4-Chlorophenol from water. Figure (4) depicts this process [74].

PV is now used in industrial organic-organic separations, particularly in the chemical and petrochemical industries. A cutting-edge application in this field alleviates concerns about  $\text{SO}_x$  emissions in the atmosphere while also being associated with the petrochemical sector. A novel method of pervaporating sulfur from gasoline will improve desulfurization. Pervaporative separation, on the other hand, may lead to a method of producing gasoline that complies with environmental regulations for ultra-low sulfur fuels[75-76].

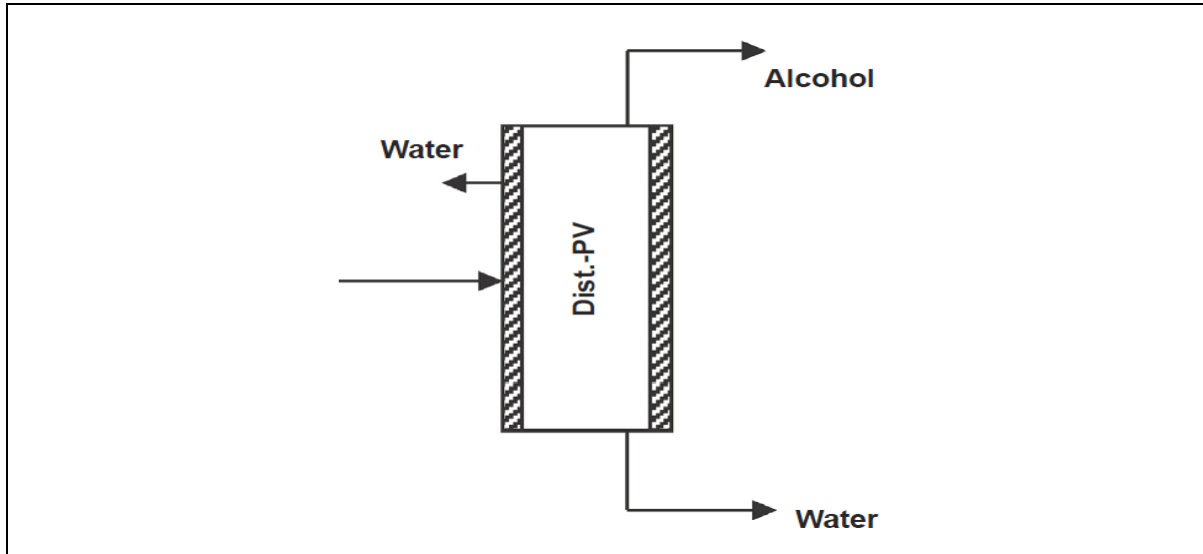


Figure 3: The pervaporation and distillation in one unit [66]

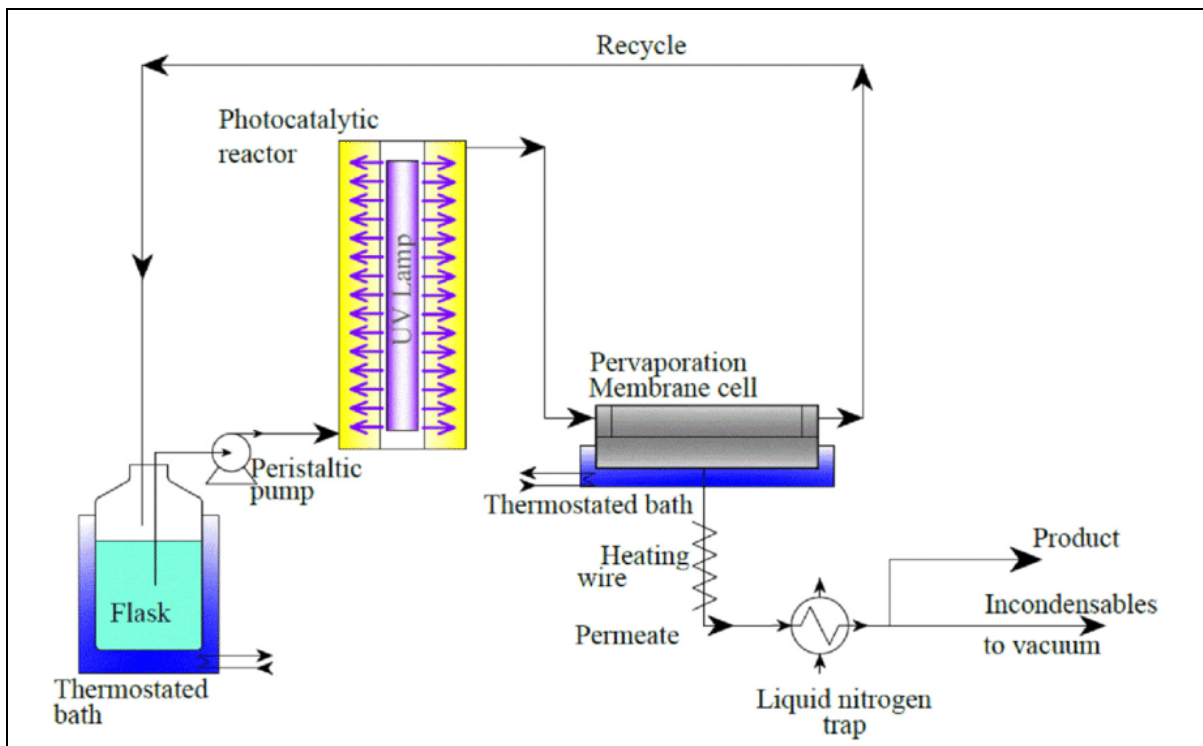


Figure 4: Photocatalyst –pervaporation hybrid process [74]

### 3. Pervaporation mechanism

Pervaporation is a membrane separation process that, like reverse osmosis, dialysis, and electrodialysis, is distinguished by the presence of two phases, the liquid phase on the upstream and the gas phase on the downstream, which is formed as a result of the use of vacuum pressure. A liquid stream of two or more components in direct contact with one side of the membrane and a vacuum or sweep gas flow to the other side of the membrane in the cells that are commonly used in PV, sorb into the membrane, permeate through it, and evaporate into the vapour phase. Outside of the cell, the vapour condenses. The main driving force for PV is the chemical potential difference of each species across the membrane, and the concentration difference of each component is frequently conveniently approximated [11].

The membrane used in the separation process is non-porous, and the process's success is dependent on the interaction between the membrane and the material passing through it, as illustrated in Figure (5a) [77].



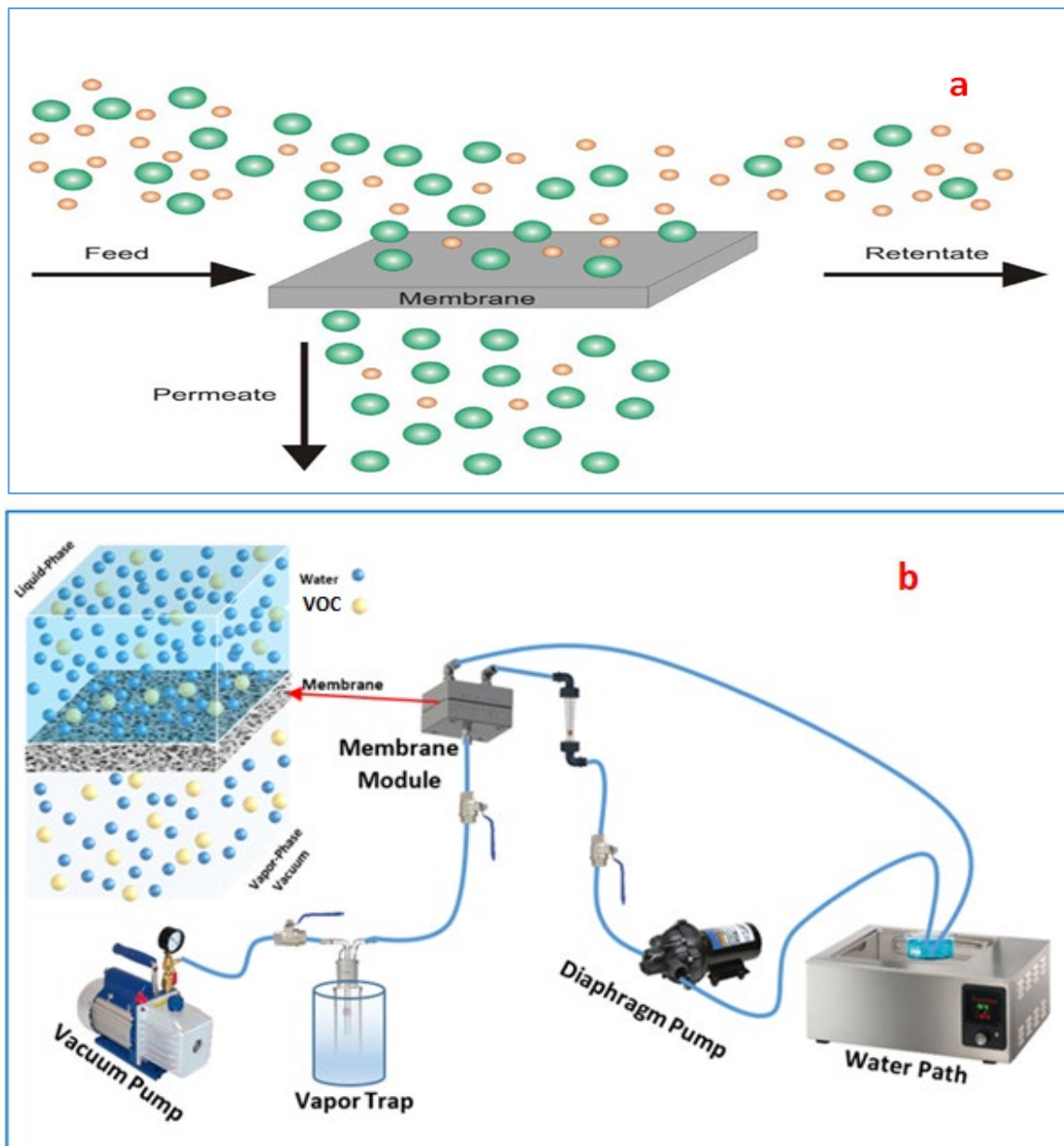


Figure 5: (a) Pervaporation process (b) Schematic diagram of the pervaporation process [77]

In general, the pervaporation tests were carried out using a laboratory scale device, as shown in the schematic diagram in Figure (5b), in which a specific volume containing a mixture of water and volatile organic compounds was prepared in a glass flask, and to control the temperature, the flask was immersed in a thermo digital water bath set to different temperatures, and the mixture was then pumped into the membrane cell. A vacuum pump designed for this purpose was used to control the vacuum pressure in the downstream section of the cell. All permeability samples were collected in a vapour trap immersed in a liquid nitrogen medium. Figure (6) [78] describes two designs for the pervaporation process.

### 3.1 Solution Diffusion Mechanism

Pervaporation procedures employ non-porous membranes that rely on a three-step solution diffusion mechanism. The first step is sorption, in which the target substance adheres to the membrane surface. The molecules can then pierce polymeric chains in the second step, diffusion. The second step is determined by the membrane's affinity for the species. Desorption is the third step, in which the material's phase changes from liquid to vapour due to the downstream vacuum pressure [79-81].

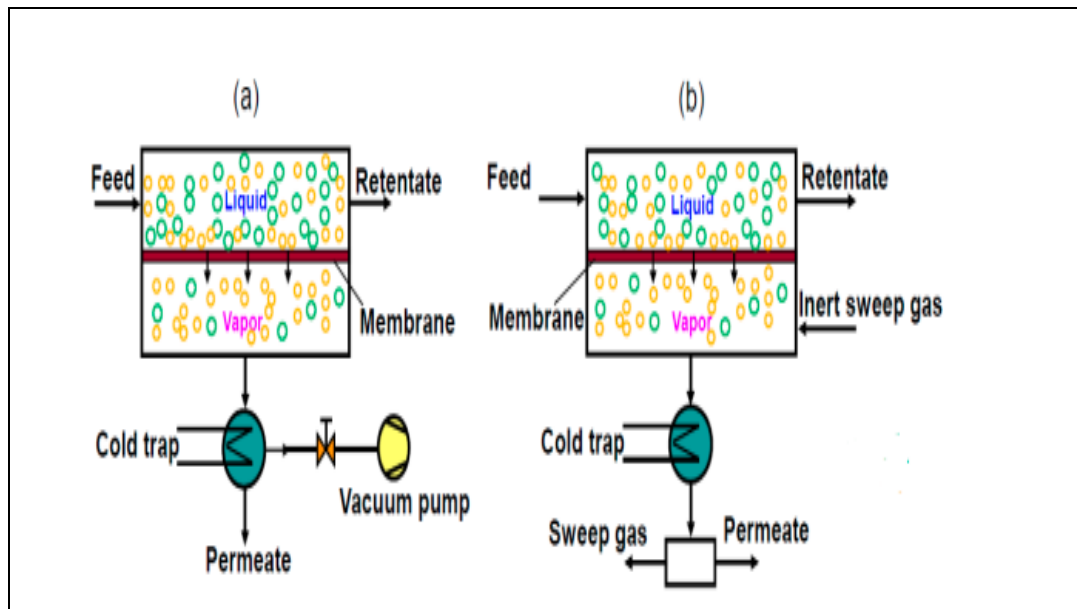


Figure 6: (a) vacuum pervaporation, (b) sweep gas pervaporation [78]

### 3.2 Preferential Sorption-Capillary Flow (PSCF) Mechanism

This mechanism is based on a porous membrane, in which the target substance is transported from upstream to downstream via tiny capillary channels and then evaporates due to vacuum pressure [82-83]. The size and distribution of the pores in the membrane, the molecular size of the target substance, and the interaction between the membrane and the target substance all influence this mechanism.

Many scientists worked tirelessly to improve the type of membrane and increase flux and selectivity across the membrane. In general, two parameters are used to evaluate membrane performance in pervaporation processes: flux and separation factor. Flux is defined as the rate of target material transfer through a unit area of the separation membrane over a given time period.  $\text{Kg/m}^2.\text{h}$  and  $\text{g/cm}^2.\text{s}$  are two frequently used flux units in pervaporation processes. Selectivity in the system, on the other hand, is composed of two substances (a and b), such as water-benzene or water-toluene, and can be defined as the ratio of the mole fraction of the components in the permeate to that in the feed:

$$\alpha = \frac{y_a/y_b}{x_a/x_b} \quad (1)$$

where  $\alpha$  is selectivity,  $y_a$ ,  $y_b$ ,  $x_a$ ,  $x_b$  are the mole fraction in the permeate (y) and the feed (x) [84].

### 4. Separation Benzene –Water

The hexagonal cyclic structure  $\text{C}_6\text{H}_6$  of the volatile chemical benzene is depicted in Figure (7). It is a flammable liquid that is non-polar and colourless, with excellent thermal stability specifications as shown in Table (2).

Table 2: Physical properties of benzene [85]

Physical properties of benzene	
Freezing point, °C	5.533
Boiling point, °C	80.100
Density at 25°C ( $\text{g/cm}^3$ )	0.8737
Refractive index	1.49792
Viscosity (absolute) at 20°C (cP)	0.6468
Surface tension at 25°C (dyn/cm)	28.18
Critical temperature (°C)	289.45

Styrene, phenol, cyclohexane, aniline, polyester resins, alkylbenzenes, and chlorobenzenes are all made from benzene. Benzene is also used in the production of drugs, dyes, insecticides, and plastics [86]. Furthermore, the benzene compound is produced by refinery operations and mixed with the water used in these operations, where its concentration can reach up to 16 ppm [87]. This percentage is considered high and very dangerous to humans and the environment, as it causes many carcinogenic diseases [88]. As a result, it must be disposed of before being thrown into the river.

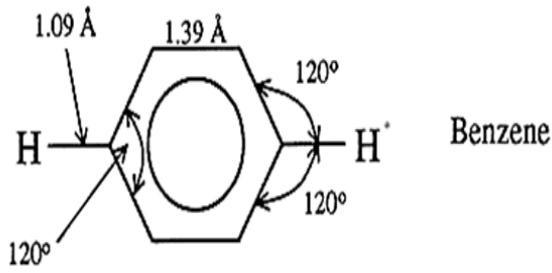


Figure 7: Benzene molecule

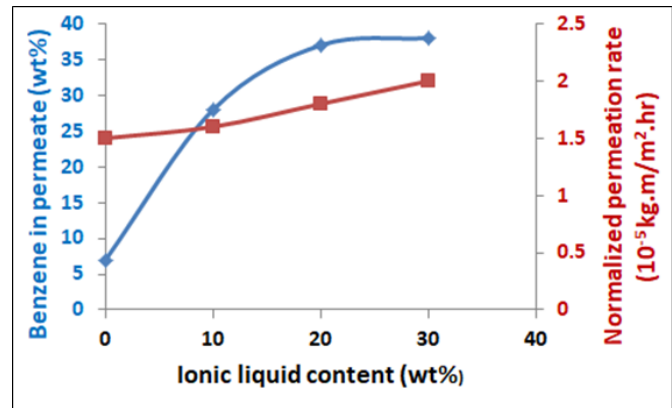


Figure 8: Effects of the ionic liquid content on the normalized permeation (■) and benzene concentration in the permeate (■) through the PVC and [ABIM] TFSI/PVC membranes during PV [89]

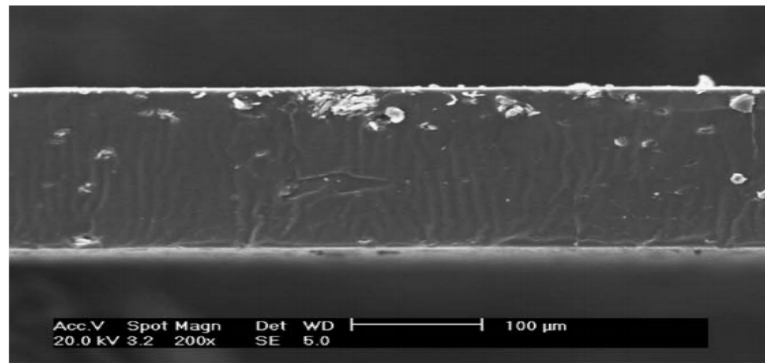
Uragami et al. [89] separated benzene-water using two distinct membrane types, the first of which is polyvinyl chloride (PVC), in operating conditions of 40°C, 1.33 Pa, 500 ppm benzene concentration, 13.8 cm<sup>2</sup> active area, 1.3910<sup>-5</sup> kg/m<sup>2</sup>.hr normalized permeation rate and 8.1 wt percent benzene in the permeate. The second contained polyvinyl chloride and 1-allyl-3-butylimidazolium bis (trifluoromethane sulfonyl imide [ABIM] TFSI, an ionic liquid with a high affinity for VOCs but a low affinity for water. The normalized permeation rate under the same conditions was 1.9110<sup>-5</sup> kg.m/m<sup>2</sup>.hr, and the permeate contained 38.4 wt percent benzene, as shown in Figure (8). Wu et al. [90] employed a novel composite made of (Calixarenes) CA-filled polydimethylsiloxane (PDMS) to construct 4 distinct membranes to remove benzene from an aqueous solution. The pervaporation process was carried out at a temperature of 60°C, a pressure of 1-10 kPa, a benzene concentration of 0.14 wt percent, and an active area of 25.6 cm<sup>2</sup>. The first was a (PDMS) membrane with a flux of 0.126 kg/m<sup>2</sup>/hr and a separation factor of 3302. The second membrane was the CA-f-PDMS membrane, with a flux of 0.116 kg/m<sup>2</sup> hr and a separation factor of 5604. The third was PDMS combined with non-woven fabric to create a composite membrane with a flux of 0.365 kg/m<sup>2</sup> hr and a separation factor of 4600. The fourth membrane was a CA-f-PDMS composite membrane with a flux of 0.407 kg/m<sup>2</sup>.hr and a separation factor of 5913. Figure 9(a-c) depicts the membrane structures in various cases.

Peng et al. [91] separated benzene from water using a polydimethylsiloxane (PDMS) membrane at temperatures ranging from 30 to 60 degrees Celsius. There was a vacuum pressure of 0.2 kPa. The benzene concentration was increased from 250 to 750 ppm, and the active area was reduced to 28 cm<sup>2</sup>. Based on the solution-diffusion mechanism, they used a mathematical model to predict mass transfer through the membrane. Figure (10) depicts the relationship between benzene concentration and total flux in the experimental and predictive models. Figure (11) depicts the effect of benzene concentration on the separation factor in the experimental and predictive models.

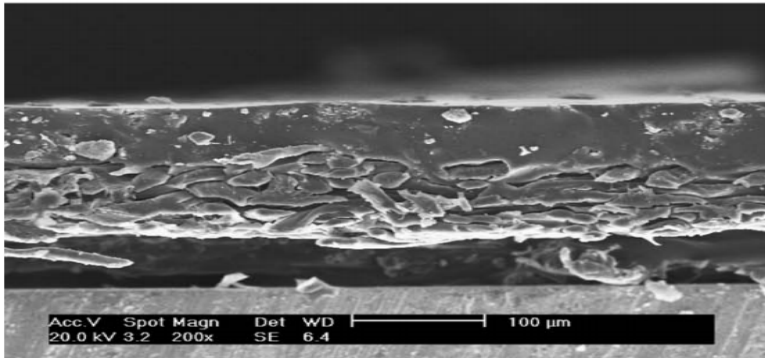
At low feed concentrations, both the predictions of the proposed mathematical model to explain total flux permeation and the separation factor showed remarkable agreement with the experimental data obtained, as shown in the figures above. It is also noticed that as the concentration of benzene increases, so does the factor of inaccuracy. It can be argued that these inaccuracies are due to the experiment failing to reach the assumed swelling equilibrium. As a result, the volume fraction of the components on the membrane's surface was overestimated by the model. In fact, it is simple to achieve a swelling equilibrium, especially at low benzene concentrations, and thus the predicted and experimental data can typically agree, whereas, at higher concentrations, the non-equilibrium is more obvious, leading to an increase in computation error [91].

Uragami et al. [92] used polydimethylsiloxane with different cross-links to separate benzene from benzene-water at a temperature of 40°C, a vacuum pressure of 0.01mmHg, a benzene concentration of 500 ppm, and an active area of 13.8 cm<sup>2</sup>. In this research, dimethyl methacrylate macromonomer, divinylbenzene (DVB), divinylsiloxane (DVS), and ethylene glycol dimethyl methacrylate (EGDM) were used. Table (3) shows the results of pervaporation processes used to separate benzene compounds from water under various conditions and with multiple membranes.

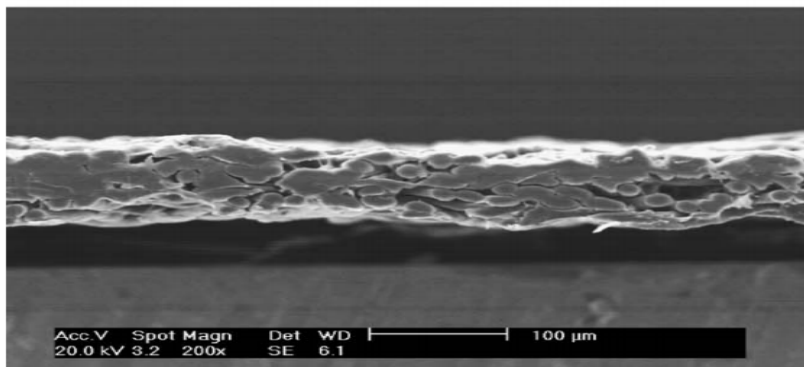




(a) Cross section of CA-f-PDMS membrane.



(b) Cross section of CA-f-PDMS composite membrane.



(c) Cross section of the non-woven fabric.

**Figure 9:** (a) CA-f-PDMS membrane, (b) CA-f-PDMS composite membrane, and (c) non-woven fabric [90]**Table 3:** Pervaporation process results and conditions for benzene separation from aqueous solution

Membrane	T (°C)	Con.	Pressure	Flux (g/m <sup>2</sup> .h)	S.F	Ref.
PDMS				0.126	3302	
Calixarene (CA) filled PDMS				0.116	5604	[90]
PDMS with non-woven fabric				0.365	4600	
CA-f-PDMS composite membrane						
PDMS	60	0.14wt%	1-10kpa	0.47	5913	
PDMS poly(dimethylsiloxane) dimethyl methacrylate macromonomer (PDMSDMMMA)	30-60	250-750ppm	0.2kpa	100-180	15000-8000	[91]
PDMS - Divinylbenzene (DVB) Cross-Linked				0.0514	1853	
PDMS -divinylsiloxane (DVS) Cross-Linked	40	500	0.01mmHg	0.0455	3099	
PDMS -ethylene glycol dimethyl methacrylate (EGDM) Cross-Linked				0.0709	2886	
				0.0496	2011	[92]

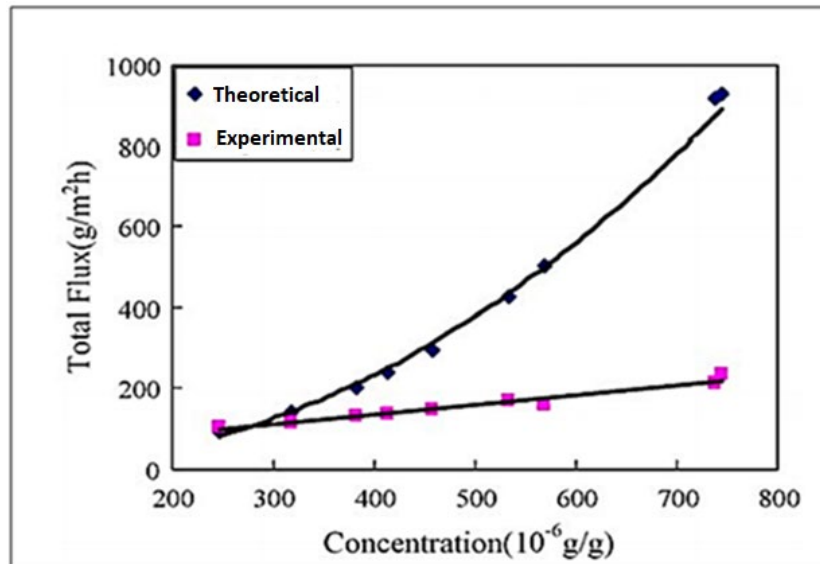


Figure 10: The relation between the benzene concentration in feed and the total flux in experimental and predicted [91]

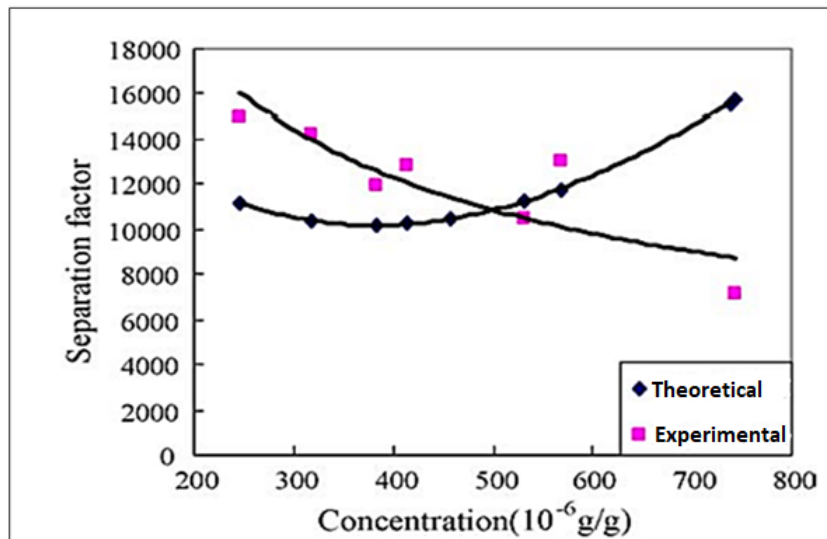


Figure 11: The relation between the benzene concentration in feed and separation factor in experimental and predicted [91]

## 5. Separation Toluene – Water

Toluene is a clear, colorless liquid with the chemical formula  $\text{C}_6\text{H}_5\text{CH}_3$ . Toluene is more reactive than benzene due to the presence of a methyl group. Table 1 shows the specifications (4).

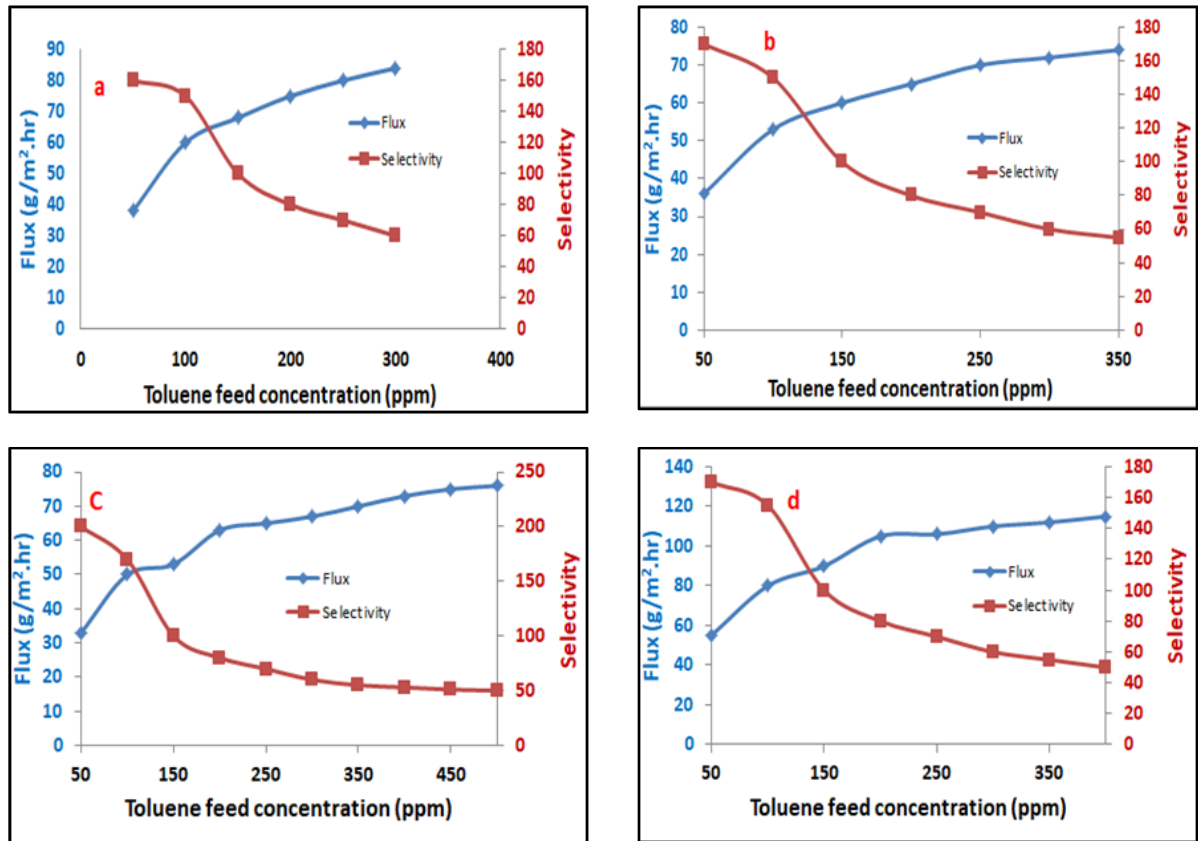
Table 4: The physical properties of toluene

Physical properties of Toluene	
Melting point of Toluene	-95 °C
Boiling point	111 °C
Density at 25°C (g/ml)	0.87 g/mL
The molecular weight of Toluene	92.141 g/mol
Refractive index	1.497 (20 °C)
viscosity	0.590 cp (20 °C)
Solubility in water	0.52 g/L (20 °C)

Toluene is a widely used solvent in paints, glues, printing ink, and leather tanners [93]. Toluene is produced during refinery operations and mixes with the water used in these operations, reaching concentrations of up to 55 ppm [87].

Hamouni et al. [44] separated toluene-water employing polydimethylsiloxan (PDMS) at a temperature of 40 °C, a pressure of 9-10 mbar, a concentration of 5 -25 wt percent, and an active area of 46.55 cm<sup>2</sup>. The separation factor was 29-24, and the flux was 0.675-0.786 kg/m<sup>2</sup> hr. Matavos et al. [94] used pure polyether-block-amide (PEBA) membranes with different thicknesses (25, 50, and 75 m) and PEBA/2 wt. percent NaX nanozeolite at 25 °C, 1 kPa, 50-400 ppm concentration, and 24.6 cm<sup>2</sup> active area. The outcomes are depicted in Figure (12) and Table (5).

Figure (12) depicts the relationship between the toluene concentration in the feed (a, b, and c) and the flux, permeation selectivity at different membrane thicknesses, and (d) PEBA/2 wt. percent NaX (d 50 μm) [94].



**Figure 12:** The relation between the toluene concentration in the feed and (a,b,c)the flux, selectivity in the permeation at a different thickness of the membrane and (d) PEBA/2 wt.% NaX (d 50μm) [94]

Salehi et al. [95] used polydimethylsiloxan (PDMS) + polyethersulfone (PES) as a composite membrane at 30-50°C, 1 mbar pressure, toluene concentration of 150-300 ppm, and an active area of 10 cm<sup>2</sup>. The flux was 0.0035 -0.0075 kg/m<sup>2</sup>/hr, and the separation factor was 1300 -2200. Chovava et al. [96] examined the effect of vacuum pressure on the performance factors in the pervaporative removal of toluene from water utilising polydimethylsiloxane (PDMS) membranes, zeolite silicalite (CBV) 3002-filled PDMS, dense styrene-butadiene-styrene (SBS), and porous SBS membranes. Under 25 °C, with an active area of 8.81 cm<sup>2</sup>. Table 1 shows the results (5).

Panek and Konieczny [97] used polyether-block amide (PEBA) membrane and polyether-block amide (PEBA)+ carbon black at 25°C, 100 Pa, 500 ppm concentration, 1.77 l/min flow rate, and 100 cm<sup>2</sup> active area. The separation factor for the polyether-block amide (PEBA) membrane was 1500 and the flux was 0.0132 kg/m<sup>2</sup>.hr. The flux for polyether-block amide (PEBA)+ carbon black was 0.01614 kg/m<sup>2</sup>/hr, with a separation factor of 900. Panek and Konieczny [98] used polydimethylsiloxan (PDMS) with carbon block (cb) under the same conditions as above, with a flux of 0.01732 kg/m<sup>2</sup>.hr and a separation factor of 300, and (PDMS) alone, with a flux of 0.01827 kg/m<sup>2</sup>.hr and a separation factor of 160. Nijhuis et al.[99] kept separate the toluene-water solution using only a polydimethylsiloxan (PDMS) membrane and revealed that the flux of water decreased as the thickness of the membrane rose, with the flux of water changing from 0.051 to 0.006 kg/m<sup>2</sup>.hr and the flux of toluene shifting from 0.020 to 0.013 kg/m<sup>2</sup>.hr. As a consequence of this practical experience, it became clear that the flux of toluene is affected less than the flux of water as the thickness of the membrane increases. However, by using ethylene propylene rubber and polyoctenamer membrane (EPDM), the water flux increased from 0.0009 to 0.00017 kg/m<sup>2</sup>.hr and the toluene flux changed from 0.0085 to 0.0035 kg/m<sup>2</sup>.hr.

**Table 5:** Pervaporation process results and conditions for toluene separation from aqueous solution

Membrane	T (°C)	Con.	Pressure	Flux (kg/m <sup>2</sup> .h)	S.F
PDMS	40	5-25wt%	9-10 mbar	0.675-0.786	29-24
PEBA Thickness 25 µm.				0.040-0.070	80-60
PEBA Thickness 25 µm.				0.037-0.160	85-50
PEBA Thickness 25 µm.	25	50- 400 ppm	1 kpa	0.032- 0.240	65-50
PEBA/2 wt.% NaX nanozeolite at thickness 50 µm.				0.055- 0.150	130-50
PDMS+ PES PDMS	30-50	150-300 ppm	1 mbar	0.0035- 0.0075	1300-2200
Zeolite silicalite (CBV) 3002 filled PDMS	25	250 ppm	1,15,40 mbar	0.220, 0.190, 0.160 0.330, 0.300, 0.260	3283 ,4680, 9921 5676, 8523, 18967
Dense styrene-butadine-styrene (SBS)				0.570, 0.560, 0.540	5650, 7196 , 1879
Porous SBS				1.170, 1.000, 0.600	885 , 1571, 4238
PEBA	25		100pa	0.0192	1500
PEBA+ carbon black		500 ppm		0.0164	900
PDMS + Carbon black	25	500 ppm	100pa	0.01732	
PDMS				0.01827	300 160

## 6. Conclusion and future work

Pervaporation is an efficient separation process, particularly when dealing with low concentrations. The PV process is now widely used across the world, particularly for breaking azeotropes in binary mixtures. It is distinguished by its ease of installation and low power consumption. The work on the separation of volatile organic compounds (VOCs) using this separation process is still in the early stages of development. Overall, pervaporation as a membrane technology is a wise option for separation, concentration, and purification applications. It is a cost-effective method for separating organic and inorganic materials, dehydrating polar compounds, and extracting organics from aqueous solutions. Using additional processes as pre- or post-treatments, on the other hand, is the preferred method (operation) for a given task. Due to the need to dispose of VOC, particularly benzene and toluene, which are carcinogens and harmful to public health, international membrane manufacturing companies are working on producing membranes with high flux and separation factors. Furthermore, increasing mechanical resistance by adding two supporting layers to prevent swelling, which leads to separation failure.

### Author contribution

All authors contributed equally to this work.

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### Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

### Conflicts of interest

The authors declare that there is no conflict of interest.

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