

Treatment of Swine Biogas Digester Effluent Using Volcanic Ash–Chitosan Composite Ceramic Membranes

Rhonalyn V. Maulion ^{*,1}

Rejie C. Magnaye ^{*,1}

Sicily B. Tiu ¹

Elisa D. Gutierrez ^{1,2}

Reggie A. Duenas ¹

¹ Department of Chemical Engineering, College of Engineering, Batangas State University – The National Engineering University, Alangilan Campus, Batangas City, Philippines

² College of Engineering and Technology, Batangas State University – The National Engineering University, Alangilan Campus, Batangas City, Philippines

*e-mail: rhonalyn.maulion@g.batstate-u.edu.ph (R.V.M.); rmagnaye635@gmail.com (R.C.M.)

Submitted 1 October 2025

Revised 12 April 2026

Accepted 15 April 2026

Abstract. Water scarcity is a growing global concern, driven by rapid population growth, industrialization, and agricultural demands. The swine industry, a major contributor to agricultural water consumption, generates large volumes of wastewater that require proper treatment to prevent environmental damage. This study developed a volcanic ash–chitosan composite ceramic membrane (VACCCM) for the treatment of swine biogas digester effluent. The developed VACCCM exhibited a porous structure with a bulk density of 1.3223 g/cm³, an apparent density of 2.69 g/cm³, and a porosity of 50.84%, indicating interconnected pore networks and the ability of ceramic membranes to allow water passage while retaining contaminants. The ceramic thickness and chitosan coating layer showed a statistically significant effect ($\alpha=0.05$) on the properties of the treated effluent, with the best condition identified at 1.0 cm membrane thickness and a single chitosan coating layer. The membrane achieved substantial reductions in key parameters, including total suspended solids (321.3 to 16 mg/L), phosphates (63.9 to 6.8 mg/L), chemical oxygen demand (770 to 220 mg/L), and coliforms (35,000,000 to 920 MPN/100 mL). Significant reductions were observed in biochemical oxygen demand from 430.0 to 108.0 mg/L and in color, which was reduced from 750 to 200 TCU. The developed VACCCM has an average pore size of (1.23±0.32 μ m), indicating a macroporous structure suitable for water filtration. Elemental analysis revealed the presence of major components, including Si (17.31%), Fe (10.97%), Al (9.50%), and O (48.01%). The TGA shows three-stage degradation: moisture and chitosan loss (~47–337 °C), polymer breakdown (~672 °C), and final ashing (~732–950 °C), leaving inorganic residue. The mean compressive strength of 2.74 MPa and flexural strength of 2.29 MPa indicate adequate mechanical stability and effective filtration performance, suggesting potential for wastewater treatment in agricultural industries.

Keywords: Chitosan, Composite, Membrane, Swine Biogas, Volcanic Ash

INTRODUCTION

Water is undeniably the most valuable natural resource, and it encompasses more

than 70% of the Earth's surface. The rapid growth of the human population and ongoing economic development worldwide have led to a significant increase in water

demand, which will be difficult to meet in the foreseeable future. Global water demand continues to outpace supply, with nearly half the world's population projected to reside in water-stressed regions by 2025 due to unsustainable consumption (Alotaibi *et al.*, 2025), making this one of the greatest challenges facing humanity today. The rapid growth of industrialization in the economic sector generated a massive volume of wastewater containing hazardous and toxic substances, which, when discharged into water bodies, affects water quality and aquatic life. Among the economic sectors with the greatest relevance to water scarcity is agriculture, which currently accounts for 72% of all global freshwater withdrawals, intensifying water scarcity as resource demand continues to grow at more than double the rate of population growth (FAO, 2025). It is considered the largest consumer of water in the global economy (Hertel & Liu, 2016).

In the Philippines, the swine industry is reported to be the 2nd largest economic contributor in the agricultural sector next to rice, with 14.47% of agriculture's value of production from 2000 to 2020 (Fang & Cenon, 2025), with an estimated total inventory of 1.74 million MT heads in 2022, with an 11.4% share in Region 4A CALABARZON (BOI, 2023). Alongside its economic growth, environmental issues have been a concern due to the waste it generates, including manure, dead animals, and wastewater. Traditionally, swine farms dump effluents into open spaces, rice fields, and bodies of water such as lakes, creeks, and rivers, which are expected to worsen soil, air, and water quality. On May 24, 2016, DENR Administrative Order (DAO 2106-08) was issued, underscoring the need for agricultural industries to invest in technologies or

methods for wastewater treatment. Anaerobic digestion is a viable technology used by agricultural industries because it produces energy while treating the water. However, biogas effluents remain characterized by elevated BOD and COD levels, with nutrients mineralized into ammonium nitrogen ($\text{NH}_4\text{-N}$) and orthophosphates ($\text{PO}_4\text{-P}$), thereby increasing nutrient density while lowering organic stability (Maneetob *et al.*, 2025). The nutrient concentration and low oxygen availability in the effluent affect the receiving bodies of water and biodiversity. Therefore, further treatment of the biogas digester effluent is required before discharge.

Chemical coagulation and membrane filtration are conventional wastewater treatment technologies. The use of coagulants has negative effects on health and the environment due to their toxic and hazardous properties (Denzil *et al.*, 2023), whereas membrane filtration is too costly. Ceramic and polymer are the two materials for membrane fabrication. Polymeric membranes are cheaply produced and have good filtration efficiency in water treatment; however, they have a short lifetime and poor stability due to fouling. Ceramic membranes, in contrast, have high resistance to fouling and high removal efficiency but are expensive. A combination of polymer and ceramic is a good material for wastewater treatment, which consists of a polymeric active layer and a ceramic support substrate (He *et al.*, 2019). Compared to polymeric alternatives, ceramic membranes exhibit exceptional durability and maintain consistent removal rates of 95.3% for Chemical Oxygen Demand and 98.3% for ammonium-nitrogen, even under significant seasonal temperature changes (Wang *et al.*, 2025). A ceramic support provides high

porosity and superior chemical and mechanical stability to the polymer membrane and has attracted tremendous attention in water and wastewater treatment. Ceramic membranes offer a durable solution for treating concentrated livestock wastewater. They achieve over 94% COD removal and sustain high flux rates under organic loads that would typically cause permanent fouling in traditional polymeric membranes (Hassan *et al.*, 2025). However, fabricating ceramic supports is costly. Utilizing volcanic ash or expanded clay granules as a mechanical scouring agent expands a self-cleaning filtration system between chemical cleaning cycles in swine waste treatment (Ghasemzadeh & Lulianelli, 2026). Thus, developing ceramic filter membranes from naturally occurring materials is of growing interest.

The main considerations in developing ceramic filters are the membrane properties and the materials that can efficiently remove contaminants from wastewater. One potential alternative material is volcanic ash from a volcanic eruption. There are 300 volcanoes in the Philippines, of which 22 are active, most of them located in Luzon. Multiple volcanic eruptions occurred at Taal volcano, which emitted thousands of km³ of ash and continued to have multiple explosions since June 2021. The mineralogical composition of volcanic debris deposits contains SiO₂, Al₂O₃, CaO, Fe₂O₃, MgO, K₂O, and Na₂O as major components with 40–75 wt% silica (Lemougna *et al.*, 2011). Owing to its physical and chemical characteristics, particularly its high silica and alumina content and its availability, it can be used as a ceramic membrane material for wastewater treatment. However, wastewater treatment using volcanic ash as a ceramic filter is constrained by its low mechanical strength in

water; thus, incorporating the highly stable chitosan polymer is necessary to obtain a stronger ceramic membrane for water treatment.

MATERIALS AND METHODS

Experimental Procedure

The flow of the experiment in this study began with the collection and preparation of raw materials used to develop VACCCM. The development of VACCCM depended on the thickness of the ceramic disk and the amount of chitosan. Treatment of the biogas digester effluent using VACCCM was conducted following an analysis of the water properties before and after treatment. Volcanic ash was produced under optimal conditions, and its properties were characterized.

Collection and Preparation of Volcanic Ash

The volcanic ash was obtained from Subic, Agoncillo, Batangas, without further purification, and placed in a plastic container. The ash was dried in a cabinet dryer at 70°C until its moisture was removed. The dried samples were sieved through a 50-mesh Tyler screen to obtain homogeneous samples and stored in zip-lock plastic bags to prevent moisture adsorption.

Collection of Biogas Digester Effluent

The effluent discharge was collected at the Agricultural Training Institute–International Training Center on Pig Husbandry (ATI-ITCPH), Lipa City, Batangas. Bulk particles in the swine biogas digester effluent were removed using a plastic kitchen strainer. Thirty liters of swine biogas digester effluent were collected for the study.

Preparation of Composite Ceramic Disk

Ceramic composite membranes were

prepared by sieving the volcanic ash using a sieve shaker to obtain homogeneous ash with an average particle distribution of 50 mesh. The membrane was fabricated by mixing the main support layer materials, including 40 wt% volcanic ash, 40 wt% red clay, 20 wt% alumina, and a 10 wt% additive mixture of carboxymethyl cellulose, polyethylene glycol, sodium citrate, and MgSO_4 . To allow the mixture to produce a viscous solution, water was added to the mixture at varying amounts (20%, 30% and 50%). The ceramic paste was molded under controlled pressure into a circular disk ($\phi = 10.0\text{cm}$; thickness of 1.00-1.50cm) and dried in ambient air for 7 days to allow gradual water removal. The ceramic disk, with no cracks encountered, was dried at 200°C for 1 h to remove residual water, heated to 300°C to remove organic content, and finally heated to 1000°C for 6 h to open the membrane pores. The design of the composite ceramic filter disk is shown in Figure 1.

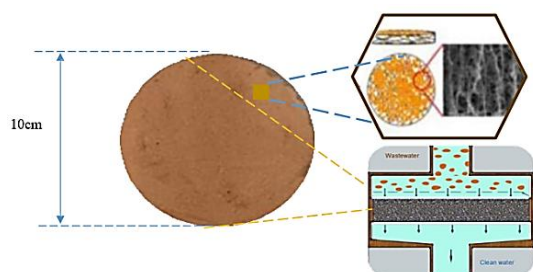


Fig. 1: Composite ceramic filter disk

Support layer coating with chitosan solution: Composite membranes were fabricated via dip-coating in chitosan solution. Chitosan solutions were formulated by dissolving 1% chitosan, 1 wt% PEG 400, and 1 wt% $\text{Al}(\text{OH})_3$ in acetic acid. The circular disk ceramic support layer was subsequently immersed in the prepared chitosan solution, with coatings applied in either a single or double layer. The membrane was heated in an oven at 40°C for 24 h.

Fabrication of ceramic filter assembly: A 2-liter capacity ceramic filter assembly was used. The composite ceramic filter disk will be installed in the middle, where the water will pass through. The flow of water can be controlled using a vacuum pump attached to the catch holder under the composite ceramic disk.

Collection of Biogas Digester Effluent

The biogas digester effluent was collected in a single batch from the Agricultural Training Institute - International Training Center on Pig Husbandry (ATI-ITCPH) in Lipa City, Batangas, to ensure sample uniformity across all treatments. Four black containers (dimensions: $34.5\text{ cm} \times 18\text{ cm} \times 39\text{ cm}$; capacity: 20 L each) were cleaned with water, dried, and used for effluent collection. ATI-ITCPH facilitated the collection process, and the filled containers were transferred to the Chemical Engineering Laboratory at Batangas State University. Upon arrival, the samples were homogenized in an 80 L drum and filtered using a filter cloth to remove large debris. For each treatment, a 1 L sample was placed in a plastic bottle, shaken thoroughly, and then subjected to the designated treatment process. The collection and handling of digester effluent follow safety protocols to prevent contamination with pathogens and bacteria in the workplace.

Treatment of Biogas Digester Effluent

The treatment process was conducted using ceramic disk filters with varying support layer thicknesses (0.80-1.20 cm) and chitosan coating layers (1 or 2). The experimental design for treating the digester effluent followed a 2^2 factorial design, with factors including ceramic disk thickness and the number of chitosan layers. Four experimental

runs were performed, each in triplicate, for a total of 12. The experimental design is shown in Table 1. The thickness of the molded membrane decreased from 1.50 cm to 1.20 cm, while the 1.00 cm samples were reduced to 0.80 cm after drying and firing. After each run, the treated samples were collected from the vacuum flask and subsequently transferred to a 1-L glass beaker for further analysis.

Table 1. 2^k factorial design matrix for treatment of digester effluent using VACCCM

Run	Thickness cm	Chitosan (coats)
1	0.80	1
2	0.80	2
3	1.2	1
4	1.2	2

A circular disk with a diameter of 10.0 cm was used to provide sufficient filtration area for laboratory-scale vacuum filtration and to ease handling and fabrication. A thickness range of 0.80–1.20 cm was used to evaluate the effect of disk thickness on filtration efficiency and flow behavior. Meanwhile, one and two chitosan coating layers were used to examine the effect of surface modification level on pollutant removal performance. The single layer provided the initial coating, while the two layers provided increased surface coverage without excessive pore blockage. These factor levels were selected as practical operating conditions based on preliminary fabrication and to capture potential changes in permeability and treatment efficiency.

Determination of Effluent Properties

The properties of swine wastewater, including pH, color, TDS, and TSS, nitrates, phosphates, chemical oxygen demand (COD), biochemical oxygen demand (BOD), and

turbidity, were measured at the Chemical Engineering Analytical Laboratory, Batangas State University, Main Campus II. The ASTM standard for non-filterable matter in water was used for TDS and TSS. The samples were tested for coliforms and iron content at Nanotech Analytical Services and Training Corp. (NASAT) Labs in Laguna.

Statistical Treatment of Data

The experimental data were analyzed using a 2^k factorial design to evaluate the effects of membrane thickness and chitosan concentration on the treatment performance of swine biogas digester effluent. Statistical analysis was performed using Analysis of Variance (ANOVA) under the General Linear Model (GLM) in Minitab to determine the significance of the main effects and their interaction at a 95% confidence level ($p < 0.05$). Additionally, a paired t-test was conducted to assess the significance of differences in the physicochemical properties of the wastewater before and after treatment. All results are presented as mean values, and statistical significance was determined based on the computed p-values.

RESULTS AND DISCUSSION

Development of VACCCM

A volcanic ash chitosan composite ceramic membrane (VACCCM) was developed by coating a ceramic membrane containing 40 wt% volcanic ash, 40 wt% red clay, 20 wt% alumina, and a 10 wt% additive with a chitosan polymer solution at varying water content (20, 30, and 50%). Low water content (20%) resulted in a mixture that was too dry, yielding a rigid, brittle consistency. When the solid components (volcanic ash, kaolin clay, alumina) are not adequately hydrated, they do not achieve the necessary

plasticity for molding, resulting in a final product that is overly hard and prone to cracking during drying and firing. Lower water content in ceramic mixtures can lead to increased brittleness and reduced workability, which may hinder the formation of a homogeneous mixture and result in poor mechanical properties due to inadequate bonding between particles (Palhares *et al.*, 2022; Zhang *et al.*, 2023).

Increasing the water content to 50 wt% resulted in a mixture that was too fluid, making it difficult to mold effectively. This watery mixture resulted in a lack of structural integrity, as the excess water can create a slurry that does not hold its shape during processing. Increasing water content generally decreases density and mechanical strength due to higher porosity and reduced particle interactions (Huang *et al.*, 2022; Zhang *et al.*, 2023). In this context, a very watery mixture poses challenges for achieving a stable form before firing.

Using 30 wt% water achieved a balance between sufficient hydration for workability and maintaining enough solid content for structural integrity. This formulation allowed for adequate moisture without compromising the mechanical strength of the mixture. The result was a pliable consistency that facilitated molding while still achieving a porous structure upon firing. A balanced ratio allows for effective particle bonding while minimizing porosity (Palhares *et al.*, 2022; Huang *et al.*, 2022). The successful molding and firing of 30 wt% water resulted in improved consistency, with no cracks observed, thereby improving the mechanical durability of the ceramic membrane.

The use of 30 wt% water provided an optimal balance between adequate hydration for workability and sufficient solid content to preserve structural integrity. This

composition ensured enough moisture to achieve a workable mixture without compromising its mechanical strength. Consequently, the paste was easily molded and developed a desirable porous structure after firing. A well-balanced water-to-solid ratio promotes effective particle bonding while controlling excessive porosity (Palhares *et al.*, 2022; Huang *et al.*, 2022). Moreover, the use of 30 wt. % water resulted in successful molding and firing, producing ceramic membranes with uniform consistency and no visible cracking, thereby enhancing their mechanical durability.



Fig. 2: (a) Raw VACCCM, (b) Fired VACCCM

The developed VACCCM exhibited a porous structure with a bulk density of 1.3223 g/cm³, an apparent density of 2.69 g/cm³, and a porosity of 50.84%. This level of porosity indicates the presence of interconnected pore networks, which enable ceramic membranes to allow water passage while retaining contaminants. The silica-rich volcanic ash and alumina-containing clay used to produce the ceramic membrane are expected to exhibit affinity for water due to the polar nature of aluminosilicate materials. Although hydrophilicity and flow behavior were not directly measured, the observed structural properties are consistent with reported characteristics of porous ceramic membranes used in filtration applications (Lemougna *et al.*, 2011; Dong *et al.*, 2021; Zhu *et al.*, 2021; Kumar *et al.*, 2025). The combination of measured porosity and material composition suggests that the

VACCCM is suitable as a filtration medium.

Performance of VACCCM

The treatment efficiency of VACCCM across varying formulations was analyzed at different thicknesses and numbers of chitosan layers, and the effects on pH, color, TDS, TSS, EC, BOD₅, and turbidity were assessed. Table 2 shows the results of the analysis based on a 2^k factorial design with 12 runs.

Table 2. Treatment of digester effluent using VACCCM

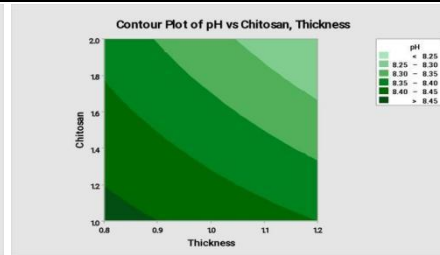
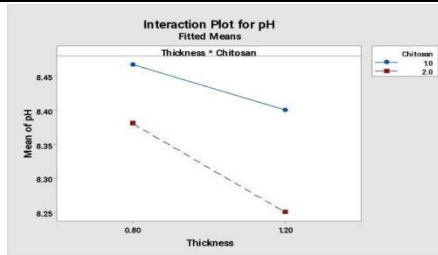
Thickness	Chitosan Layer	pH	Color (TCU)	TDS (mg/L)	TSS (mg/L)	EC (uS/cm)	BOD ₅ (mg/L)	Turbidity (NTU)
0.8	1	8.55	500	1527	86	3092	249	160.48
1.2	1	8.35	300	1393	26	2776	249	89.4
0.8	2	8.35	175	1420	18	3014	254	121.93
1.2	2	8.25	200	1120	16	2916	103	49.4
0.8	1	8.43	500	1560	88	3087	249	157.59
1.2	1	8.4	300	1354	25	2758	250	101.69
0.8	2	8.38	175	1400	19	2975	254	126.75
1.2	2	8.2	200	1080	17	2845	109	59.04
0.8	1	8.42	500	1530	87	3102	247	152.29
1.2	1	8.45	300	1385	24	2795	249	108.92
0.8	2	8.41	175	1420	20	2998	253	126.99
1.2	2	8.3	200	1080	15	2891	113	54.46

The interaction plot and contour plot in Figure 3a illustrate an inverse relationship between the thickness of the volcanic ash chitosan composite ceramic membrane (VACCCM) and the pH of the biogas digester effluent. An increase in membrane thickness is associated with a decrease in pH after treatment. Doubling the chitosan coating on the membrane further reduces pH, potentially reaching neutral levels as the coating thickness increases. With a single coat, increasing the membrane thickness from 0.80 cm to 1.20 cm results in a pH decrease from approximately 8.47 to 8.41, and when upgraded to a double coat, the slope becomes steeper, causing the pH to drop from approximately 8.38 to 8.26 as the membrane thickness increases from 0.80 cm

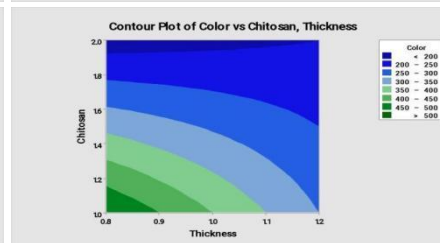
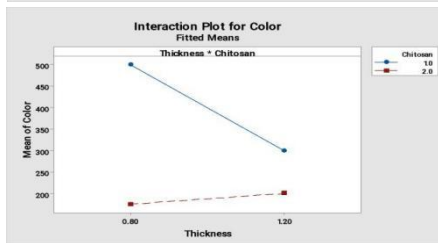
to 1.20 cm. The biogas digester effluent maintains the highest pH when treated with a double-coated membrane with a thickness below 0.9 cm. In contrast, the effluent's pH reaches its lowest value when the membrane is single-coated, and the thickness exceeds 1.1 cm. The thickness ($p=0.012$) and the chitosan layer ($p=0.005$) have a significant effect on pH; the interaction is not significant ($p=0.329$). The combination of volcanic ash and chitosan in the membrane likely intensifies the release of acidic substances, explaining the observed pH reduction in the VACCCM study.

The opposite effects of single and double chitosan coatings on the color of the biogas digester effluent were observed, similar to those reported by Hidayati *et al.* (2021). Chitosan significantly reduced the color of shrimp-washing wastewater, achieving an 84% reduction in True Color Units (TCU) from 278 to 46 TCU at an optimal concentration of 200 ppm. This aligns with the VACCCM study's observation that increasing the thickness of the single-coated membrane drastically lightens the color, reducing TCU from 500 to 300 as the thickness increases. The steep reduction in color with a single coat suggests that chitosan's ability to coagulate and remove color-causing particles is highly efficient in the initial coating. In contrast, the double-coated membrane in the VACCCM study darkens the effluent's color as membrane thickness increases but still produces a lighter color than the single-coated membrane overall. The thickness ($p<0.001$), chitosan layer ($p<0.001$), and their interaction ($p<0.001$) have a significant effect on color. This trend could be explained by the saturation of chitosan's adsorption sites, as noted in the study by Mary & Leena (2022), which found that chitosan completely

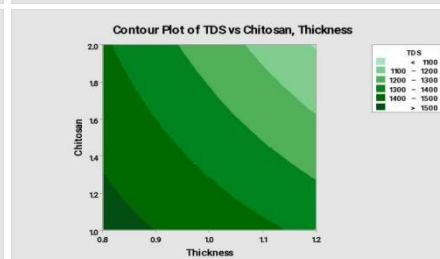
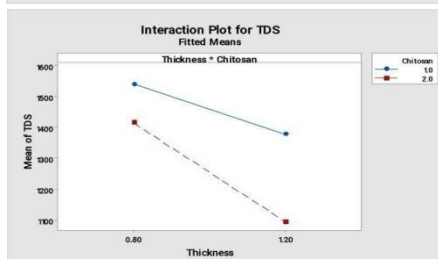
(a)



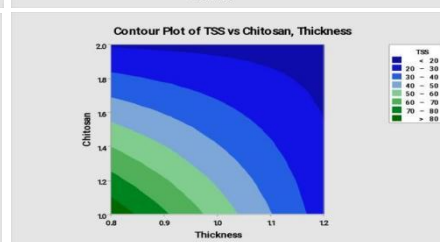
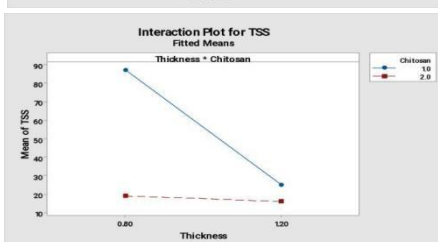
(b)



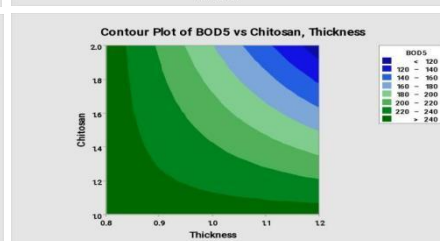
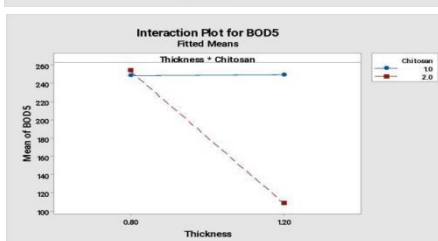
(c)



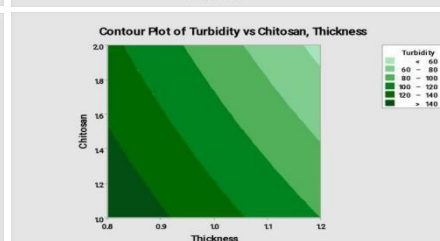
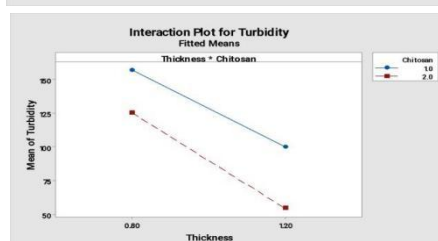
(d)



(e)



(f)



(g)

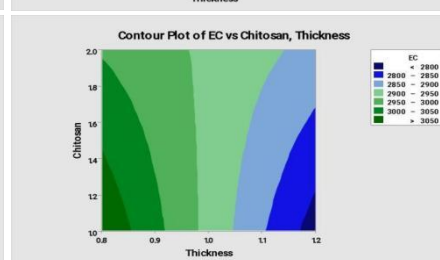
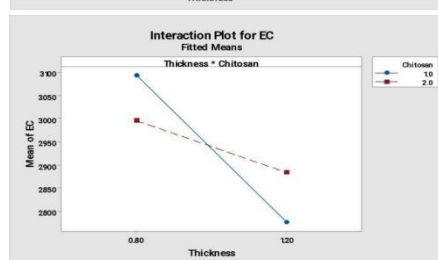


Fig. 3: Interaction plot of thickness and chitosan layer against (a) pH, (b) color, (c) TDS, (d) TSS, (e) BOD5, (f) turbidity and (g) electrical conductivity-EC

removed color from textile effluent. Still, the adsorption efficiency depends on proper dosage and application.

Regarding TDS, there is an inverse relationship between membrane thickness and TDS removal. In the VACCCM study, both single- and double-coated membranes reduce TDS, with the double-coated membrane being more effective as thickness increases. As the thickness increases from 0.80 cm to 1.20 cm, the single-coated membrane reduces TDS from 1550 mg/L to 1370 mg/L, while the double-coated membrane achieves a larger reduction from 1430 mg/L to 1090 mg/L. The thickness ($p < 0.001$) and chitosan layer ($p < 0.001$) and their interaction ($p < 0.001$) have a significant effect on TDS, supported by the study of Al-Manhel *et al.* (2016), who found that higher concentrations of chitosan significantly reduced TDS, with 1 g/100 ml reducing TDS to 4.13 g/L. The increased efficiency of the double-coated membrane likely stems from the additional chitosan coating, enhancing its adsorption capacity, similar to the dosage-based improvement.

The interaction plot for TSS shows that a double-coated membrane is more effective at removing total suspended solids (TSS) compared to a single-coated membrane. Increasing the thickness resulted in a drop in TSS from approximately 87 mg/L to 25 mg/L with the single-coated membrane, whereas it decreased slightly from approximately 19 mg/L to 15 mg/L with the double-coated membrane. In contrast, using a double-coated membrane with a thickness greater than 1.1 cm, the TSS significantly dropped to below 20 mg/L. A study by Kochan *et al.* (2009) investigated the filtration performance of coating-modified polymeric membranes, including the effects of membrane thickness on filtration efficiency. The study concluded

that increasing membrane thickness can affect suspended-solid removal efficiency, providing insights relevant to this study. The thickness ($p < 0.001$), chitosan layer ($p < 0.001$), and their interaction ($p < 0.001$) have a significant effect on TSS.

Regarding BOD₅, the study reveals that the single- and double-coated membranes exhibit distinct effects on BOD₅ levels as membrane thickness increases. The single-coated membrane shows a slight increase in BOD₅, rising from approximately 250 to 255 mg/L, while the double-coated membrane demonstrates a significant decrease in BOD₅, dropping from about 257 mg/L to 110 mg/L. This stark contrast in BOD₅ performance can be linked to findings from supporting studies, such as the work by Castaneda-Olivera *et al.* (2023), which reported that a chitosan-based sponge achieved a 63.15% reduction in BOD₅ at a concentration of 15 mg/mL. This suggests that the chitosan coating enhances the membrane's ability to coagulate and adsorb organic matter effectively, resulting in a substantial decrease in BOD₅ when using the double-coated membrane. In Bonisławska *et al.* (2016), a two-stage ceramic membrane filtration system achieved up to 96.1% BOD₅ removal from aquaculture effluent. This supports the observation in the VACCCM study that a double-coated membrane effectively reduces BOD₅, as the additional chitosan layer likely provides greater surface area and more active sites for binding organic pollutants. The thickness ($p < 0.001$), chitosan layer ($p < 0.001$), and their interaction ($p < 0.001$) have a significant effect on BOD. Similarly, Lawal *et al.* (2020) reported BOD₅ removal efficiencies of 72.91% to 78.93% using composite ceramic filters, emphasizing that the ceramic component effectively reduces organic load. The mechanisms observed in these supporting

studies reinforce the idea that increasing the chitosan content in the VACCCM enhances coagulation and organic matter adsorption, thereby drastically lowering BOD₅ levels.

The single-coated membrane reduces turbidity from approximately 155 Nephelometric Turbidity Units (NTU) to 110 NTU, while the double-coated membrane achieves a more significant reduction from around 126 NTU to 55 NTU. The thickness ($p < 0.001$) and chitosan layer ($p < 0.001$) have significant effects on turbidity, but their interaction ($p < 0.771$) does not have a significant effect on BOD. This improved performance of the double-coated membrane can be explained by mechanisms highlighted in the study by Zeng *et al.* (2012), which demonstrated that chitosan acts as a coagulant, effectively bridging colloidal particles to promote their aggregation and sedimentation. This study supports the observation that chitosan enhances the coagulation and adsorption of organic matter, leading to substantial reductions in BOD₅ when incorporated into membrane systems.

Electrical conductivity (EC) reduction in biogas digester effluent highlights significant differences between single-coated and double-coated membranes. The study found that increasing the thickness of the single-coated membrane from 0.80 cm to 1.20 cm resulted in a notable decrease in EC, reaching a minimum of approximately 2760 $\mu\text{S}/\text{cm}$. This is in contrast to the double-coated membrane, where the EC only decreased slightly, from around 3000 $\mu\text{S}/\text{cm}$ to 2900 $\mu\text{S}/\text{cm}$. The improved performance of the single-coated membrane in lowering EC can be attributed to its mechanism of binding and removing dissolved minerals. This observation is consistent with the findings of Li *et al.* (2024), who reported that increased

membrane thickness enhances ionic removal efficiency by improving adsorption capacity and extending diffusion pathways. Chitosan effectively reduces EC by binding salts through chelation, with significant EC reduction due to ion binding and sedimentation mechanisms (Al-Manhel *et al.*, 2016). However, the non-significant effect of the coating layer ($p < 0.723$), despite its interaction with thickness ($p < 0.001$), can be explained by saturation of active sites and mass-transfer limitations. The reduction in EC from 10.18 to 5.27 mS/cm when increasing chitosan concentration to 1 g/100 ml, achieving a maximum reduction of 18.92%. Once a sufficient chitosan layer is established, additional coating does not proportionally increase ion removal because diffusion resistance increases, while the number of accessible functional groups remains relatively constant. This phenomenon is further supported by Fernandez *et al.* (2025), who emphasized that excessive polymer coating leads to diffusion-controlled transport due to active site saturation and increased resistance to mass transfer. Similarly, Zhang *et al.* (2024) and Kumar *et al.* (2025) confirmed that increasing coating thickness beyond the optimal level results in diminishing returns due to pore blockage, reduced permeability, and limited ion diffusion into deeper layers. Thus, while membrane thickness significantly enhances EC reduction by improving adsorption capacity and contact time, adding multiple coating layers does not yield a statistically significant improvement because the process becomes diffusion-controlled rather than adsorption-limited. This explains why the single-coated membrane exhibited superior EC reduction performance compared to the double-coated configuration.

Based on the results of the 2^k factorial

analysis, the best VACCCM parameter for treating biogas digester effluent is at the center of the minimum and maximum settings (1.0cm), while 2-layer coats provide better results.

Characterization of the Developed VACCCM under the Best Conditions

Surface Morphology

The volcanic ash–chitosan composite ceramic membrane filter contains pores that provide essential insights into filtration applications, and the pores distribution was presented. The percent composition of elements present contains Oxygen (48.01), C (4.85), Si (17.31), Fe (10.97), Al (9.5), Na (2.47), Ca (3.43), Ti (0.54), Mn (0.14), Mg (1.02), S (0.07), and K (0.01). The carbon is attributed to the presence of chitosan in the sample. At the same time, while the dominant elements such as Si, Al, Fe, Na, and Ca, are due to the volcanic ash, clay, and alumina used in the preparation of the ceramic disk.

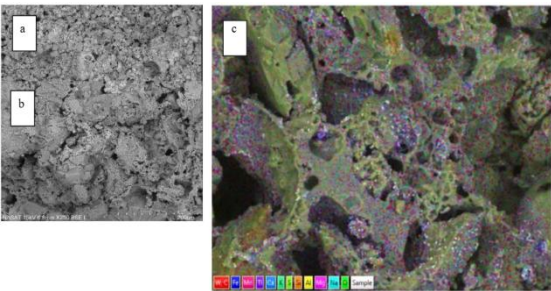


Fig. 4: SEM images of volcanic ash chitosan composite membrane (a) 50x; (b) 250x and (c) 1000x magnification

Pore Size

A large number of interconnected pores are available, which is important for the efficiency of the VACCCM in treating of digester effluent. All the pores fall within the macroporous range, as their lengths exceed 50 nm. This classification is crucial because

macroporous membranes are typically used in filtration and scaffolding applications due to their larger pore sizes, which allow them to filter larger particles and provide structural support. The pores are classified as macroporous ($1.23 \pm 0.32 \mu\text{m}$), suitable for water filtration applications that require larger pore sizes to permit the water passage while trapping contaminants.

Thermal Stability

VACCCM exhibited three (3) stages of degradation throughout the thermal stability testing. The TGA-DTGA relationship of VACCCM and TGA thermograms was presented in Figures 5 and 6.

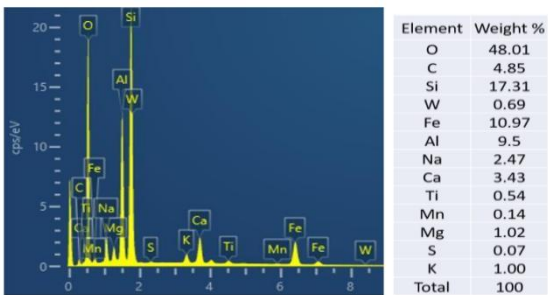


Fig. 5: EDS spectra of volcanic ash chitosan composite membrane and elemental composition

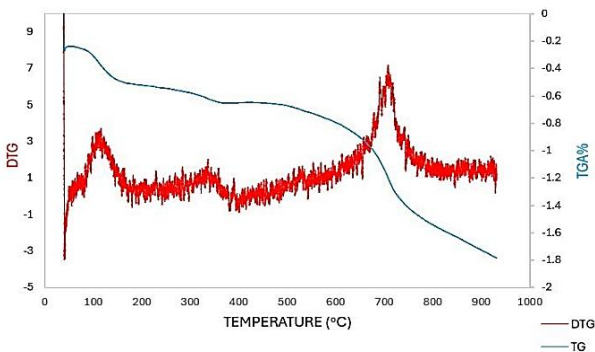


Fig. 6: TGA-DTGA relationship of VACCCM

The first stage of degradation occurred between 47.19 °C and 337.35 °C, with a peak temperature (T_{max}) of 311.56 °C. This amounted to 22.629% (5.892 μg) loss of the sample. According to Stephy (2022), chitosan

undergoes thermal degradation in a single-step reaction, with initial degradation temperatures typically around 31 °C to 313 °C, depending on the molecular weight and composition of the chitosan sample. At elevated temperatures, chitosan dehydration is followed by its degradation, with the primary pathway involving cleavage of glycosidic bonds and release of volatile compounds. This coincides with the second stage, observed at 672.36 °C and accounting for an additional mass loss of 24.784% (approximately 9.809 µg), reflecting the breakdown of organic components within the composite. At this temperature, the polymer chains degrade further as evidenced by a significant mass loss. The major reactions at this stage are the cleavage of glycosidic bonds and volatilization of small organic components. TGA analysis reveals that at 672.36 °C, chitosan has presumably decomposed to a significant extent, as the sample weight percentages will likely be substantially different before and after this temperature. Finally, the third stage occurred from 732.36 °C to 950 °C, peaking at 930.17 °C, during which the sample experienced a significant mass loss of 52.115% (approximately 23.041 µg), resulting in ash residue indicating the remaining inorganic content after thermal treatment.

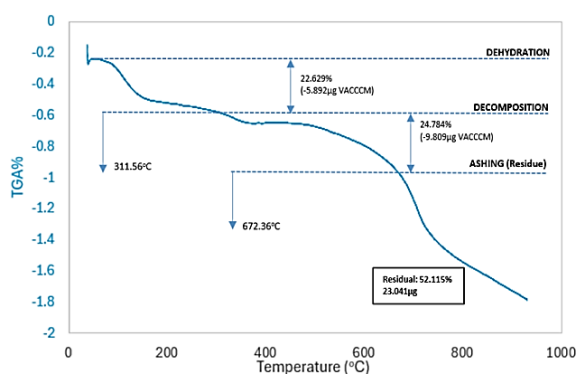


Fig. 7: TGA thermogram of VACCCM

According to Aranaz (2021), the ashing stage in thermogravimetric analysis (TGA) of chitosan typically occurs at high temperatures, such as 900-950 °C, where residual organic components are incinerated. It can be observed that minerals mainly contribute to inorganic residues, but also other non-combustible materials.

Flexural test

The mean flexural strength of 2.29 MPa, with a standard deviation of 0.503, indicates moderate strength, with some variation likely due to differences in material composition or microstructural defects. Flexural stress at break is recorded at 2.20 MPa, slightly lower than the flexural strength, and a standard deviation of 0.626 suggests moderate variability in how specimens behave under stress before breaking. The flexural modulus, representing the material's stiffness, is 0.269 GPa with a low standard deviation of 0.004, indicating consistent flexibility across samples.

Compressive strength

The mean compressive strength is 2.74 MPa, with a standard deviation (SD) of 2.03 MPa, which indicates that the material's capacity to withstand compressive forces varies somewhat around this average. The compressive strength at yield, where the material begins to deform permanently, is also measured at 2.74 MPa with an SD of 2.03 MPa, suggesting consistency between the peak compressive strength and the yield point.

The modulus of elasticity, a measure of the material's stiffness or resistance to elastic deformation, is 0.096 GPa, with a relatively small SD of 0.031 GPa. This indicates that the material exhibits moderate stiffness, with only minor variation in its elastic deformation under stress.

Membrane Performance Evaluation

In addition to effluent quality, membrane performance was evaluated based on permeate flux behavior and operating conditions. The best VACCCM formulation exhibited an average permeate flux of $608.75 \text{ L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$, with a maximum flux of $731.67 \text{ L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$, observed at approximately 10 minutes of operation. The calculated transmembrane pressure (TMP) was 85.325 kPa based on a feed pressure of 101.325 kPa and a permeate/vacuum pressure of 16 kPa. The filtration process showed an initial adjustment period followed by a relatively stable flow regime, as indicated by a flux decline ratio of 0.2675 (Figure 8).

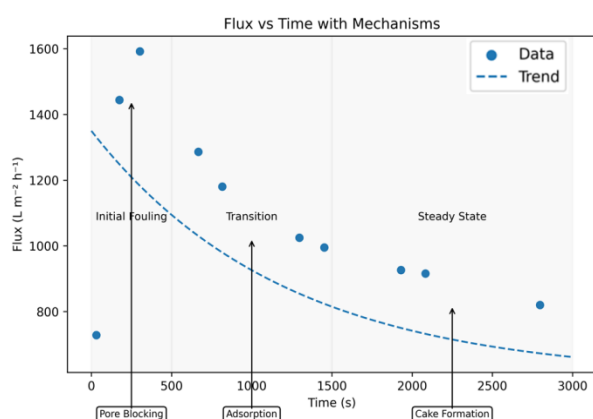


Fig. 8: Flux versus time profile of VACCCM showing an initial adjustment period followed by stabilization

The flux profile shows an initial fluctuation followed by gradual stabilization, indicating the development of filtration resistance due to partial pore blocking. The dashed line represents the fitted trend, indicating steady-state behavior resulting from a balance between permeation and fouling mechanisms. The relatively stable flux at later stages suggests a balance between permeation and fouling mechanisms with acceptable antifouling performance of the membrane. Similar flux-stabilization behavior

has been reported in composite ceramic membranes and biopolymer-modified systems (Zhang *et al.*, 2024; Kumar *et al.*, 2025). This behavior may be associated with the membrane's porous structure and material composition, which facilitate water transport while limiting rapid pore blockage. Moreover, the applied TMP has helped maintain a relatively stable permeation rate during operation (Li *et al.*, 2024; Fernandez *et al.*, 2025). Based on the figure, the flux–time profile can be divided into three distinct regions: (i) an initial fouling phase (0–500 s) characterized by a rapid decline in flux due to pore blocking and adsorption; (ii) a transition phase (500–1500 s), where the rate of flux decline decreases as cake layer formation begins; and (iii) a steady-state phase (>1500 s), where flux stabilizes, indicating a dynamic equilibrium between foulant deposition and removal. The relatively stable flux behavior, as reflected in the low flux decline ratio, further supports the membrane's moderate fouling tendency and acceptable antifouling performance.

Comparison of the Properties of Biogas Digester Effluent Before and After Treatment Using the Developed VACCCM at the Best Condition

Table 3 presents the comparison of digester effluent before and after treatment, including % removal efficiencies for key parameters to assess treatment performance. Non-concentration parameters (pH and temperature) are reported as absolute changes.

Temperature

Analysis of the treated biogas digester effluent using the developed VACCCM showed a reduction in temperature from 84.0°F to 82.6°F ($p = 0.02$), indicating a

statistically significant change. However, the magnitude of the reduction ($1.4^{\circ}\text{F} \approx 0.8^{\circ}\text{C}$) is minimal and does not represent a practically significant effect in wastewater treatment, and it falls within the DAO Class C standard ($77.0\text{--}87.8^{\circ}\text{F}$). This confirms that effluent temperature remains within acceptable regulatory limits before and after treatment. The observed variation may be attributed to normal heat exchange during filtration and to sampling conditions, such as contact with the porous ceramic matrix and the ambient environment. Due to a small difference, this parameter is not considered a primary indicator of membrane performance, and no definitive conclusion can be drawn regarding the effect of the VACCCM on temperature.

Table 3. Comparison of digester effluent before and after treatment

Properties	Before Treatment	After Treatment	% Reduction	T-value	p-value
Temperature	84.0	82.6	*	7.0	0.02
TDS	1878.7	1093.3	41.82%	26.86	0.001
pH	8.8	8.3	*	6.68	0.022
Electrical Conductivity	3761.7	2884.0	23.33%	27.35	0.001
Turbidity	338.0	54.3	83.93%	32.30	0.001
TSS	321.3	16.0	95.02%	16.75	0.004
Phosphates	63.9	6.8	89.36%	41.36	0.001
COD	770.0	220.0	71.43%	47.06	<0.001
BOD ₅	430.0	108.0	74.88%	92.43	<0.001

*% Removal efficiency is not applicable to temperature and pH as they are non-concentration-based parameters; thus, they are reported as absolute changes ($\Delta T = 1.4^{\circ}\text{C}$; pH: $8.8 \rightarrow 8.3$, indicating slight neutralization)

Total Dissolved Solids (TDS)

A notable improvement in water quality was observed in the reduction of Total Dissolved Solids (TDS), which decreased by 41.82% from 1878.7 mg/L to 1093.3 mg/L,

representing a statistically significant reduction ($p = 0.001$). This substantial decrease in dissolved salts and particles enhances the effluent's quality, making it less harmful when discharged into the environment. Supporting this conclusion, Al-Manhel *et al.* (2016) found that increasing chitosan concentration decreased TDS from 5.67 g/L to 4.13 g/L. This trend indicates that chitosan, a natural biopolymer, effectively binds to dissolved particles and facilitates their aggregation during filtration.

pH

The pH of effluent is a critical parameter that reflects the water's chemical characteristics and influences its treatment efficacy. In this study, the pH of the effluent decreased from 8.8 before treatment to 8.3 after treatment ($p=0.022$), indicating a significant decrease in alkalinity. This reduction in pH is notable, as it suggests that the treatment process effectively neutralized some of the wastewater's alkalinity. The shift toward a lower pH is important for several reasons: it brings the effluent closer to neutral, enhancing its suitability for environmental discharge and potential reuse in industrial applications. As highlighted in the study by Al-Manhel *et al.* (2016), the use of chitosan in water purification has been shown to effectively reduce pH, along with other parameters such as turbidity and electrical conductivity. Their study demonstrated that increasing chitosan concentration significantly decreased pH from 6.1 to 5.71. This finding reinforces the importance of using coagulants like chitosan not only for removing contaminants but also for stabilizing treated water's pH, ensuring it meets environmental discharge standards. Extreme pH levels, whether too acidic or too alkaline, can harm aquatic ecosystems; thus,

the observed adjustment toward neutral pH is beneficial for the overall health of receiving waters and for compliance with regulatory requirements.

Electrical Conductivity

The reduction of 23.33% in electrical conductivity from 3761.7 $\mu\text{S}/\text{cm}$ to 2884.0 $\mu\text{S}/\text{cm}$ ($p = 0.001$) after treatment indicates a statistically significant difference in the concentration of dissolved ions. This finding aligns with the study conducted by Al-Manhel *et al.* (2016), which reported a decrease in EC from 10.18 mS/cm to 5.27 mS/cm as chitosan concentration increased. Chitosan is known to reduce EC by removing charged particles from water, such as salts and dissolved metals, through adsorption and coagulation. Furthermore, recent studies have shown that both chitosan and ceramic membranes can significantly influence EC in wastewater treatment. In a study conducted by Rasouli *et al.* (2021), ceramic membranes were shown to effectively reduce salt levels from wastewater, achieving over 98% removal of total suspended solids (TSS). Salt reduction is crucial because it directly affects the EC of the treated water. As salt concentrations increased, the permeate flux decreased due to fouling and concentration polarization. The significant reduction in EC observed in the study demonstrates the VACCCM's ability to produce treated effluent with lower EC and greater suitability for reuse, particularly in agricultural applications where high EC can affect soil salinity and crop yield.

Turbidity

The statistically significant decrease ($p=0.001$) in turbidity from 338 NTU to 54.3 NTU, representing a 83.93% reduction, highlights the effectiveness of the VACCCM in removing suspended solids. This noticeable

improvement shows the membrane's effective filtration capacity. These results are also supported by a study conducted by Al-Manhel *et al.* (2016), which showed that turbidity decreased from 1.98 NTU to 0.98 NTU with increasing chitosan concentration. According to Vijayan (2018), chitosan demonstrated prominent coagulation capabilities in water treatment applications. Specifically, at an optimal concentration of 80 mg/L and a pH of 9, chitosan reduced turbidity from 88 NTU to 3 NTU. This efficiency was observed in comparative analyses against conventional coagulants, such as aluminum sulfate (alum). The study highlighted chitosan's ability to significantly aggregate and precipitate suspended particulate matter, thereby enhancing water clarity. This demonstrates chitosan's effectiveness in aggregating and precipitating suspended particles, thereby enhancing water clarity. In comparison, the VACCCM study achieved a turbidity reduction from 338 NTU to 54.3 NTU, highlighting the membrane's effective filtration capacity. While both studies demonstrate significant turbidity removal, the VACCCM's performance suggests that combining chitosan with a ceramic membrane structure can further enhance turbidity reduction. These findings support the notion that integrating chitosan into membrane systems can lead to more efficient water treatment processes. Research by Abebe *et al.* (2016) further supports the use of chitosan in turbidity reduction. This study explored the application of chitosan as a coagulant in ceramic water filtration systems for household drinking water treatment. The results showed that chitosan, a biodegradable polymer derived from chitin in crustacean shells, effectively reduced turbidity in contaminated water samples. The

study employed model test water contaminated with *Escherichia coli* and coliphage MS2, with kaolinite clay used to simulate turbidity. By applying modified chitosan at doses ranging from 5 to 30 mg/L, the study achieved impressive turbidity reductions, consistently yielding values below 1 NTU, meeting both US EPA and WHO guidelines for safe drinking water.

Moreover, incorporating chitosan not only reduced turbidity but also enhanced the effectiveness of microbial removal in the filtration system. The average log reductions for *E. coli* ranged from 4.7 to 7.5, while virus reductions for MS2 ranged from 2.8 to 4.5, demonstrating the dual benefits of chitosan as a coagulant. This reinforces the findings of the current study, which show that chitosan's coagulation properties significantly improve the filtration efficacy of the VACCCM. As reported by Hidayati *et al.* (2021) and Mary & Leena (2022), chitosan has proven highly effective as a bio-coagulant for reducing turbidity. Chitosan's strong binding properties allow it to coagulate suspended particles and facilitate their removal through filtration. In shrimp-washing wastewater, for instance, adding chitosan reduces turbidity by 83%. When combined with ceramic membranes, particularly zirconia and alumina, which are known for their porous structure and hydrophilic nature, VACCCM can significantly enhance turbidity removal.

Total Suspended Solids (TSS)

The statistically significant decrease ($p=0.003$) in total suspended solids (TSS) from 321.3 mg/L to just 16.0 mg/L shows an effective reduction of 95.02%. This outcome aligns with findings from Iber *et al.* (2023), where chitosan's coagulation-flocculation properties were shown to achieve a 69.49% reduction in TSS in aquaculture wastewater,

primarily due to the interaction of chitosan's amino groups with suspended particles. Similarly, the study by Devi *et al.* (2014) demonstrated that chitosan effectively reduced TSS in textile effluent, underscoring the importance of optimizing dosages to maximize removal efficiency. The combined results of these studies highlight the critical role of chitosan in enhancing treatment processes to achieve substantial TSS reductions.

Phosphates and Iron

A substantial reduction in phosphate concentration was observed, decreasing from 63.9 mg/L to 6.8 mg/L, corresponding to an 89.36% reduction, which is statistically significant ($p<0.001$). This indicates a strong membrane effect on phosphate removal and suggests potential benefits for mitigating nutrient loading, which is associated with eutrophication in receiving water bodies. This performance is comparable to recent studies reporting that polymer-modified ceramic-based membranes achieve phosphate removal efficiencies typically ranging from 70% to 90% under similar treatment conditions (Kumar *et al.*, 2025). Similarly, the concentration of iron decreased from 0.19 ppm to 0.026 ppm, corresponding to 86.32% reduction, with a statistically significant difference ($p<0.001$). This is consistent with ceramic and composite membranes that achieve 80% to 95% removal of dissolved metal ions, depending on membrane composition and operating conditions (Li *et al.*, 2025). This result indicates the membrane's effectiveness in reducing iron levels, thereby improving the quality of the treated effluent.

The Chemical Oxygen Demand (COD)

The effluent exhibited a substantial

decline, decreasing from 770.0 mg/L to 220.0 mg/L, corresponding to 71.43% reduction following treatment. This significant reduction highlights the effectiveness of the applied treatment methods in reducing the organic load in wastewater. A lower COD indicates that the effluent contains fewer organic pollutants, which are known to deplete oxygen levels in receiving water bodies. Such high levels of organic pollution can lead to serious ecological consequences, including the deterioration of aquatic ecosystems due to hypoxia (low oxygen conditions). Thus, the treated water's COD level of 220.0 mg/L indicates improved water quality. This reduction aligns with findings from various studies emphasizing the efficiency of chitosan and ceramic membranes in wastewater treatment. For instance, Iber *et al.* (2023) reported that the use of chitosan in aquaculture wastewater resulted in significant reductions in both total suspended solids and COD, supporting the notion that these treatment methods effectively enhance water quality. Similarly, Devi *et al.* (2014) demonstrated that crab shell chitosan could effectively reduce COD levels in textile effluents, with optimal dosages achieving 80% reduction COD. This reinforces the importance of selecting appropriate coagulants for specific wastewater types. The study by Nasir *et al.* (2024) investigated the use of chitosan in combination with ceramic membranes to treat peat water, demonstrating a 29.11% reduction in TDS.

BOD₅

The Biological Oxygen Demand (BOD₅), which measures the oxygen required for biological decomposition of organic matter, decreases from 430.0 mg/L to 108.0 mg/L, corresponding to 74.88% reduction.

Considering that typical BOD₅ levels in wastewater from swine farms range from 2,000 to 4,400 mg/L, this reduction highlights that the treated water contains much less organic matter. The reduction of biochemical oxygen demand (BOD₅) is crucial in evaluating the organic load in wastewater, and the combination of chitosan and ceramic membranes has shown promising results in this regard. In a study conducted by Castaneda-Olivera *et al.* (2023), a chitosan-based sponge was used to treat wastewater from automotive repair shops, achieving 63.15% reduction in BOD₅ at a concentration of 15 mg/mL. This study highlights the versatility of chitosan, not only as a coagulant but also as an adsorbent, effectively capturing organic pollutants while enhancing overall treatment efficiency. The ability of chitosan to interact with organic materials enables effective removal, thereby improving water quality and reducing environmental impact.

Further emphasizing the efficacy of ceramic membranes, Bonisławska *et al.* (2016) studied a two-stage filtration system using ceramic membranes to treat aquaculture effluent. Their findings indicated a BOD₅ removal efficiency of 76% and a complete reduction in suspended solids. The first stage of filtration alone achieved significant reductions, while the second stage further enhanced BOD₅ removal to 96.1%. This study demonstrated the capabilities of ceramic membranes for treating complex wastewater streams and their potential to complement chitosan in effectively reducing organic loads.

Coliform

A substantial reduction in coliform levels was observed, decreasing from 35,000,000 to 920 MPN/100 mL. This change was statistically significant ($p < 0.001$), which

indicates a strong effect of the membrane on microbial reduction. The results demonstrate the effectiveness of the VACCCM in lowering coliform concentrations and improving the microbiological quality of the treated effluent.

Color

The effluent color decreased from 750 to 200 True Color Units (TCU), with a statistically significant difference ($p < 0.001$). This strong reduction suggests the removal of dissolved and particulate substances responsible for discoloration. Studies by Hidayati *et al.* (2021) and Mary & Leena (2022) further support the current study's findings, demonstrating the effectiveness of chitosan in reducing wastewater color. In shrimp-washing wastewater, chitosan reduced color by 84% at 200 ppm, while in textile effluent treatment, it eliminated color by the sixth day of treatment. With the current study, the color removal process is enhanced by a dual-action mechanism. Chitosan adsorbs color-causing molecules, while the ceramic membrane, composed of materials like alumina and titania, filters larger organic molecules that contribute to watercolor. This combination ensures that the treated water is both visually clear and free from harmful organic compounds.

Mechanism of Contaminant Removal

The removal of contaminants using the developed VACCCM is attributed to the combined effects of multiple mechanisms, rather than solely to membrane thickness and chitosan layers, as shown in Figure 9.

The macroporous ceramic matrix contributes significantly through physical filtration or pore sieving, in which the suspended solids (TSS) and coliform bacteria are retained within the interconnected pore

structure. In addition, the porous aluminosilicate membrane composition derived from volcanic ash and clay provides active sites that facilitate the adsorption of dissolved species, thereby reducing BOD₅, phosphates, and metal ions in the treated sample. Due to the cationic nature of chitosan, it further enhances removal efficiency through coagulation and adsorption, particularly on negatively charged species. Moreover, electrostatic interactions between charged contaminants and the membrane surface may contribute to the reduction of dissolved organic matter as reflected in the observed decrease in COD. Similar multi-mechanistic removal behavior has been reported, with composite and biopolymer-modified ceramic membranes demonstrating improved contaminant removal through combined filtration, adsorption, and electrostatic interactions (Zhang *et al.*, 2024; Kumar *et al.*, 2025; Li *et al.*, 2025). These combined mechanisms are governed by pore sieving, adsorption, electrostatic interactions, and chitosan-induced coagulation, which act synergistically to improve overall treatment performance while demonstrating that both the ceramic support and the chitosan coating play important roles in contaminant removal.

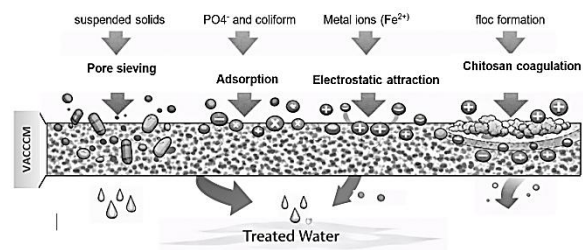


Fig. 9: Mechanism of contaminant removal using VACCCM.

Comparison of the Properties of the Treated Biogas Digester Effluent using the Developed Composite Ceramic Membrane with the DAO Class C Standard for Water.

The properties of the treated biogas digester effluent using the developed composite ceramic membrane were compared to the DAO Class C standard for water quality. Statistical differences between the before and after-treatment conditions were evaluated using a paired t-test with three replicates ($n=3$), in which the same samples were measured before and after treatment. The results are summarized in Table 4.

The comparison of treated biogas digester effluent against the DAO Class C standard reveals a mixed compliance profile. Most parameters, including temperature, total dissolved solids (TDS), pH, electrical conductivity (EC), total suspended solids (TSS), phosphates, chemical oxygen demand (COD), coliforms, and iron, show compliance with the DAO Class C standards. For example, the effluent temperature of 82.6°F is within the acceptable limit of less than 86°F, and the TDS concentration of 1093.3 mg/L falls within the specified range of 500 - 2000 mg/L.

However, two critical parameters—biochemical oxygen demand (BOD) and color indicate non-compliance. The BOD level of 108.0 mg/L significantly exceeds the Class C limit of 20-60 mg/L, with a p-value of 0.002 suggesting a meaningful difference that warrants attention. This value indicates a higher organic load in the effluent, which could potentially harm aquatic life if left untreated. Additionally, the color measurement of 200.0 TCU (true color unit) surpasses the allowable limit of <150 TCU, with a p-value of 0.001 indicating a significant deviation from the standard. The presence of color can be attributed to various organic compounds and may affect light penetration in water bodies. Further treatment is necessary to improve aesthetic quality and reduce potential environmental impacts.

In comparison, BOD₅ does not comply with the standards. Reducing Biochemical Oxygen Demand over 5 days (BOD₅) to acceptable levels is often difficult due to several interconnected physicochemical and biological factors (Tchobanoglous *et al.*, 2014). These challenges are particularly pronounced in complex wastewater such as aquaculture effluent, municipal sewage, and

Table 4. Comparison of treated effluent vs DAO class C standard

Properties	After Treatment	Class C Standard	p-value	Interpretation	Compliance with the DAO Class C
Temperature (F)	82.6	<86	0.994	Not significant	Compliant
TDS (mg/L)	1093.3	500 - 2000	1.000	Not significant	Compliant
pH	8.3	6.5 – 8.5	0.993	Not significant	Compliant
EC	2884.0	1000-3000	0.985	Not significant	Compliant
Turbidity (NTU)	54.3	1 - 50	0.131	Not significant	Compliant
TSS (mg/L)	16.0	<100	1.000	Not significant	Compliant
Phosphates (mg/L)	6.8	1 - 10	0.985	Not significant	Compliant
COD	220.0	150 - 500	1.000	Not significant	Compliant
BOD ₅	108.0	20 - 60	0.002	Significant	Non-Compliant

industrial discharge. According to Tchobanoglous *et al.* (2014), traditional primary and secondary treatments remove ~85% of BOD, but polishing the dissolved fraction requires advanced treatment. Crini & Lichtfouse (2019) note that the variability in organic content prevents uniform microbial treatment efficiency, especially in non-optimized systems. Judd (2011) reports that as membrane pores clog, dissolved organics may pass through more easily, reducing treatment efficiency. In essence, BOD₅ is hard to reduce to regulatory levels (often <20 mg/L for treated effluent) because simple filtration or conventional biological methods can't fully handle the diverse, dissolved, and sometimes refractory organic components of many wastewaters. To overcome this, integrated approaches—such as advanced oxidation (e.g., UV/H₂O₂), bioaugmentation, or membrane bioreactors (MBRs)—are often needed.

CONCLUSION

The Volcanic Ash–Chitosan Composite Ceramic Membrane (VACCCM) demonstrated strong potential in improving the treatment of swine biogas digester effluent. The membrane effectively reduced key physicochemical and microbiological contaminants, thereby improving water quality and supporting environmental sustainability in livestock operations. Despite these significant improvements, some parameters remain above regulatory standards, indicating that further optimization of the treatment process is necessary. Enhancements in system design and operational conditions may help achieve full compliance with environmental discharge requirements. VACCCM represents a promising and sustainable approach for

wastewater treatment; however, continued refinement is recommended to maximize its efficiency and broaden its practical application.

RECOMMENDATIONS

The Volcanic Ash–Chitosan Composite Ceramic Membrane (VACCCM) demonstrated superior filtration capabilities; however, additional optimization of its composition is advised to improve overall efficiency. Future research should focus on optimizing the ratios of volcanic ash, chitosan, and supplementary additives to enhance membrane durability, achieve more uniform pore structures, and ensure consistent filtration performance. Also, although the membrane significantly improved most water quality parameters, some indicators remain above the required levels. To solve this problem, it is suggested that VACCCM be combined with other treatment methods, such as biological methods or advanced oxidation processes, to enhance overall treatment effectiveness. Changes to membrane design, such as increasing pore size, increasing thickness, and using multi-stage filtration systems, could make it even easier to remove organic pollutants. Given its promising laboratory-scale performance, scaling up the production and application of VACCCM is also recommended. Future efforts should explore cost-effective fabrication techniques and the development of automated manufacturing processes to ensure quality remains consistent and make it easier to use in larger or industrial wastewater treatment systems.

ACKNOWLEDGEMENT

The authors would like to express their sincerest gratitude and appreciation to the following, who greatly contributed to the completion of the study and its realization. To the Batangas State University–The National Engineering University, for funding the research project, and to the Analytical Research Center (ARC), for providing the materials/equipment needed for the completion of the laboratory experiments and for their requisite observations and practical analyses important to the improvement of the study. To the Department of Agriculture–Agricultural Training Institute–International Training Center on Pig Husbandry (ATI-ITCPH), Lipa City, Batangas, for providing wastewater.

REFERENCES

- Abebe, L. S., Chen, X., & Sobsey, M. D., 2016. "Chitosan coagulation to improve microbial and turbidity removal by ceramic water filtration for household drinking water treatment." *Int. J. Environ. Res. Public Health*, 13(3), 269. <https://doi.org/10.3390/ijerph13030269>
- Al-Manhel, A. J., Al-Hilphy, A. R. S., & Niamah, A. K., 2016. "Extraction of chitosan, characterisation and its use for water purification." *J. Saudi Soc. Agric. Sci.*, 17(2), 186–190. <https://doi.org/10.1016/j.jssas.2016.04.001>
- Alotaibi, B. A., Baig, M. B., Najim, M. M. M., Shah, S. A., & Alamri, M. S., 2025. "Water scarcity: A global hindrance to sustainable development and agricultural production – A critical review of the impacts and adaptation strategies." *Cambridge Prisms: Water*, 3(e1), 1–18. <https://doi.org/10.1017/pwa.2024.12>
- Board of Investment, 2023. "Resource-Based Industries Service, Philippine Swine Industry."
- Bonisławska, M., Nędzarek, A., Drost, A., Rybczyk, A., & Tórz, A., 2016. "The application of ceramic membranes for treating effluent water from closed-circuit fish farming." *Arch. Environ. Prot.*, 42(2), 59–66. <https://doi.org/10.1515/aep-2016-0012>
- Castaneda-Olivera, C. A., Naupa Garay, Y. V., Ramon Gamboa, M. E., Espinoza Farfan, E. R., & Calderon Celis, J. M., 2023. "Crab chitosan-based sponge as an adsorbent for oil and grease in wastewater from an automotive repair shop." *Chem. Eng. Trans.*, 100, 19–24. <https://doi.org/10.3303/CET2310000>
- Crini, G., & Lichtfouse, E., 2019. "Advantages and disadvantages of techniques used for wastewater treatment." *Environ. Chem. Lett.*, 17(1), 145–155. <https://doi.org/10.1007/s10311-018-0785-9>
- Denzil D., Innocent N., and Walter R.R., 2023. "The potential and constraints of replacing conventional chemical coagulants with natural plant extracts in water and wastewater treatment." *Environ. Adv.*, 13, 100421. <https://doi.org/10.1016/j.envadv.2023.100421>
- Devi, K. S., & Ramasamy, K., 2014. "The effectiveness of chitosan as a coagulant aid in coagulation and flocculation of synthetic and real textile wastewater." *Int. J. Environ. Health Eng.*, 3(1), 8. <https://doi.org/10.4103/2277-9183.134911>
- Dong, Y., Chen, S., Zhang, X. and Yang, J., 2021. "Low-Cost Ceramic Membrane

-
- from Waste Materials for Water Filtration: A Review." *J. Environ. Chem. Eng.*, 9(2), 105047. <http://doi.org/10.1016/j.jece.2021.105047>
- Fang, P and Cenon, E., 2025. "An Assessment of Swine Industry in the Philippines." *J. Econ. Manag. Agricul. Dev.*, 7(1), 2148. <https://doi.org/10.22004/ag.econ.323954>
- Fernandez, M. A., Torres, E. and Gutierrez, J., 2025. "Role of Diffusion Resistance and Active Site Saturation in Biopolymer-Coated Filtration Membranes." *J. Environ. Chemical Eng.*, 13, (1), 111234. <http://doi.org/10.1016/j.jece.2024.111234>
- Food and Agriculture Organization of the United Nations., 2025. The state of the world's land and water resources for food and agriculture 2025: The potential to produce more and better. FAO, Rome, Italy. <https://doi.org/10.4060/cd7054en>
- Ghasemzadeh, K., & Iulianelli, A., 2026. "Hybrid models, digital twins, and digital shadows for sustainable membrane technologies." *Adv. Membr.*, 8, 100219. <https://doi.org/10.1016/j.advmem.2026.100219>
- Hassan, G., El-Gohary, F., & Tawfik, A., 2025. "Performance evaluation of ceramic vs. polymeric membranes in aerobic bioreactors for the treatment of piggery wastewater." *J. Environ. Manag.*, 374, 121402. <https://doi.org/10.1016/j.jenvman.2025.121402>
- He, Z., Lyu, Z., Gu, Q., Zhang, L., & Wang, J., 2019. "Ceramic-based membranes for water and wastewater treatment." *Colloids Surf. A: Physicochem. Eng. Asp.*, 578. <https://doi.org/10.1016/j.colsurfa.2019.05.074>
- Hertel, T and Liu, J., 2016. "Implications of water scarcity for economic growth." *OECD Env. Work. Pap.*, 109. <https://doi.org/10.1787/5jlssl611r32-en>
- Hidayati, N., Suryani, M., & Darnianti, D., 2021. "Effectiveness of chitosan to reduce the color value, turbidity, and total dissolved solids in shrimp-washing wastewater." *Russ. J. Agric. Soc. -Econ. Sci.*, 115(3), 1–7. <https://doi.org/10.18551/rjoas.2021-03.01>
- Huang, X., Wang, T., Luo, Y., & Guo, J., 2022. "Study on the Influence of Water Content on Mechanical Properties and Acoustic Emission Characteristics of Sandstone: Case Study from China Based on a Sandstone from the Nanyang Area." *Sustain.*, 15(1), 552. <https://doi.org/10.3390/su15010552>
- Iber, B. T., Torsabo, D., Che Engku Noramalina Che Engku Chik, C., Wahab, F., Sheikh Abdullah, S. R., Abu Hassan, H., & Kasan, N. A., 2023. "A study on the recovery and characterization of suspended solids from aquaculture wastewater through coagulation/flocculation using chitosan and its viability as organic fertilizer." *J. Agric. Food. Res.*, 11, 100532. <https://doi.org/10.1016/j.jafr.2023.100532>
- Judd, S., 2011. The MBR Book: Principles and Applications of Membrane Bioreactors for Water and Wastewater Treatment. Second Edition. Elsevier, Oxvord
- Kochan, J., Wintgens, T., & Melin, T., 2009. "Characterization and filtration performance of coating-modified polymeric membranes used in membrane bioreactors." *Chem. Pap.*, 63(2), 152–157. <https://doi.org/10.2478/s11696-008-0096-x>
-

- Kumar, R., Singh, P. and Das, S. 2025. "Transport Limitations and Adsorption Behavior in Polymer-Coated Ceramic Membranes for Wastewater Treatment." *Sep. Purif. Technol.*, 339, 126789. <https://doi.org/10.1016/j.seppur.2025.126789>
- Lemougna P.N., MacKenzie K. J. D. and Melo, U. F. C. 2011. "Synthesis and Thermal Properties of Inorganic Polymers (Geopolymers) for Structural and Refractory Applications from Volcanic Ash." *Ceramics International*, 37(8), 37, 3011-3018. <https://doi.org/10.1016/j.ceramint.2011.05.002>
- Li, Q., Zhao, L., Sun, Y. and Gao, F., 2024. "Influence of Membrane Thickness and Surface Functionalization on Ionic Conductivity Reduction in Wastewater Filtration." *Chem. Eng. J.*, 482, 148765. <https://doi.org/10.1016/j.cej.2024.148765>
- López, F.J., Sugita, S. & Kobayashi, T., 2014. "Cesium-adsorbent geopolymer foams based on silica from rice husk and metakaolin." *Chem. Lett.*, 43(1), p. 128–130. <https://doi.org/10.1246/cl.130851>
- Maneetob, S., Polprasert, C., & Kootatep, T., 2025. "Nutrient recovery and organic matter stabilization in biogas effluent: A review of current challenges and technologies." *J. Water Process Eng.*, 64, 105612. <https://doi.org/10.1016/j.jwpe.2025.105612>
- Mary, S., & Leena, S., 2022. "A comparative study on color removal from textile industry effluent using shrimp and crab shell chitosan." *Nat. Environ. Pollut. Technol.*, 21(4), 1231–1238. <https://doi.org/10.46488/NEPT.2022.v21i04.001>
- Nasir, S., Sambeghana, D. Y. N., Purbalesmana, F., Rendana, M., Nukman, N., & Ibrahim, E., 2024. "Peat water treatment using biocoagulant and ceramic membrane." *Desal. Water Treat.*, 320, 100608. <https://doi.org/10.1016/j.dwt.2024.100608>
- Palhares, L. B., Galvão, D. F., & De Paiva, P. R. P., 2022. "Effects of plaster to water ratio on physical and mechanical properties of ceramic pieces produced by the slip casting process." *Cerâmica*, 68(386), 143–151. <https://doi.org/10.1590/0366-69132022683863221>
- Rasouli, Y., Parivazh, M. M., Abbasi, M., & Akrami, M., 2022. "The effect of ceramic membranes' structure on the oil and ions removal in pre-treatment of the desalter unit wastewater." *Membranes*, 12(1), 59. <https://doi.org/10.3390/membranes12010059>
- Tchobanoglous, G., Stensel, H. D., Tsuchihashi, R., & Burton, F. L., 2014. "Wastewater engineering: Treatment and resource recovery." (5th ed.). McGraw-Hill Education.
- Vijayan, V., 2018. "A study on chitosan as natural coagulant in water treatment." *SSRN Electron. J.*, 7(5), 12242-2247. <https://doi.org/10.2139/ssrn.3591432>
- Wang, J., Zhang, L., Liu, Y., & Chen, X., 2025. "Practical application and performance of inorganic ceramic membranes in high-strength agricultural wastewater treatment." *J. water Process Eng.*, 66, 105612. <https://doi.org/10.1016/j.jwpe.2025.105612>
- Zhang, Q., Liu, Y., He, G., Chen, Q., Ou, X., & Tian, J., 2023. "Study on the effects of different water content rates on the strength and brittle plasticity of limestone." *Appl. Sci.*, 13(8), 4685.

-
- | | |
|---|--|
| <p>https://doi.org/10.3390/app13084685
 Zhang, Y., Liu, H., Chen, X. and Wang, J. 2024.
 "Effect of Chitosan Coating Thickness on
 Ion Removal Efficiency and Mass Transfer
 in Composite Membranes," <i>J. Membr. Sci.</i>,
 689, 121345.
 https://doi.org/10.1016/j.memsci.2024.1</p> | <p>21345
 Zhu, L., Chen, X., Li, W. and Xu, Y., 2021.
 "Recent Progress in Ceramic Membranes
 for Water and Wastewater Treatment: A
 Review," <i>Chem. Eng. J.</i>, 420, 129882.
 https://doi.org/10.1016/j.cej.2020.129882
 2</p> |
|---|--|
-