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Research article

Sustainable ceramic membrane for decontamination of water: A cost-effective approach

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ABSTRACT

A sustainable ceramic membrane embedded with silver has been developed using quartz, kaolin and calcium carbonate. All the chemicals involved in this process were commonly available, non-toxic and cheap. The process was very simple, convenient and does not involve any wastage of water. Decoration of silver particles onto the porous ceramic membrane with the help of APTES as a connecting molecule leads to the formation of a durable material having strong antibacterial capacity. The fabricated membrane holds wide pore morphology with pore size of 4.4 μm and average porosity of 19.5% with an estimated cost of fabrication of about 60 dollar/m^2. The membrane was found capable in reducing the TDS, BOD and COD of water samples that confirms that it is efficient for water treatment applications.

1. Introduction

World's first and foremost medicine is pure water. Four important characteristics quality, quantity, reliability, and cost makes any purification method effective. Water acts as the regulator of all body functions. Various developing and undeveloped countries are going with the problem of impure drinking water and facing many water borne diseases. Impure water causes various critical diseases which might not be noticed immediately but long-term exposure has been led to cardiovascular and other diseases [1,2]. A sustainable and cost-effective supply of clean drinking water is one of the major needs of living beings. Several practices have been developed for water purification including both physical and chemical methods [3–7]. Membrane technology is best one for elimination or reduction of various salts, bacteria and heavy metals. In present time various water treatment technologies such as reverse osmosis, UV disinfection, media filtration and demineralization are in trends, but again there is an issue with its capital cost, operating cost, and wastage of water for purification [8]. For portable water, this process is not cost effective one. Therefore, there is a need to find economic and effective water treatment methods. Appropriate water treatment technology can be developed using membrane technology or nanotechnology. Low-cost polymeric membranes have been applied for bacterial removal from portable water [9]. The drinking water production which basically aims at removing turbidity in the form of suspended and colloidal material involves a variety of chemicals. In recent times, there is a wide application of aluminum salt and synthetic organic polymer such as polyacryl amide derivatives and polyethylene amine for water treatment [10,11]. These organic polymers contain residual monomers which are highly undesirable because of their neurotoxicity [12–14]. Ceramic membranes are favorable over these polymeric membranes because they have longer life with less replacement and lower operational cost [15]. Ceramic membranes are made up of inorganic materials and have shown

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extreme potential applications in tough conditions also such as high temperature, extreme pH values etc. [16–18]. In the last decade, researchers have explored various types of low-cost ceramic membranes for water treatment applications [19–22].

However, the development of sustainable, cost-effective and energy efficient technology for water purification in rural areas is still challenging. Due to its high mechanical stability, cost effectiveness, and chemical and thermal stability, kaolin based ceramic membrane proved to be very effective for making ceramic membrane [23]. Since quantity and quality of water, both are equally important. There are limitations in every individual treatment technology, so water purification system in rural areas is chosen according to affordability, acceptability, and raw water characteristics. Therefore, we can assume that ceramic membrane coated with silver will prove to be a cost-effective and efficient membrane for portable water purification in rural areas.

2. Experimental

2.1. *Material selection*

Raw material selected for this work includes kaolin, quartz and calcium carbonate in a fixed ratio of 2:1:1 g respectively. Kaolin and Quartz were procured from CDH India. Calcium carbonate was collected from SRL India. These three raw materials used in present work for preparation of membrane served for their special characteristic properties. Kaolin helped in giving low plasticity and high refractory properties to the membrane. Quartz was used to increase mechanical strength and thermal stability of the membrane and calcium carbonate as a pore forming agent. Analytical grade $AgNO_3$ (99.8%, SRL), ethylene glycol (99%, Renkem), polyvinylpyrolidone (PVP K90, CDH) and 3-aminopropyltriethoxysilane (APTES) aqueous solution (98%, SRL) were used as reactants for the coating of membrane with silver. All these raw materials were used as received.

2.2. *Preparation of membrane*

The whole mechanism for this purpose included mixing, powdering, sieving, hydraulic pressing, drying, sintering of the raw material to get the desired membrane. The membrane was prepared using a well-defined method [24]. Quartz, kaolin and calcium carbonate were used in different ratios for different membranes. These raw materials were mixed in a ball mill at 40 rpm for 20 min, then the resulting powder was sieved using 30 mesh standard screen. The required amount was then pressed in a stainless-steel mold to get a disk-shaped membrane. Hydraulic pressure in the range 20–40 MPa was given for the membranes. Ceramic membranes of diameters 40 mm with different heights were prepared. Then the prepared membranes were dried for 24 h at 110 °C for complete removal of loose moisture. The membranes were finally sintered at a temperature between 900 and 1000 °C for 6 h in a muffle furnace with a heating rate of 2 °C/min. To obtain a flat surface, the membrane was polished using silicon carbide abrasive paper.

2.3. *Fixation of silver nanoparticles to the membrane*

Synthesis of colloidal solution of silver nanoparticles was performed using a reported method [25]. The process involved firstly the formation of $AgNO_3$ and polyvinylpyrolidone (PVP) solutions separately in 10 ml ethylene glycol. For this purpose, $AgNO_3$ (0.017 g) and PVP (0.022 g) were used, and the solutions were vigorously stirred for 10 min. The $AgNO_3$ solution was then drop-wise added to PVP solution and the product solution was vigorously stirred for 4 h at room temperature. A brownish colored colloidal solution of silver was obtained. Originally, membrane's surface channels were reformed with amino group by immersing it in a 1% ethanol solution of APTES for 30 min at room temperature. Then the porous ceramic membrane was washed with ethanol and treated in a vacuum oven at 100 °C for 2 h to allow full condensation of APTES molecules onto the membrane.

Now this porous ceramic membrane was absorbed in the already prepared colloidal solution of silver for 24 h. Afterwards, the membrane was washed with ethanol to detach all unbounded particles from its surface. A light pinkish-white colored membrane was gained which was further dried to perform further characterization and measurements.

2.4. *Characterization of membrane*

The morphological and structural assessment of prepared ceramic membrane was performed by X-ray diffraction analysis (XRD, Philips PW-1140/90) and field emission Scanning Electron Microscopy (FESEM, Quanta 200). The total porosity of the prepared membrane was evaluated by Archimedes principle using the relation,

$$\varepsilon = \frac{w_2 - w_1}{w_1} \tag{1}$$

where w_1 and w_2 are the weights of dry and wet membranes (in g), respectively. For this purpose, the membrane was firstly dried in a hot air oven at 110 °C for 6 h to obtain its dry weight. The it was immersed in water for 24 h at room temperature and its surface was wiped with tissue paper. Then the weight of wet membrane was measured. Fourier-transform infrared (FT-IR) spectra were recorded using KBr films in a PerkinElmer spectrophotometer.

2.5. Water permeation studies

A self-designed filtration setup having dead end was designed as shown in Fig. 1 and used for water permeation experiments. The setup was made up of stainless steel (300 mL capacity) consisting of a circular base plate to keep the membrane in leak-proof condition during direct flow of water. Afterwards, Ag coated ceramic membrane was used to treat different water samples for various physiochemical parameters like Total Dissoved Solids (TDS), Chemical oxygen demand (COD) and Biological oxygen demand (BOD). Two water samples were taken in this study namely a local river water sample and tap water sample. Water sample from a home RO purifier was also tested for better comparison of the tested parameters. For measuring COD, the water sample was titrated against ferrous ammonium sulphate solution and the end point was measured. For BOD measurements, water sample was pipetted out into a BOD bottle containing aerated dilution water. After determining DO content, the bottle was incubated in dark for five days at 20 °C. At the end of fifth day, the final DO content was determined and the difference between the final and initial DO reading was calculated. The decrease in DO is corrected for sample dilution and represents the BOD of the water sample.

3. Results and discussion

3.1. Morphology

A typical XRD pattern of porous ceramic membrane is shown in Fig. 2. Crystal characterization studies have revealed that after sintering the membrane, the peak corresponding to kaolin disappears due to the transformation of kaolinite to metakaolinite [24]. On the other hand, the peaks corresponding to quartz are not changed in the entire XRD patterns, which confirm the thermal stability of the phase. The XRD pattern of present study was consistent with the previous study therefore, the sintering temperature between 900–1000 °C taken in this work is justified [24]. A digital photograph of prepared membrane is shown in Fig. 3. The ceramic membrane was white initially and after decorating it with silver particles, the colour turned to light pinkish-white. The colour depends on the size of Ag-particles and it arises due to particle's capacity of absorption of light those adhere to the membrane's channel wall. The decorated membrane was incubated in an atmospheric environment for several weeks and no loss in the morphology was detected. The FESEM images of blank ceramic and Ag-decorated ceramic membrane is shown in Fig. 4. It shows uniform embedment of silver particles throughout the ceramic membrane. The difference in pore size can easily be seen in the images and the average pore size was 4.4 μm. The total porosity of the fabricated membrane obtained from equation (1) is 19.5%.

3.2. Spectral studies

FTIR analysis confirmed the connection between APTES and Ag particles (Fig. 5). The FTIR spectra of pure APTES is shown in Fig. 5 (a) and that of Ag particles coordinated APTES is shown in Fig. 5(b). The weak bands appearing at 3368 cm^{-1} and 3297 cm^{-1} in Fig. 5 (a) and broad band appearing at 3351.6 cm^{-1} in Fig. 5(b) corresponds to N–H stretching vibrations [26]. For the APTES coordinated Ag particles, the band was intense and broad owing to the formation of N–Ag coordinate bonds Fig. 5(b). This result clearly confirms that

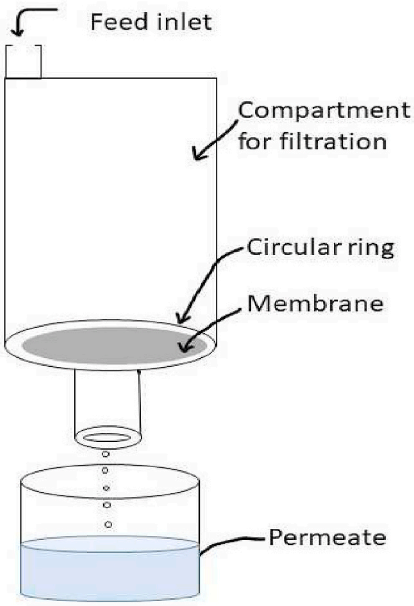

Fig. 1. Experimental setup for filtration test.

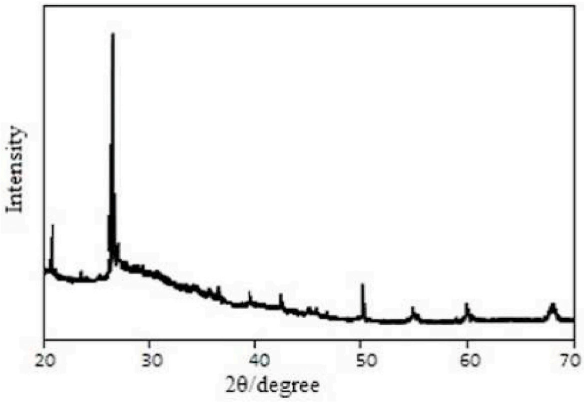

Fig. 2. XRD pattern of porous ceramic membrane.

Fig. 3. Silver decorated porous ceramic membrane.

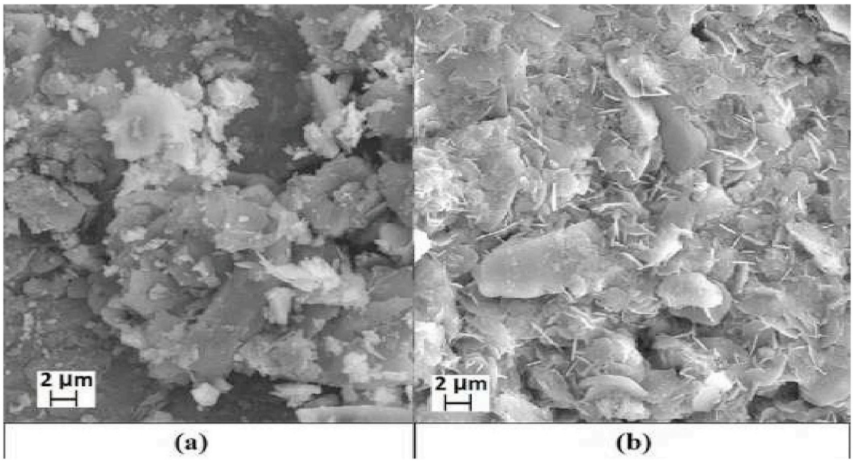

Fig. 4. FESEM images of (a) blank ceramic and (b) Ag-decorated ceramic membrane.

there is an interaction between the nitrogen of APTES molecule (NH_2 group) and Ag particles. The broad and intense peaks at 2974-2879 cm^{-1} in both the spectra are due to $–CH_2$ group asymmetric stretching and symmetric stretching vibrations. These peaks are little deformed in Ag-APTES spectra due to the interaction between NH_2 group of carbon chain and Ag particles [27]. The empty orbital

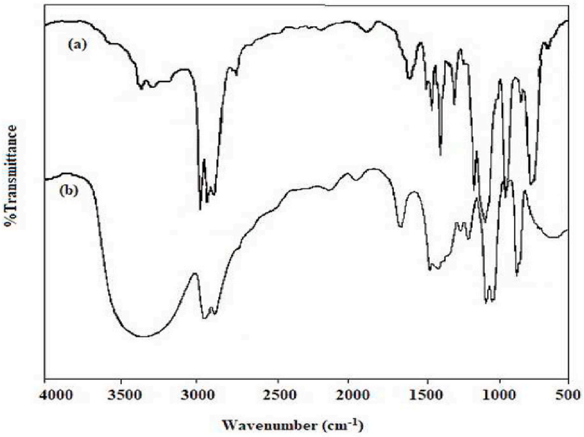

Fig. 5. FTIR spectra of (a) APTES (pure) and (b) Ag coordinated APTES.

of silver and lone pair of nitrogen facilitates the coordination of Ag with APTES. On the other hand, APTES molecules can be fixed to the channel surface of porous ceramics [28]. This type of connection confirms that the Ag particles remain tightly adhered to the membrane's interior channel walls to release an adequate amount of Ag ions for antibiosis. This type of Ag-ceramic membrane will be effective in purification of drinking water.

3.3. Water treatment studies

Permeation of water samples through the synthesized membrane using a self-designed system showed promising results for the efficacy of the membrane intended for purification of water. Biological oxygen demand and Chemical oxygen demand of water, both determines the amount of organic matter present in water, former determining the oxygen utilized by microorganisms in its oxidation. The results of water treatment studies for 2 different water samples are shown in Table 1. The average value of the treated water samples for TDS, BOD and COD was found to be within the permissible limit of Water Quality Standards for drinking water. According to WHO, the permissible limit of TDS, BOD and COD is 300 mg/L, 3 mg/L and 25 mg/L respectively. These results shows that the treated water from synthesized ceramic membrane is effective in reducing TDS, BOD and COD of water. It is very clear from these results that the ceramic membrane can effectively purify water, making it suitable for drinking and other purposes.

4. Conclusion

Decoration of silver particles onto the porous ceramic membrane with the help of APTES as a connecting molecule leads to the formation of a durable material having strong antibacterial capacity. As the chemicals involved in this process were commonly available, non-toxic, and cheap, and the method was also very simple, convenient, low cost and do not involve any wastage of water. The fabricated membrane holds wide pore morphology with pore size of 4.4 μm and average porosity of 19.5%. Based on retail cost of materials used, electric and labor cost etc., the average cost of the fabricated membrane has been estimated to be about 60 dollar/m^2. The fabricated membrane is less expensive as compared with the commercially available and previously reported membranes [29] used for gravity fed applications for water filtration. Being synthesized from kaolin and quartz, the membrane possesses high mechanical strength. The membrane was also found capable in reducing the TDS, BOD and COD of water samples that confirms that it is efficient for water purification. Therefore, a water filter incorporating this low-cost ceramic membrane will prove to be very beneficial for people of rural areas who cannot afford expensive filters. It can also be analyzed for other water treatment applications.

Author contribution statement

Mamta Latwal: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials,

Table 1
Values of studied parameters of different water samples.

Water samples		TDS (mg/L)	BOD (mg/L)	COD (mg/L)
River water	**Untreated**	325	7.21	82
	Treated	110	3.1	20
Tap water	**Untreated**	225	7.89	70
	Treated	69	2.92	12
Water filter (RO)	**-**	80	2.8	8

analysis tools or data; Wrote the paper.

Shefali Arora: Analyzed and interpreted the data; Wrote the paper.

Abhishek Joshi; Md. Irfan: Performed the experiments.

Ganesh Pandey: Analyzed and interpreted the data.

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Data availability statement

Data will be made available on request.

Declaration of interest's statement

The authors declare no competing interests.

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