

Sustainable Valorization of Ceramic Waste for the Fabrication of Ceramic Membranes for As(V) Removal

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Abstract

The valorization of industrial ceramic waste into functional separation materials offers a promising route toward reducing membrane fabrication costs while mitigating solid-waste disposal. This study developed a low-cost ceramic membrane using ceramic dust and wall ceramic sludge as the sole inorganic raw materials, followed by surface functionalization with polyamide 6 (PA6) and Fe_2O_3 to treat the arsenic-contaminated water. The waste-derived membrane was prepared using a 3:1 sludge-to-dust ratio and sintered at 1100°C for 1.75 h. The resulting membrane exhibited 19.15 MPa flexural strength and a permeability of $103.75 \text{ L/m}^2\cdot\text{h}$. Surface modification decreased the overall porosity from 39.7% to 35.5% and reduced the median pore diameter from 0.615 to $0.420 \mu\text{m}$, confirming pore-coating and partial pore narrowing. SEM-EDX and FTIR analyses verified the incorporation of Fe_2O_3 and PA6 onto the membrane surface. The modified membrane exhibited a zeta potential of 6.84 and achieved As(V) rejection of 84% with a flux of $394.25 \text{ L/m}^2\cdot\text{h}$ at an initial concentration of 1 ppm. The membrane also demonstrated 90.0% flux recovery and only 9.2% irreversible fouling, highlighting its potential for sustainable treatment of arsenic-contaminated water.

1. Introduction

Ceramic membranes are widely recognized as durable and highly adaptable separation materials for a broad range of industrial and environmental processes [1]. Compared with polymer-based membranes, they offer outstanding resistance to elevated temperatures, aggressive chemicals, and mechanical stress, providing extended service life under demanding operating conditions [2]. Despite these advantages, their broader commercial implementation remains limited by the high cost of fabrication. These costs are largely attributed to the use of premium raw materials, including high-purity kaolin, alumina, and other refined ceramic powders, in addition to manufacturing methods that require substantial energy consumption [3, 4].

Kaolin plays a central role in ceramic membrane fabrication due to its abundance, plasticity, favorable sintering behavior, and ability to form stable porous structures after thermal treatment [5, 6]. However, the increasing demand for kaolin, together with the costs associated with its extraction, beneficiation, and transportation, has motivated researchers to seek alternative raw materials [7]. The production of ceramic membranes typically involves multiple stages, including raw material selection, powder preparation, shaping, drying, and sintering [5]. Meanwhile, the ceramic industry generates substantial quantities of waste materials, including ceramic dust and ceramic sludge, which pose serious environmental challenges if not properly managed [8].

Ceramic dust is generated in the rotary kiln as a by-product of improper sintering, whereas ceramic sludge is produced during wet processing and wastewater treatment in ceramic plants. Against this backdrop, the valorization of ceramic wastes as alternative raw materials for ceramic membrane fabrication represents a promising strategy that simultaneously addresses economic, environmental,

and sustainability concerns [9]. These wastes are often rich in silica, alumina, and other ceramic-forming oxides, making them promising candidates for reuse in ceramic membrane production.

The ceramic membrane industry is highly energy-intensive, particularly during the drying and sintering stages, and requires significant quantities of raw materials [10]. Although ceramic membranes provide substantial environmental benefits during their operational lifetime, including long service life, chemical resistance, and superior separation efficiency, their manufacturing stage can contribute significantly to greenhouse gas emissions, fossil energy depletion, and mineral resource consumption [11, 12]. Consequently, understanding and mitigating the environmental impacts of ceramic membrane production have become essential research and industrial priorities [13]. Although numerous studies have investigated low-cost ceramic membranes incorporating industrial wastes [14], limited research has explored the complete replacement of kaolin with ceramic dust and ceramic sludge [15–18]. This represents an important research gap because of the beneficial characteristics of ceramic waste. The present study investigates ceramic membranes fabricated exclusively from ceramic waste, following the findings of a previous study that recommended a composition of 75% ceramic sludge and 25% ceramic dust sintered at 1100°C for 1.7 h [19]. The resulting membrane surface was subsequently modified using polyamide 6 (PA6) and ferric oxide. Under these conditions, the membrane properties, including boiling water adsorption %, cold-water adsorption %, bulk density, water flux, and flexural strength, were evaluated. In addition, the zeta potential of the modified membrane, scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDX) were examined to assess the characteristics of the deposited layers.

2. Materials and Methods

Ceramic wastes, including ceramic dust and ceramic sludge, were obtained from Ceramic Rondy Company in the industrial zone of Beni Suef Governorate, Egypt. PA6 ($C_6H_{11}NO$)_n from Dop Organik Kimya was used for the membrane's surface modification. Formic acid (CH_2O_2) from El-Nasr Pharmaceutical Chemicals Company was used to dissolve the polymer. Ethylenediamine ($C_2H_8N_2$), ferric oxide (Fe_2O_3), and arsenic corresponding to As(V) (As_2O_5 in H_2O) from Sigma-Aldrich.

2.1. Raw materials characterization

The density of the ceramic wastes was measured using the density bottle method, and the mineralogical phases were determined by X-ray diffraction (XRD) with a Bruker D8 Discover diffractometer (Germany). The chemical compositions were obtained using an X-ray fluorescence (XRF) Spectrometer (Netherlands). Thermal gravimetric analysis (TGA) and differential thermogravimetric analysis (DTA) were analyzed by THEMYS Thermal Analyzer (France) at a rate of 10°C/min over a temperature range of (35–1000) °C. The standard pycnometer test method (Density flask) was used to assess the true density of the powder in accordance with ASTM B311 [20]. The BT–2001 Laser Particle Size Analyzer was used to determine the particle size distribution (PSD) in accordance with ISO 13320 [21].

2.2. Preparation of the membranes

The ground ceramic sludge, 80 µm in size, was dried at 110°C for 2 h, then mixed with wall ceramic dust in a 3:1 ratio, and water was added at 15 wt.% of the total solids. The ceramic membranes were formed into cylindrical samples by pressing at 25 MPa on a lab scale. The mold was stainless steel, 6 mm thick and 50 mm in diameter. Drying stages were performed at 50°C for 8 h, then at 80°C for 6 h, and at 110°C overnight. The sintering was performed by gradually increasing the firing temperature at 5°C/min from room temperature to 1100°C; the sintering period was 1.75 h [18].

For surface modification, Fe₂O₃ was suspended in PA6 dissolved in formic acid and ethylenediamine. This mixture consisted of 15 g of PA6 gently added to 90 g of formic acid mixed with 2 g of ethylenediamine in an ice bath. This solution was kept at 4°C for 24 h, after which Fe₂O₃ was gradually added, and then sonication was applied for 30 min. Finally, the membrane was dipped in this suspension overnight, then washed and dried at 50°C for 2 h [19, 22].

2.3. Membrane characterization

2.3.1. Physical evaluation

The physical characteristics of the fabricated ceramic membrane before surface modification were characterized using standard ASTM procedures. Linear and volumetric dry, firing, and total shrinkage were measured according to ASTM C326 [23]. Saturation coefficient, boiling water absorption, cold water absorption, and bulk density were determined following ASTM C67 [24] and ASTM C373 [25], respectively. Furthermore, membrane permeability and pore size distribution were analyzed to evaluate the hydraulic performance and pore structure of the prepared membrane.

The Pore size distribution was determined in accordance with ISO 15901-1 [26] by the mercury porosimetry method. During evacuation, the produced membrane was subjected to mercury penetration under hydraulic pressure ranging from 0.125 to 2068.4 MPa, corresponding to pore radii ranging from 6 nm to 100 µm.

2.3.2. Mechanical properties

The most important mechanical property is the flexural strength of the prepared membranes, which was measured according to ASTM C1505 [27] using a CROMETRO BEPD LATE CR5 650, Italy, as shown in Eq. 1 [18].

$$\text{Flexural strength (N/mm}^2\text{)} = (3 \times L \times S) / (2 \times W \times T^2) \quad (1)$$

Where: L is the maximum load (N), S is the span between the supporting cylinders (mm), W is the specimen width (mm), and T is the specimen thickness (mm).

2.3.3. Functional groups and morphology

The functional groups of the produced ceramic membranes and the coating material were defined by Bruker Vertex 80 Fourier-Transform Infrared Spectroscopy (FTIR), Germany, with an internal reflector, 4 cm^{-1} resolution, and refractive index of 2.4. The surface morphology was examined by Scanning Electron Microscopy (SEM), QUANTA, USA, while the elemental composition was determined by Energy-Dispersive X-ray Analysis (EDX). Before SEM analysis, the samples were coated with a 200–300 Å gold layer using an S150A Sputter-Coater, EDWARD, England.

2.3.4. Zeta potential

The surface-charge behavior of the prepared modified membrane was evaluated by determining its zero point of charge (pH_{zpc}). In this method, a series of beakers containing 50 mL of 0.01 M NaCl solution was adjusted to a pH from 2 to 11 using NaOH or HCl. 0.5 g of ceramic membrane powder was placed in each beaker and agitated for 24 h at ambient temperature, and the pH was measured by a digital pH meter [28].

2.4. Membrane performance

Filtration experiments were conducted with a laboratory membrane-filtration unit, CERAFILTEC, Germany. At pH 7, As(V) rejection was determined for initial concentrations of 1, 2, 5, and 10 ppm, and the permeate flux was recorded. Rejection and flux were calculated as [29, 30]:

$$R\% = [(C_i - C_f) / C_i] \times 100 \quad (2)$$

Where: C_i is the initial concentration (mg/L), C_f is the permeate concentration (mg/L).

$$\text{Flux} = V / (T \times A) \quad (3)$$

Where: V is the volume of filtrate (L), T is the permeation period (h), and A is the membrane area (m^2).

The fouling behavior was defined by measuring the permeability of the membrane using contaminated water after compacting the membrane with deionized water for 60 min. The water flux was measured to assess the cycle of filtration and backwash. The membrane was employed for a synthetic arsenic-contaminated water solution, containing 10 ppm As(V) and 100 ppm humic acid under identical conditions. A three-cycle experiment was applied continuously for 3 h; the backwash using deionized water lasted 15 min after each filtration period. The flux recovery ratio (FRR), total fouling (F_t), irreversible fouling (F_{ir}), and reversible fouling ratio (F_r) were calculated from:

$$FRR\% = (J_{w2} / J_{w1}) \times 100 \quad (4)$$

$$F_r\% = [(J_{w2} - J_p) / J_{w1}] \times 100 \quad (5)$$

$$F_{ir}\% = [(J_{w1} - J_{w2}) / J_{w1}] \times 100 \quad (6)$$

$$F_t\% = [(J_{w1} - J_p) / J_{w1}] \times 100 \quad (7)$$

Where: J_{w1} is the initial pure water flux, L/m².h;

J_{w2} is the final pure water flux, L/m².h;

J_p is the total permeating flux after 3 h, L/m².h

3. Results and Discussion

The results demonstrate that ceramic sludge and ceramic dust can serve as the principal inorganic constituents of a functional ceramic membrane. The results and discussion below relate the chemical and mineralogical composition of the wastes to membrane structure, surface modification, arsenic removal, and fouling behaviour.

3.1. The characterization of raw material

XRF analysis, as shown in Table 1, illustrates that the predominant component of both types of ceramic waste is silica, followed by alumina and oxides of alkali and alkaline-earth metals, such as MgO, Na₂O, CaO, and K₂O, and trace oxides like CuO and Cr₂O₃. The composition rich in SiO₂ and Al₂O₃ is consistent with the broader use of aluminosilicate-rich wastes as feedstocks for low-cost ceramic membranes, as demonstrated by Mouratib *et al.* [31], who fabricated a flat ceramic membrane using silica-and alumina-rich water treatment sludge mixed with clay to clarify textile effluent.

Table 1
Chemical compositions of the ceramic wastes

Compounds	Ceramic sludge (wt.%)	Wall dust (wt.%)
SiO ₂	60.945	52.81
Al ₂ O ₃	17.660	17.77
Na ₂ O	3.166	1.64
CaO	6.325	6.35
Fe ₂ O ₃	1.720	6.54
TiO ₂	1.315	1.06
K ₂ O	1.209	2.08
MgO	0.747	0.42
P ₂ O ₅	0.293	0.67
SO ₃	0.066	0.44
MnO	0.028	0.13
ZnO	0.571	0.022
BaO	0.142	0.000
Cl	0.032	0.23
Trace oxides	0.08	0.121
LOI	5.70	9.71
Total	99.999	99.993

Odewole *et al.* [32] studied the phase diagram of the SiO₂-Al₂O₃ binary system and provided a detailed discussion of the SiO₂- and Al₂O₃-Rich raw materials. The raw material, which has an SiO₂/Al₂O₃ ratio of 1.28 and LOI of 13.07, has a high green strength, low water content, and high fusion point. In contrast, a ratio of 1.78 and LOI of 7.24 has higher strength and higher plasticity. Meanwhile, that of a ratio of 4.79 is more refractory, reducing shrinkage and drying problems. These results elucidate the current study: the mixture of raw materials contains 58.91% SiO₂ and 17.6875% Al₂O₃ at a ratio of 3.33, which enhances strength and improves plasticity.

The primary composition of ceramic waste is silica and quartz; kaolinite, albite, and calcite phases are also observed in the XRD pattern, which is attached in the supplementary file S1. The albite pattern indicates the presence of feldspar and calcite in the ceramic dust. Ceramic sludge comprises all the

components present in the raw materials used to produce wall and floor tiles. The coexistence of quartz/silica with kaolinite, albite, and calcite indicates that the starting powders contain both relatively refractory phases and minerals that can undergo dehydration, dihydroxylation, and carbonate decomposition.

TGA–DTA for raw materials shows three peaks for the ceramic wastes, which is attached in the supplementary materials S2. The first zone is endothermic (70–150) °C and expresses the loss of water. The second endothermic zone (350–610) °C corresponds to the loss of lattice water. The third endothermic peak (615–710) °C is attributed to the decomposition of the calcite mineral. Ceramic dust analysis exhibited two major peaks in the ranges: (440–550) °C and (645–730) °C.

The density bottle method was used to determine the density of both wastes, yielding mean true densities of 2.57 g/cm³ for wall dust waste and 2.554 g/cm³ for sludge waste. The particle size distribution of the two wastes is practically the same, as shown in Fig. 1. The results for sludge waste revealed that the milled silica ranges from 0.610 µm to 77.00 µm. The median particle size (D50) corresponding to a percent passing of 50% is equal to 7.627 µm. The median particle size (D50) of wall dust is 8 µm, and the particle diameters range from 0.235 µm to 145.1 µm. In waste-derived ceramic membranes, the particle-size distribution must be considered together with binder content, pore-forming agents, and sintering temperature because these variables jointly determine the balance between densification, porosity, and hydraulic transport [31, 33].

3.2. Membrane properties

3.2.1. Mechanical and Physical properties

Before surface modification, the linear dry shrinkage is 0.8%, volume dry shrinkage is 4.6%, linear firing shrinkage is 5.97%, volume firing shrinkage is 18.14%, total linear shrinkage is 6.72%, total volume shrinkage is 21.91, cold water absorption is 10.43%, and boiling water absorption is 14.113%. The saturation coefficient is 0.62, the bulk density is 1.61 g/cm³, and the permeability is 103.75 L/m²h. The flexural strength of the prepared membranes is 19.15 N/mm². These results are congruent with those achieved by Mouratib *et al.* [31], where a mixture of clay and derived waste from treated water sludge was sintered at 1050°C, producing a mechanical strength of 14.5 N/mm², a pore size of 0.92 µm, and a porosity of 39.7%.

Pore size distribution (PSD) indicates how pore volume is distributed across different pore sizes, as shown in Fig. 2. The data clearly show that the modification successfully induced pore narrowing. The dominant pore size, represented by the main peak, shifted from approximately 0.0075 µm (7.5 nm) in the unmodified membrane to 0.0055 µm (5.5 nm) after surface treatment. This reduction in the mean pore diameter, attributed to material deposition within the pore channels, is expected to enhance the membrane's selectivity and rejection rate for fine particles and solutes. Furthermore, the modified membrane exhibits a slight broadening of the PSD and a more pronounced secondary peak in the 0.02

μm to 0.04 μm range, suggesting a change in the internal pore network structure beyond simple homogeneous pore shrinkage [6].

The data presented in Table 2 quantitatively confirm these structural changes. The key parameters reflecting pore size showed substantial reductions following modification. The median pore diameter (volume) decreased significantly from 0.615 μm for the unmodified membrane (G8) to 0.42 μm for the modified membrane (G9). Similarly, the average pore diameter (4V/A) decreased from 0.088 μm (G8) to 0.055 μm (G9). These quantitative decreases strongly support the visual evidence of pore narrowing presented in the PSD plot [34, 35].

Crucially, the surface modification reduced both total intrusion volume (from 0.248 mL/g to 0.228 mL/g) and overall porosity (from 39.7% to 35.5%). This contrasts with the previous interpretation and indicates that the modification mechanism primarily involved coating the pore walls and partially plugging some of the existing larger pores. This pore-plugging and narrowing effect simultaneously reduced the total pore area (from 10.58 m²/g to 9.25 m²/g), which is the expected structural change responsible for increasing the membrane's selectivity and rejection at the expense of hydraulic permeability (flux) [36, 37].

Table 2 Porosity and Pore Structure Characteristics of Unmodified and Surface-Modified Ceramic Membranes			
Properties	units	Membrane without surface treatment (G8)	Membrane with surface treatment (G9)
Porosity	%	39.7	35.51
Skeletal density	g/cm ³	2.67	2.45
Bulk density	g/cm ³	1.61	1.58
Mean pore size (4v/a)	μm	0.088	0.055
Total pore area	m ² /g	10.58	9.25
Total intrusion volume	mL/g	0.248	0.228

3.2.2. FTIR and morphology

FTIR analysis was conducted to examine the chemical properties of the ceramic membrane prior to and following its modification with PA6/Fe₂O₃. As depicted in Fig. 3, both spectra display a wide band around 3415 cm⁻¹, attributed to O–H stretching of surface hydroxyl groups and absorbed water, validating the hydrophilic characteristics of the membrane surface. The peak around 2920 cm⁻¹, indicating aliphatic C–H stretching, exhibits a significantly increased intensity post-modification, likely due to the addition of the PA6 polymer.

A faint band at about 2370 cm^{-1} is linked to atmospheric CO_2 , whereas the bands near 1620 and 1626 cm^{-1} for both the unmodified and modified membranes, respectively, are primarily connected to the bending vibration of adsorbed H_2O . The bands around 1385 and 1454 cm^{-1} in the modified membrane correspond to C-H deformation vibrations and further indicate the existence of the polymeric phase [38, 39].

The intense peak near 1020 cm^{-1} and the peaks at 870 , 610 , and 460 cm^{-1} are indicative of Si-O-Si and Si-O-Al vibrations, verifying the silicate/aluminosilicate composition of the ceramic matrix. The endurance of these bands post-modification signifies that the surface treatment did not change the essential ceramic structure. The addition of Fe_2O_3 to the PA6 matrix is anticipated to create more hydroxylated iron sites, potentially improving the membrane surface's interaction with dissolved arsenic species and thereby aiding in enhanced arsenic removal efficiency [38, 39].

The ceramic membrane's morphology post-surface treatment was analyzed using SEM at 1000 X magnification, along with EDX analysis, as shown in Fig. 4. The white spots of the iron oxide appear in the SEM image in Fig. 4A. The high peak of iron is clear in the EDX of Fig. 4B. Figure 4C shows the layers of the membrane surface after treatment; the thickness and the morphology of these layers are shown in the SEM capture in Fig. 4D and 4E.

Iron oxide was particularly selected for surface modification due to its ability to adsorb arsenic ions [40]. Meanwhile, polyamide 6 is used as a carrier for the iron oxide to ensure its smooth application to the surface and optimal depth [20]. The observed distribution of Fe-rich regions at the treated surface and within the near-surface membrane body is also consistent with the broader literature on iron-oxide-functionalized ceramic membranes. Barati *et al.* [41] reported that in situ-generated iron oxide nanoparticles could be distributed across the membrane surface and within the active-layer pores, thereby enhancing hydrophilicity and organic rejection while improving flux recovery and resistance to irreversible fouling. In the presented system, such a distribution is particularly useful because it can provide two complementary functions: the ceramic matrix supplies durable mechanical and chemical properties, and the iron oxide-containing layer contributes specific adsorption sites and electrostatic interactions with arsenate [41]. The deposition geometry is therefore likely to be as important as the total Fe_2O_3 loading. Excessive penetration or pore filling can reduce hydraulic performance, whereas a well-distributed near-surface loading can increase active-site density without completely sacrificing water transport.

3.2.3. Zero electrical charge point

The pH-drift experiment produced a strong linear relationship with $R^2 = 0.9953$, and gave a zero point of charge (pHzpc) of 6.84 as shown in Fig. 5. This parameter indicates that the charge state of the modified surface depends strongly on solution pH. Below pH 6.84, protonation of surface hydroxyl groups associated with the ceramic matrix and Fe_2O_3 produces a net positive surface charge. At pH values

above 6.84, deprotonation becomes dominant, and the surface becomes negatively charged. Ceramic membrane surface electrochemistry is sensitive to ionic strength and the identity of dissolved ions [42].

This behavior helps explain the arsenate-removal mechanism. Under typical aqueous conditions, As(V) mainly exists as negatively charged oxyanions, including H_2AsO_4^- and HAsO_4^{2-} [43, 44]. Therefore, at pH values below the pHzpc value, the positively charged membrane surface promotes electrostatic attraction toward arsenate species, resulting in enhanced adsorption and rejection efficiency. In contrast, increasing the pH above the pHzpc increases the negative membrane surface, which repels arsenate anions, potentially lowering removal efficiency.

3.3. Ceramic membrane performance

3.3.1. Removal efficiency

The membrane's efficacy was evaluated prior to and following surface modification by assessing arsenic removal and the associated permeate flux. The results revealed that the rejection % of the untreated membrane is 6.8% at an initial feed concentration of 10 ppm. In contrast, it is 61.3% at the same initial feed concentration after the surface treatment. Figure 6-A shows the performance of the treated-surface ceramic membrane, applying a statistical t-test for $n = 3$ and $p = 0.03$, at initial concentrations of 1, 2, 5, and 10 ppm. Arsenic removal efficiencies are 84%, 77.5%, 69%, and 61.3%, while the flux is 394.25, 363.12, 338.92, and 325.08 $\text{L/m}^2\cdot\text{h}$, using feed solutions containing 1, 2, 5, and 10 ppm arsenic, respectively.

The increase in arsenic rejection from 6% for the untreated membrane to 61% at 10 ppm after modification demonstrates that the Fe_2O_3 -containing surface contributes substantially to arsenic capture. This is superior to that achieved by Usman *et al.* [45] in developing microscale conventional iron oxide-based adsorbents as dynamic membranes for removing arsenic from water with an efficiency of 90% at a flux of 31 $\text{L/m}^2\cdot\text{h}$ for initial concentrations ranging from 0.19 to 0.38 ppm. Meanwhile, the presented approach achieved 84% at a flux of 394.25 $\text{L/m}^2\cdot\text{h}$ for an initial concentration of 1 ppm.

3.3.2. Fouling behavior

The hydraulic performance of the modified membrane (G9) was assessed over time to determine its susceptibility to fouling. As shown in Fig. 6-B, the flux declined significantly from approximately 234.53 $\text{L/m}^2\cdot\text{h}$ to a stable minimum of 98.50 $\text{L/m}^2\cdot\text{h}$ over the first 240 minutes of operation, applying a statistical t-test for $n = 3$ at $p = 0.05$. This pronounced flux drop is the expected consequence of the tightened pore structure of G9, which exhibits a reduced average pore diameter of 0.055 μm and a high arsenic rejection rate (up to 84%).

The observed fouling is primarily consistent with concentration polarization and cake-layer development. Rejected arsenic-containing species and other foulants accumulate near the membrane surface, increasing hydraulic resistance. A critical finding for the practical application of the modified membrane (G9) is its response to the cleaning procedure performed at the 240-minute mark. Figure 6 shows a

sharp and substantial recovery in flux, jumping from 98.5 L/m²·h to 211.1 L/m²·h. This behavior confirms that the majority of the fouling is reversible and effectively removed by the cleaning protocol.

The calculated total loss of permeation is 46.092%. Nevertheless, the response to cleaning demonstrated that most of this resistance was reversible. The Flux Recovery Ratio (FRR) is excellent, reaching 90.0%. The Reversible Fouling (F_r) component accounts for 36.9% of the total resistance. These values indicate that the majority of the deposited foulants can be removed by the applied cleaning procedure. Crucially, the Irreversible Fouling (F_{ir}) component is low at only 9.2%. This low irreversible fouling indicates a significant chemical and mechanical stability of the surface modification layer. The modification successfully created a highly selective barrier while maintaining a surface that resists the permanent adherence and deep intrusion of foulants, which is essential for sustainable operation within the process limitation. The most important limitation in this study is that the rejection results are specific to the tested conditions. However, the laboratory-scale experiments were applied using synthetic arsenic-contaminated water with a high concentration of arsenic (10 ppm), and the fouling factor was examined using a high concentration of humic acid (100 ppm). Other limitations related to the real contaminated water include organic concentration, suspended solids, temperature variation, and studying long-term industrial-scale validation.

4. Conclusion

Producing a waste-derived ceramic membrane is technically feasible under laboratory conditions. The optimized membrane composition, combined with polyamide 6 and ferric oxide surface modification, produced a membrane exhibiting suitable mechanical strength, a controlled pore structure, high permeability, and arsenic rejection of up to 84%, while maintaining excellent fouling resistance and hydraulic recovery. Comprehensive characterization of the ceramic wastes confirmed that the waste-derived raw materials possess physicochemical properties suitable for ceramic membrane fabrication without compromising structural integrity or filtration performance, supporting their potential application within circular-economy-oriented membrane manufacturing. The use of ceramic waste as the principal inorganic feedstock provides a potentially attractive route for waste valorization and reduction of reliance on conventional ceramic raw materials. However, quantitative environmental and economic assessments are required to establish the overall sustainability benefits. These findings highlight the strong potential of ceramic waste valorization as an effective circular economy strategy for membrane manufacturing. Future research should focus on long-term industrial-scale validation, continuous filtration under real wastewater conditions, regeneration durability, and optimization of coating materials to further improve selectivity and membrane lifespan. The proposed technology represents a promising sustainable alternative for advanced water treatment, simultaneously addressing industrial waste management and resource conservation.

Abbreviations

DTA Differential Thermogravimetric Analysis

EDX	Energy-Dispersive X-ray Analysis
ISO	International Organization for Standardization
TGA	Thermogravimetric Analysis
XRD	X-ray Diffraction
XRF	X-ray Fluorescence

Declarations

Ethics approval and consent to participate: Not applicable.

Consent for publication: Not applicable.

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8. Authors' contributions

Conceptualization was performed by S.A.E., M.S.M., and Sh.K.A. Methodology and data curation were conducted by A.A., S.A.E., and Sh.K.A. Formal analysis was performed by A.A., S.A.E. and Sh.K.A. Supervision was provided by S.A.E., M.S.M., S.M., and Sh.K.A. The original draft was written by Sh.K.A and S.A.E., and all authors contributed to writing, review, and editing.

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Figures

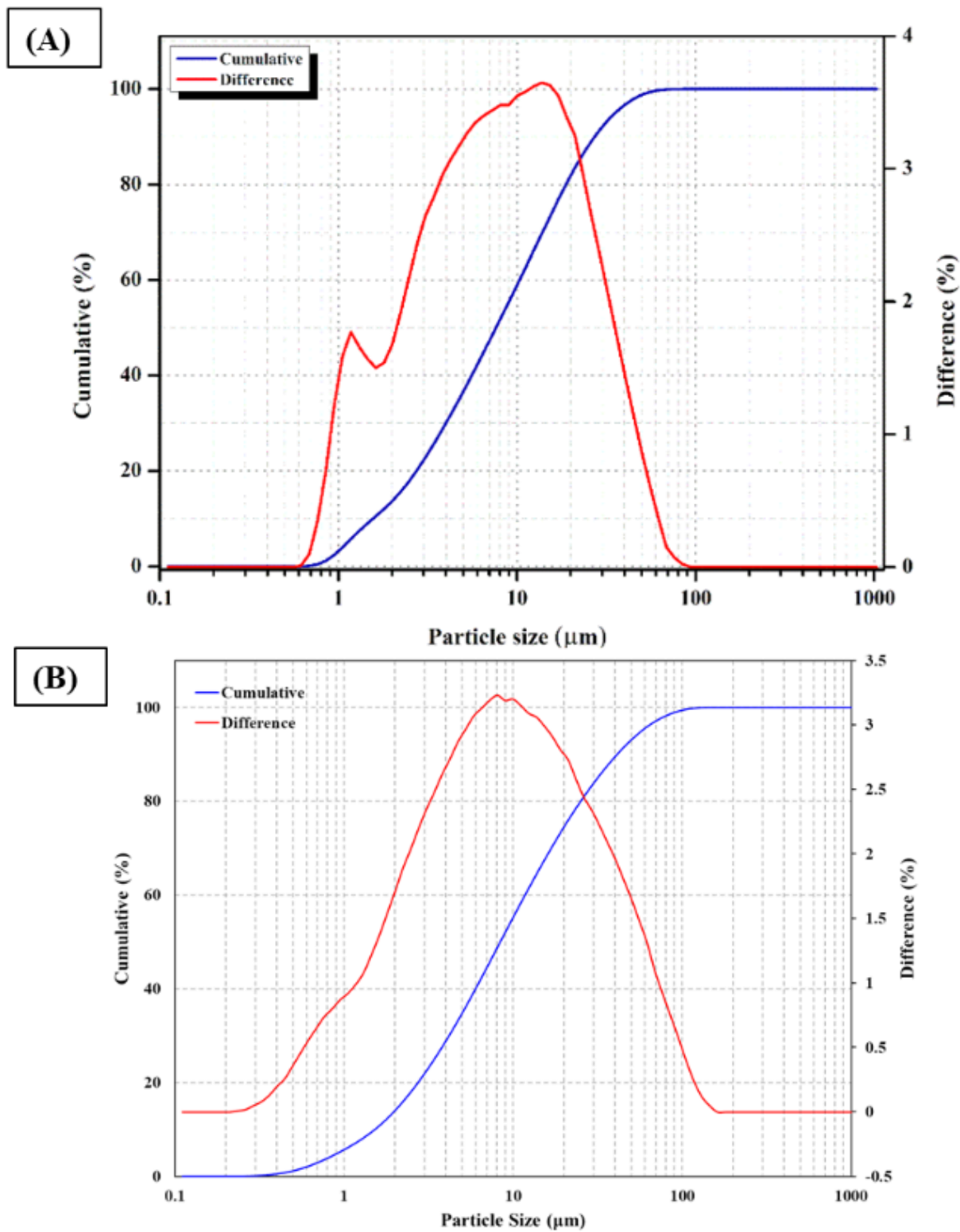


Figure 1

Particle size distribution of: (A) ceramic sludge waste, and (B) Ceramic wall dust

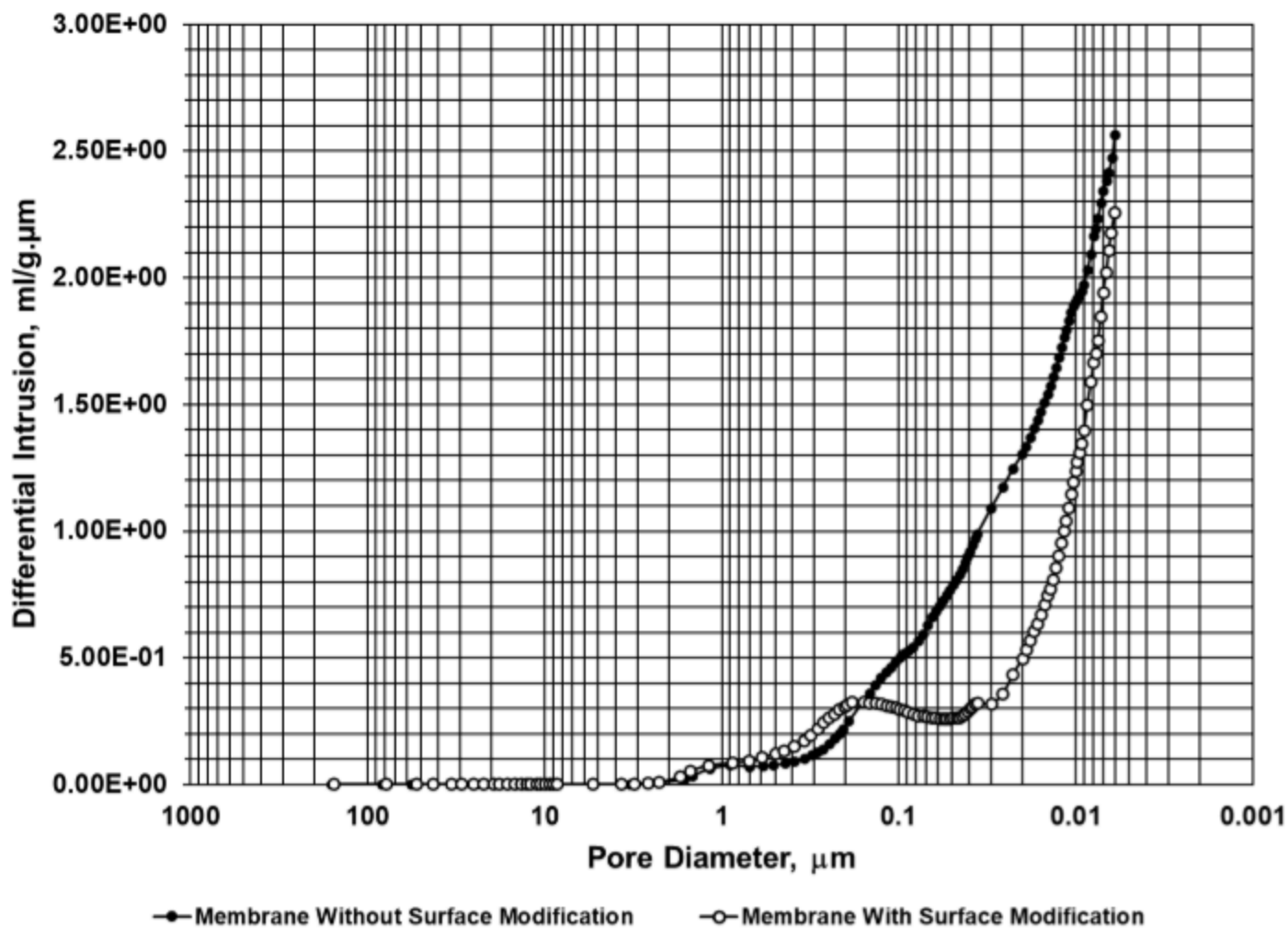


Figure 2

Effect of surface modification on the pore size distribution of the ceramic membrane

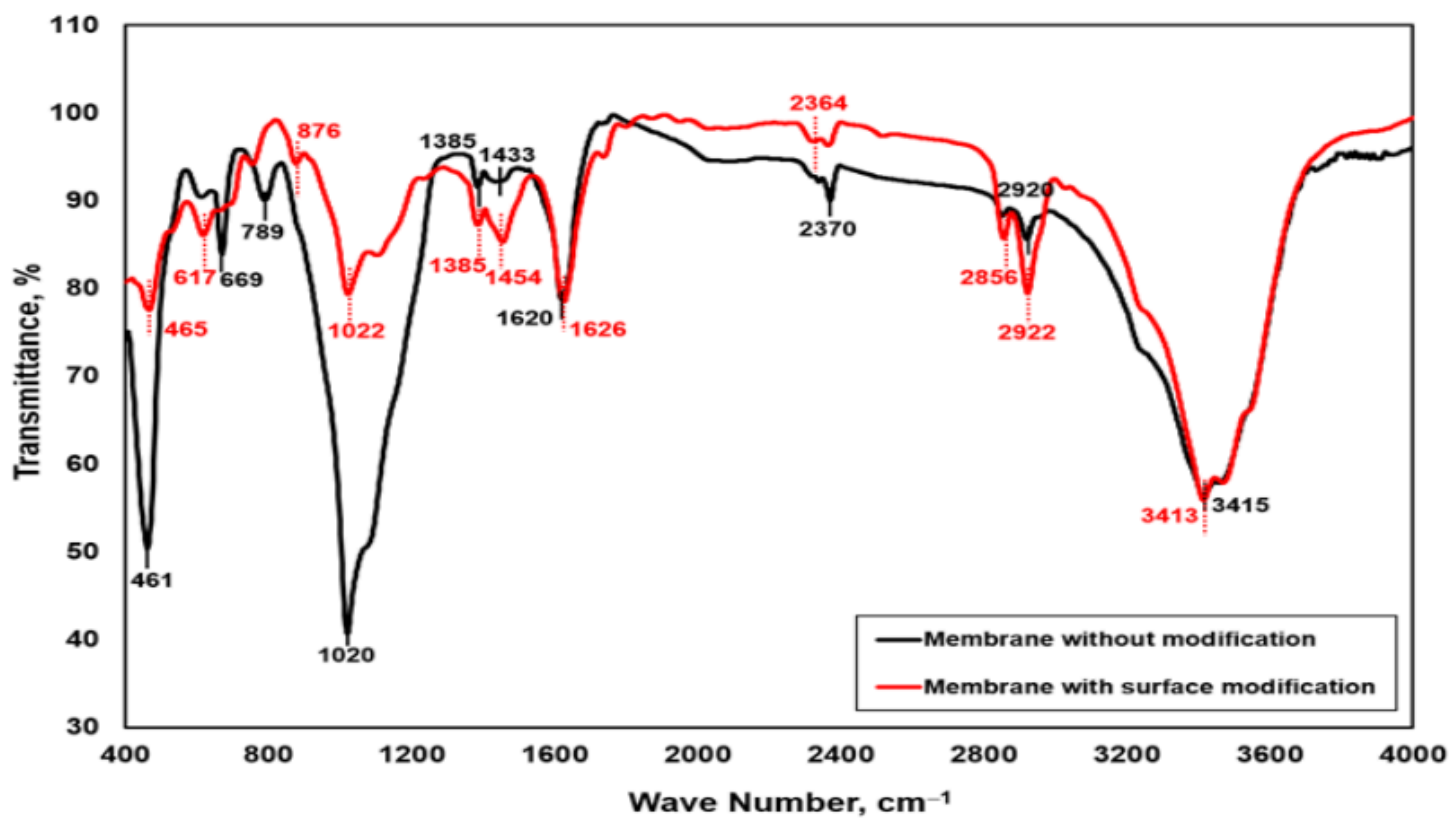


Figure 3

FTIR analysis of the produced ceramic membranes

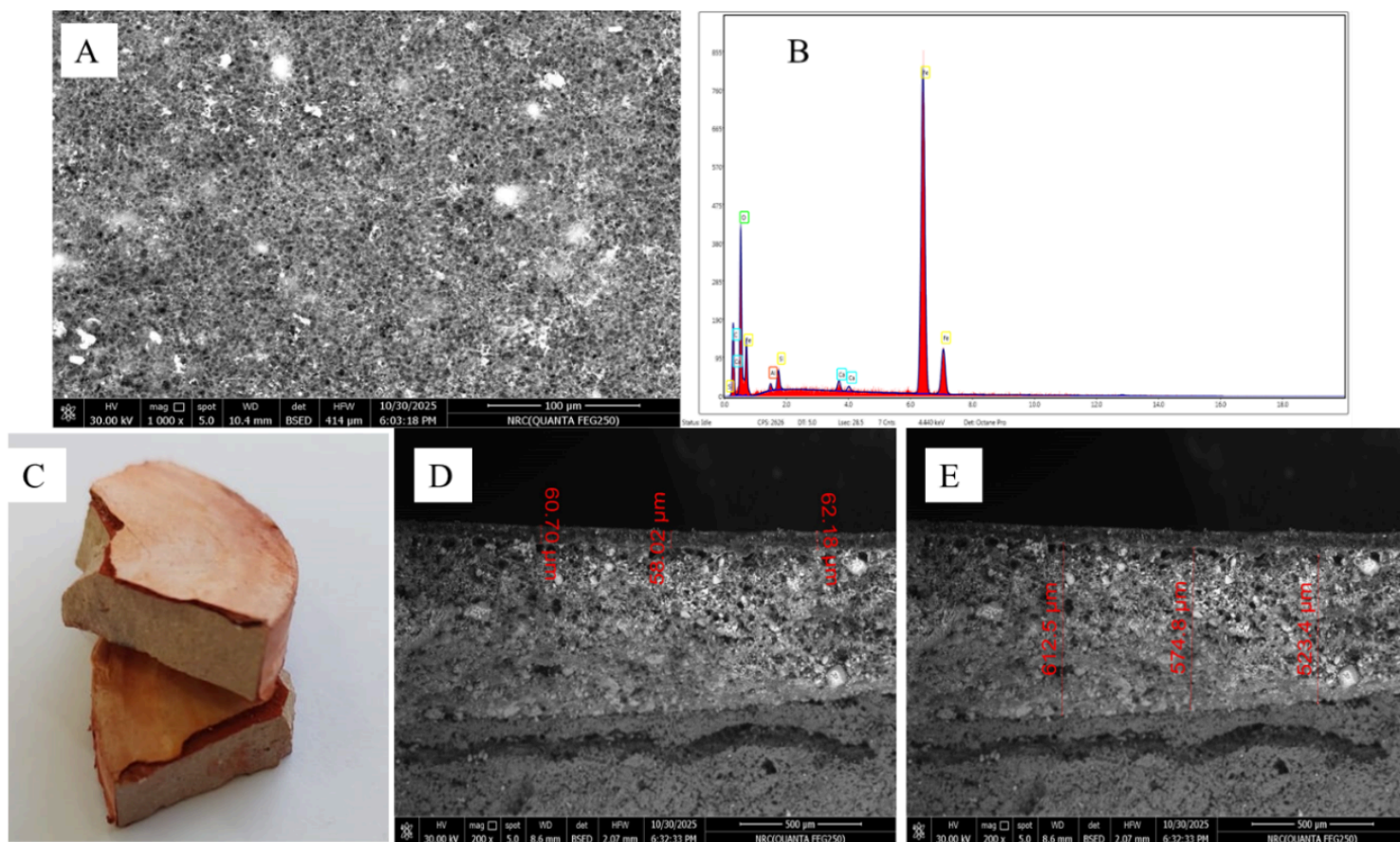


Figure 4

SEM and EDX for the treated ceramic membranes: (A) 1000X magnified sample, (B) EDX analysis, (C) cross-section of the treated ceramic membrane, (D) morphology of the outer layer of the treated membrane, (E) penetration of iron oxide inside the membrane body

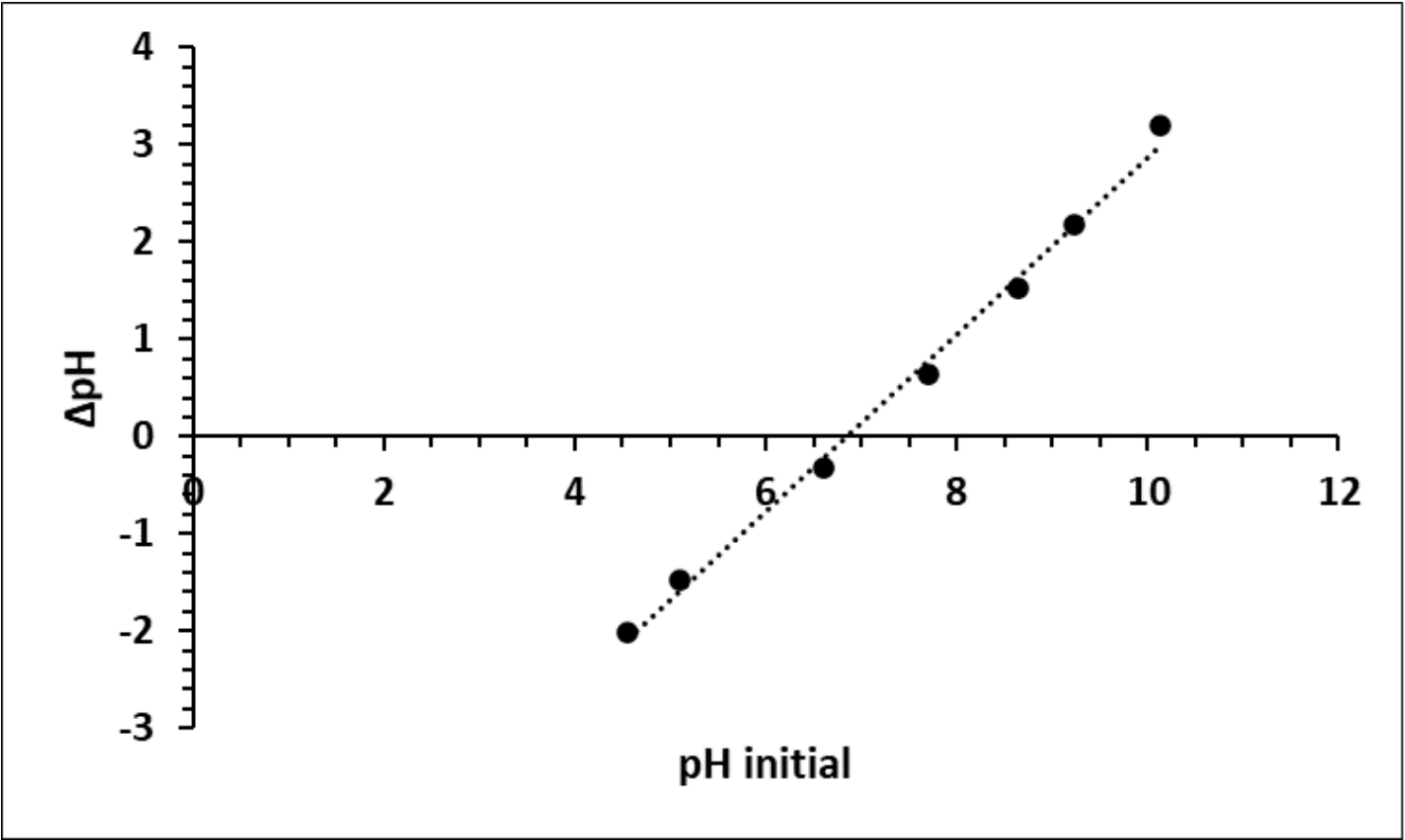


Figure 5

The pH_{zpc} of the treated-surface ceramic membrane

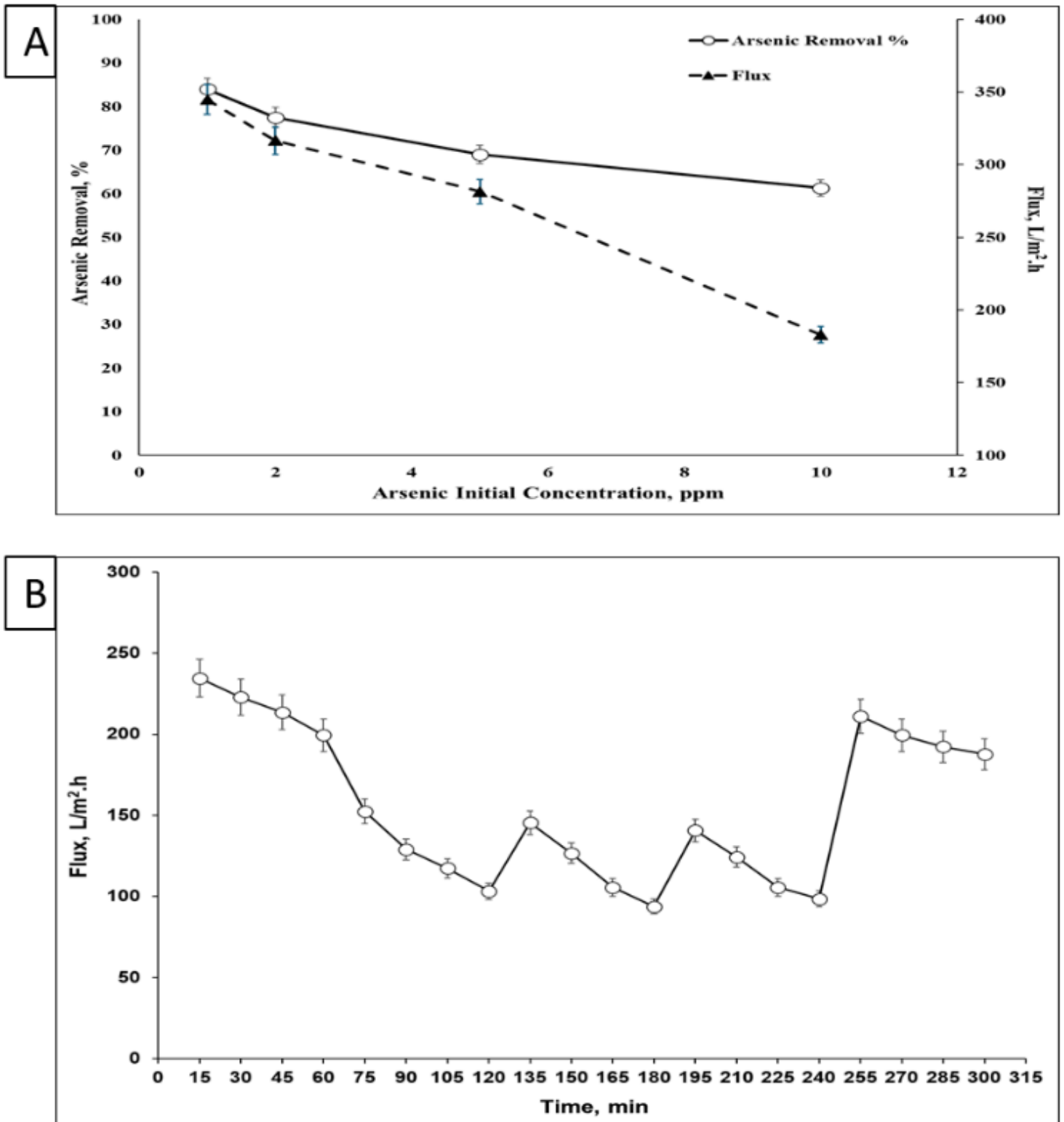


Figure 6

(A) Removal efficiency, (B) Fouling behavior

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