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HYDROPHILIZING SiO_2 NANOPARTICLES FOR REVERSE OSMOSIS MEMBRANES: TEM/EDS CHARACTERIZATION AND PARTICLE SIZE ANALYSIS

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Abstract. *Silicon dioxide (SiO_2) nanoparticles were synthesized and characterized to evaluate their potential as modifiers for nanocomposite reverse osmosis membranes. Transmission electron microscopy revealed predominantly quasi-spherical primary particles forming branched aggregates, with particle sizes mainly between 10 and 25 nm. Quantitative image analysis showed that nanoscale particles dominate the sample, with nearly 71% below 20 nm and an average diameter of 18.4 ± 14.7 nm. Gaussian and log-normal modeling indicated that size asymmetry is mainly driven by aggregation, consistent with nucleation and growth followed by partial clustering. Energy-dispersive X-ray spectroscopy confirmed stoichiometric SiO_2 without detectable impurities, demonstrating high chemical purity. The combination of small particle size, hierarchical morphology, and compositional integrity suggests strong potential for improving membrane wettability, enhancing flow recovery, and increasing resistance to organic fouling while maintaining salt rejection at optimized nanoparticle loadings. These results provide a solid structural basis for incorporating SiO_2 nanoparticles into advanced nanocomposite reverse osmosis membranes for sustainable water treatment.*

Materials and methods. *SiO_2 nanoparticles were synthesized using a wet-chemical method and characterized by TEM and EDS to examine morphology and elemental composition. Particle size distributions were obtained from TEM images using an ImageJ–OpenCV workflow including Gaussian filtering, Otsu thresholding, and contour detection. Equivalent diameters were calculated from projected areas, and Gaussian and log-normal models were applied for statistical analysis.*

Results. *TEM analysis revealed quasi-spherical SiO_2 nanoparticles forming branched aggregates, with primary particle sizes mainly between 10 and 25 nm. Quantitative image analysis showed that nearly 71% of particles were below 20 nm, with an average diameter of 18.4 ± 14.7 nm. Gaussian and log-normal fitting indicated aggregation-driven size asymmetry. EDS confirmed stoichiometric SiO_2 with no detectable impurities.*

Keywords: *SiO_2 nanoparticles; reverse osmosis membranes; TEM analysis; particle size distribution; nanocomposite membranes; antifouling properties; membrane hydrophilicity*

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ГИДРОФИЛИЗИРУЮЩИЕ НАНОЧАСТИЦЫ SIO_2 ДЛЯ МЕМБРАН ОБРАТНОГО ОСМОСА: TEM/EDS-ХАРАКТЕРИЗАЦИЯ И АНАЛИЗ РАСПРЕДЕЛЕНИЯ РАЗМЕРОВ ЧАСТИЦ

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Аннотация. *Наночастицы диоксида кремния (SiO_2) были синтезированы и охарактеризованы с целью оценки их потенциала в качестве модификаторов нанокомпозитных мембран обратного осмоса. Просвечивающая электронная микроскопия выявила преимущественно квазисферические первичные частицы, формирующие разветвлённые агрегаты, при этом основные размеры частиц находились в диапазоне 10–25 нм. Количественный анализ изображений показал, что почти 71% частиц имеют размеры менее 20 нм, а средний диаметр составляет 18.4 ± 14.7 нм. Моделирование распределения размеров с использованием гауссовского и логнормального законов показало, что асимметрия распределения обусловлена главным образом агрегацией, что согласуется с механизмом зарождения и роста с последующей частичной кластеризацией. Энергодисперсионная рентгеновская спектроскопия подтвердила стехиометрический состав SiO_2 без обнаруживаемых примесей, что свидетельствует о высокой химической чистоте. Совокупность малых размеров частиц, иерархической морфологии и композиционной целостности указывает на высокий потенциал улучшения гидрофильности мембран, повышения коэффициента восстановления потока и устойчивости к органическому загрязнению при сохранении селективности по солям. Полученные результаты создают прочную структурную основу для применения наночастиц SiO_2 в перспективных нанокомпозитных мембранах обратного осмоса для устойчивых технологий водоочистки.*

Материалы и методы. *Наночастицы SiO_2 были получены влажно-химическим методом и охарактеризованы с использованием TEM и EDS для анализа морфологии и элементного состава. Распределение размеров частиц определяли по TEM-изображениям с применением алгоритма ImageJ–OpenCV, включающего гауссову фильтрацию, пороговую*

сегментацию по Отсу и детекцию контуров. Эквивалентные диаметры рассчитывали по проекционной площади, а для статистического анализа использовали гауссовскую и логнормальную модели.

Результаты. *ТЕМ-анализ показал, что наночастицы SiO_2 имеют квазисферическую форму и образуют разветвлённые агрегаты, при этом размеры первичных частиц в основном составляют 10–25 нм. Количественный анализ изображений выявил, что около 71% частиц имеют размеры менее 20 нм, а средний диаметр равен 18.4 ± 14.7 нм. Аппроксимация распределения гауссовской и логнормальной функциями показала асимметрию, обусловленную агрегацией. EDS подтвердил стехиометрический состав SiO_2 без обнаружения примесей.*

Ключевые слова. *наночастицы SiO_2; мембраны обратного осмоса; ТЕМ-анализ; распределение размеров частиц; нанокомпозитные мембраны; антиобрастающие свойства; гидрофильность мембран.*

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TESKARI OSMOS MEMBRANALARI UCHUN GIDROFILLASHTIRUVCHI SiO_2 NANOZARRALAR: TEM/EDS TAVSIFI VA ZARRACHA O‘LCHAMLARINI TAHLIL QILISH

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Annotatsiya*. Kremniy dioksidi (SiO_2) nanozarralari sintez qilinib, nanokompozit teskari osmos membranalarini modifikatsiyalash uchun ularning imkoniyatlari baholandi. Transmissiyali elektron mikroskopiya natijalari asosan kvazi-sferik birlamchi zarrachalar tarmoqlangan agregatlar hosil qilishini ko‘rsatdi, zarracha o‘lchamlari esa asosan 10–25 nm oralig‘ida joylashgan. Tasvirlarni miqdoriy tahlil qilish natijasida zarrachalarning qariyb 71% i 20 nm dan kichik ekani va o‘rtacha diametri 18.4 ± 14.7 nm ekanligi aniqlandi. Gauss va log-normal modellashtirish o‘lchamlar assimmetriyasi asosan agregatsiya bilan bog‘liqligini ko‘rsatdi, bu esa yadrolanish va o‘sishdan keyingi qisman klasterlash jarayonlariga mos keladi. Energiya-dispersiv rentgen spektroskopiyasi SiO_2 ning stoxiometrik tarkibini tasdiqladi va aralashmalar aniqlanmadi, bu yuqori kimyoviy tozalikka ishora qiladi. Kichik zarracha o‘lchami, ierarxik morfologiya va tarkibiy barqarorlik membrana gidrofilligini oshirish, oqimni tiklash koeffitsientini yaxshilash hamda organik ifloslanishga chidamlilikni kuchaytirish imkonini beradi, shu bilan birga tuzlarni ajratish samaradorligi saqlanadi. Ushbu natijalar barqaror suv tozalash uchun ilg‘or*

nanokompozit teskari osmos membranalarida SiO_2 nanozarralarini qo‘llashga mustahkam strukturaviy asos yaratadi.

Materiallar va usullar. *SiO_2 nanozarralari nam-kimyoviy usulda sintez qilindi va TEM hamda EDS yordamida morfologiyasi va element tarkibi o‘rganildi. Zarracha o‘lchamlarining taqsimoti TEM tasvirlari asosida ImageJ–OpenCV algoritmi orqali (Gauss filtrlash, Otsu bo‘yicha chegaralash va konturlarni aniqlash) hisoblandi. Ekvivalent diametrlar proyeksiya maydonidan aniqlandi, statistik tahlil uchun Gauss va log-normal modellar qo‘llandi.*

Natijalar.TEM tahlili SiO_2 nanozarralari kvazi-sferik shaklda bo‘lib, tarmoqlangan agregatlar hosil qilishini ko‘rsatdi, birlamchi zarrachalar o‘lchami asosan 10–25 nm ni tashkil etdi. Miqdoriy tahlil zarrachalarning taxminan 71% i 20 nm dan kichik ekanini va o‘rtacha diametri 18.4 ± 14.7 nm ekanini ko‘rsatdi. Gauss va log-normal moslashtirish agregatsiya bilan bog‘liq assimmetriyani aniqladi. EDS esa stoxiometrik SiO_2 tarkibini va aralashmalarning yo‘qligini tasdiqladi.

Kalit so‘zlar. *SiO_2 nanozarralar; teskari osmos membranalari; TEM tahlil; zarracha o‘lchamlari taqsimoti; nanokompozit membranalar; antifouling xossalari; membrana gidrofilligi*

Introduction: Global Water Shortage and the Need for Advanced Reverse Osmosis Membranes.

Global water shortage has become a serious problem worldwide. Today, billions of people have limited access to clean drinking water, and climate change continues to make this situation worse. Mountain glaciers, often called the world’s “water towers,” supply freshwater to many regions, but their rapid melting is reducing long-term water availability. According to [1], mountains and glaciers play a key role in global water supply, yet their degradation is increasing water stress and uncertainty for downstream communities. Because of these challenges, desalination technologies, especially reverse osmosis (RO), are becoming more important for producing safe drinking water.

Although RO is widely used, conventional membranes still have several problems, such as low water permeability and serious membrane fouling.These limitations reduce efficiency and increase operational costs. To improve membrane performance, pursued to add nanoparticles into membrane structures. Between the nanoparticles SiO_2 nanoparticles are best candidate to improve the hydrophilicity, chemical stability and besides that such kind of particles considered as low-cost, and easy to modify.

Literature review: Nanoparticles in RO membranes

Many studies have reported clear improvements when SiO_2 nanoparticles are incorporated into RO membranes. Peyki *et al.* showed that membranes containing hydrophilic SiO_2 nanoparticles achieved higher water flux while keeping salt rejection up to 96.5% [2]. Shen *et al.* also reported improved permeability in polyamide thin-film nanocomposite membranes prepared using in-situ silica polymerization [3]. These enhancements mainly come from increased membrane hydrophilicity and the formation of additional pathways for water transport. On the other hand, characterization of nanoparticles for using as a RO membrane modifier is so crucial. Transmission electron microscopy (TEM) and energy-dispersive X-ray spectroscopy (EDS) are important techniques for understanding nanoparticle structure and distribution. TEM images usually show SiO_2 nanoparticles with sizes between 10 and 100 nm, evenly dispersed inside the polyamide active layer, leading to smoother membrane surfaces [2]-[5]. EDS analysis confirms the presence of silicon and oxygen elements, proving successful nanoparticle incorporation and uniform distribution across the membrane surface [2], [6], [7]. These structural features help attract water molecules and reduce surface roughness, which directly improves water permeability and fouling resistance. Surface hydrophilicity increases with the addition of SiO_2 nanoparticles, as shown by lower contact angle values, allowing water to pass more easily through the membrane [2]. However, too high nanoparticle loading can cause aggregation and increased surface roughness, which may reduce performance. Therefore, controlling nanoparticle concentration is very important. In addition, SiO_2-modified membranes show better antifouling properties. Several studies reported lower flux decline

during long-term operation, indicating reduced attachment of organic matter and microorganisms [2], [6]. Besides morphology, structural properties such as particle size, pore structure, and surface charge strongly influence membrane performance. Yang *et al.* demonstrated that bimodal silica nanoparticles with micro–mesoporous structures significantly enhance water flux while maintaining high salt rejection [10]. Surface functionalization of SiO_2 nanoparticles further improves hydrophilicity and membrane stability [11]. However, silica scaling remains a major challenge. Rathinam *et al.* showed that positively charged membrane surfaces can accelerate silica precipitation during brackish water desalination, which shortens membrane lifetime and reduces efficiency [12], [13]. To better understand current research trends in nanoparticle-enhanced membrane desalination, a keyword co-occurrence analysis was conducted using VOSviewer (Figure 1) based on the Scopus database.

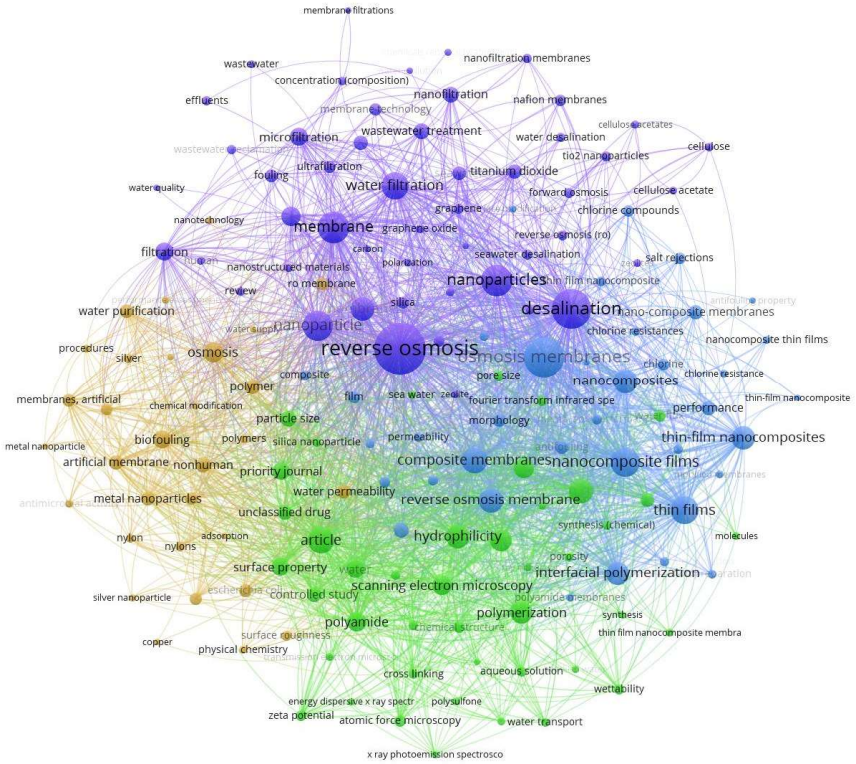

Figure 1. Keyword co-occurrence network of nanoparticle-modified membrane desalination research generated using VOSviewer.

As shown on the figure.1 “reverse osmosis”, “desalination”, “nanoparticles”, and “nanocomposites” as the most dominant keywords, indicating their central role in contemporary studies. Several thematic clusters were identified, including membrane fabrication and nanocomposite thin films, polymer chemistry and interfacial polymerization, antifouling strategies, and filtration processes. The strong interconnections between nanoparticles and membrane-related keywords demonstrate a clear research shift toward nanomaterial-enabled membrane engineering. Despite extensive investigation of nanocomposite membranes, limited attention has been devoted to silica-based hybrid nanofluids and their influence on membrane performance under arid climatic conditions. This gap motivates the present study.

Statement of the Problem

Although reverse osmosis membranes are widely used in desalination, their performance is often limited by low surface wettability and membrane fouling. Among different nanomaterials, SiO_2 nanoparticles are considered one of the most effective modification options because of their strong hydrophilicity, chemical stability, low cost, and good compatibility with polymer membranes. Previous studies show that SiO_2 can improve water flux and antifouling properties; however, real applications are still challenged by nanoparticle aggregation and an incomplete understanding of structure–performance relationships. In particular, how SiO_2 surface coverage

affects membrane morphology remains unclear. Therefore, this study focuses on modifying membranes with SiO_2 nanoparticles and examining the microstructure and elemental distribution of nanoparticles using TEM and EDS to better understand dispersion behavior and support sustainable membrane development.

Materials

As proposed in the section of statement of the problem, SiO_2 nanoparticles was used to modify the membranes, which purchased from Evonik Chemical. The powder is composed of amorphous hydrophilic silica nanoparticles (Aerosil 200) with a primary diameter of 12 nm and a specific surface of 200 m^2/g according to the manufacturer.

Methods

Low-density polyethylene (LDPE) type reverse osmosis (RO) membranes were modified by an alcohol-based treatment using sodium dodecyl sulfate (SDS) for surface activation followed by deposition of SiO_2 nanoparticles. Briefly, membrane coupons were first rinsed with alcohol to remove possible surface contaminants and then immersed in an alcohol solution containing 0.01 M SDS for 1 h at room temperature to improve surface wetting and activation. After this activation step, 0.01 g of hydrophilic amorphous SiO_2 nanoparticles (Aerosil 200) was added to the same alcohol/SDS medium and the suspension was dispersed in an ultrasonic bath for 5 min to reduce agglomeration and obtain a more uniform dispersion. The activated membranes were then kept in the freshly prepared SiO_2 dispersion for 1 h at room temperature under mild agitation to promote adsorption of nanoparticles on the membrane surface. After modification, the membranes were removed, rinsed thoroughly with чистым alcohol and затем с deionized water to eliminate loosely attached particles and residual SDS, and finally dried under ambient conditions prior to characterization and further testing.

Transmittance electron microscopy

Nanoparticle morphology and agglomeration were examined by transmission electron microscopy (TEM) using a Thermo Scientific Talos F200i (S)TEM (Thermo Fisher Scientific, USA), a field-emission instrument operated at an accelerating voltage of 200 keV. For sample preparation, a droplet of the aqueous nanoparticle dispersion was drop-cast onto a carbon-coated copper grid and allowed to dry by solvent evaporation, leaving the particles deposited on the grid. To minimize particle aggregation during drying, highly diluted dispersions were used.

Energy-dispersive X-ray spectroscopy (EDS)

Energy-dispersive X-ray spectroscopy (EDS) integrated with transmission electron microscopy (TEM) was used to determine the elemental composition and to map the spatial distribution of SiO_2 nanoparticles on the membrane surface. The EDS analyses were performed directly in the (S)TEM chamber using the built-in Bruker XFlash 6-30 silicon drift detector (SDD) installed on the Thermo Scientific Talos F200i microscope (Thermo Fisher Scientific, USA), operated at an accelerating voltage of 200 keV. EDS spectra and elemental maps were acquired from representative areas containing deposited nanoparticles to verify the presence of Si and O and to assess the uniformity of nanoparticle coverage/dispersion. The correlative TEM/EDS workflow enabled direct linking of nanoscale morphology (TEM/STEM contrast) with local chemical composition, thereby confirming that the observed surface features correspond to SiO_2 deposits rather than membrane artifacts.

Results and discussion

TEM imaging

This section discusses the morphology and particle size characteristics of the SiO_2 nanoparticles used for reverse osmosis (RO) membrane modification and relates these structural features to their expected influence on membrane performance. The discussion begins with TEM-based morphological analysis and quantitative particle size evaluation, followed by interpretation of the results in the context of membrane wettability, permeability, and fouling resistance.

Nanoparticle Morphology and Particle Size Distribution

Figure 2 presents the TEM micrograph of the synthesized SiO_2 nanoparticles employed as fillers for RO membrane modification. The nanoparticles exhibit predominantly quasi-spherical

primary morphology with partial agglomeration, forming branched and fractal like aggregates on an amorphous background. This aggregation behavior is typical for oxide nanoparticles due to their high surface energy. Importantly, individual primary particles remain clearly distinguishable within the clusters, indicating that aggregation mainly occurs during solvent evaporation on the TEM grid rather than through irreversible particle fusion.

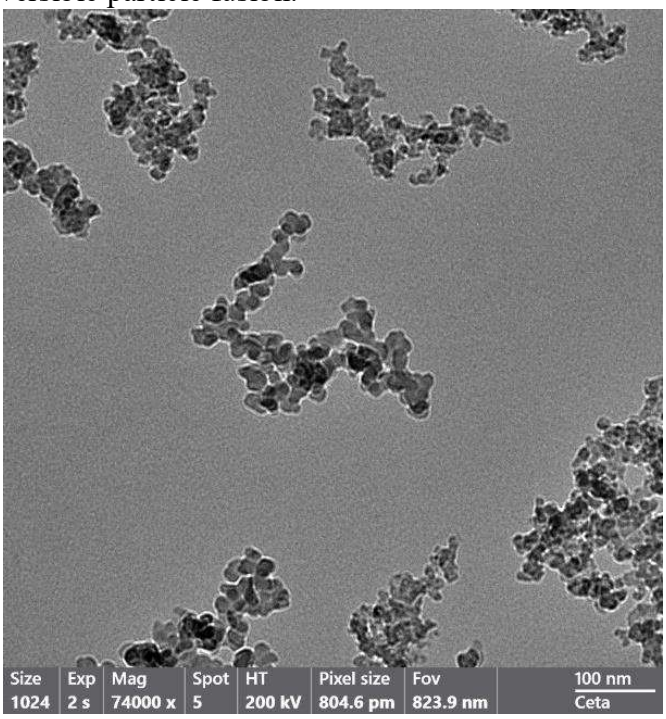

Fig.2. TEM micrograph of SiO_2 nanoparticles for RO membrane modification, showing quasi-spherical primary particles and branched aggregate structures.

Calibrated TEM measurements indicate that the primary particle sizes lie mainly in the range of approximately 10–25 nm, while the transverse dimensions of the aggregates extend from about 50 to 150 nm. This hierarchical structure comprising nanoscale primary particles assembled into loosely connected aggregates is particularly favorable for membrane applications. Such morphology promotes fine dispersion within the polyamide selective layer at low nanoparticle loadings and supports the formation of interconnected hydrophilic pathways. In addition, the short interparticle distances and fractal aggregation are expected to contribute to mechanical stabilization of the nanocomposite matrix.

Quantitative particle size analysis

Quantitative particle size analysis was performed using a combined ImageJ–OpenCV image-processing workflow. TEM images were first calibrated using the 100 nm scale bar to determine the pixel-to-length conversion factor. The images were then converted to grayscale and processed using Gaussian filtering to reduce background noise. Automatic thresholding based on the Otsu method was applied to segment nanoparticles from the background, followed by morphological opening to remove isolated artifacts. Individual particles were subsequently identified using contour detection, and only objects exceeding a minimum projected area were retained to eliminate noise. The equivalent circular diameter of each particle was calculated from its projected area using an eq.1.

$$d = \sqrt{\frac{4A}{\pi}} \quad (1)$$

where, A represents the particle area. ImageJ was used for scale calibration and visual verification, while Python-based OpenCV and NumPy libraries were employed for automated segmentation and statistical analysis, ensuring reproducibility of the procedure.

Based on the above mentioned calculation method figure 3 illustrates the particle size histogram of SiO_2 nanoparticles derived from TEM analysis, together with Gaussian and log-normal fitting curves.

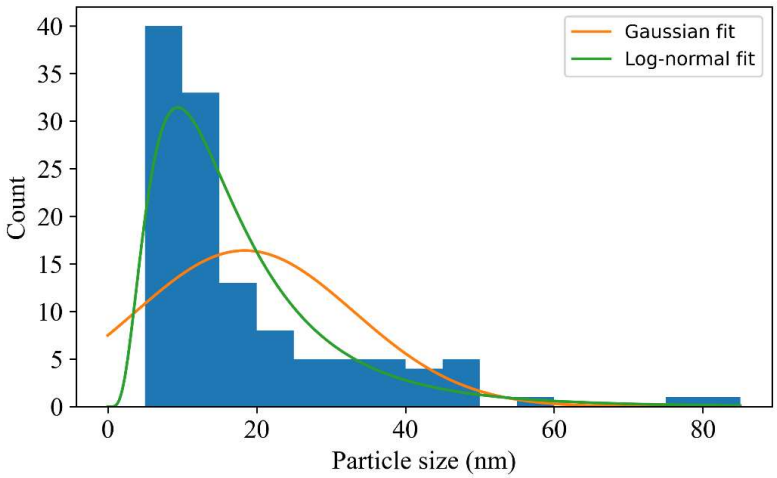

Fig.3. TEM-Derived Particle Size Distribution of SiO_2 Nanoparticles with Gaussian and Log-Normal Fits.

A total of 121 primary nanoparticles were evaluated from representative TEM images. The corresponding particle size histogram figure 3 shows a wide size distribution ranging from approximately 5 to 55 nm, with the largest fractions found in the 5–10 nm (33.1%) and 10–15 nm ranges. As a result, more than 60% of the particles are smaller than 15 nm, and nearly 71.1% fall below 20 nm, clearly demonstrating that nanoscale particles dominate the sample. The mean particle diameter was calculated to be 18.4 ± 14.7 nm, indicating moderate-to-high polydispersity. The larger sizes observed in the upper tail of the distribution are mainly attributed to particle agglomeration, which is consistent with the branched aggregate structures visible in the TEM micrographs.

Statistical Analysis of Particle Size Distribution Using Gaussian and Log-Normal Models

To better understand the particle size distribution, both Gaussian and log-normal models were fitted to the experimental histogram (Figure 3). The Gaussian distribution is expressed as

$$f(d) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(d-\mu)^2}{2\sigma^2}\right) \quad (2)$$

where d denotes the particle diameter, μ represents the mean size, and σ is the standard deviation. The log-normal distribution, which assumes that the logarithm of particle size follows a normal distribution, is given by

$$f(d) = \frac{1}{d\,\sigma_l\sqrt{2\pi}} \exp\left(-\frac{(\ln d-\mu_l)^2}{2\sigma_l^2}\right) \quad (3)$$

with μ_l and σ_l corresponding to the mean and standard deviation in logarithmic space.

To gain deeper insight into the particle size distribution, both Gaussian and log-normal models were fitted to the experimental histogram (Figure 3) using measurements from 121 primary nanoparticles. The Gaussian fit yielded an average particle diameter of 18.42 nm with a standard deviation of 14.71 nm, indicating a relatively broad size distribution. While this model describes the central size population reasonably well, the log-normal distribution-characterized by logarithmic parameters μ_l= 2.674 and σ_l = 0.657- provides a better representation of the asymmetric tail toward larger particle sizes. This asymmetry reflects the typical formation pathway of nanoparticles, in which primary particles form through nucleation and growth and subsequently undergo partial aggregation. As a result, the larger measured diameters mainly arise from agglomerated clusters rather than intrinsic particle growth, which is consistent with the branched aggregate structures observed in the TEM micrographs. These size-distribution characteristics are commonly reported for SiO_2 nanoparticles synthesized via wet-chemical routes and offer valuable insight into their dispersion and aggregation behavior, both of which play an important role in determining how effectively the nanoparticles are incorporated into nanocomposite RO membranes.

Elemental Composition Analysis (EDS)

Figure 4 shows the EDS spectrum of the synthesized nanoparticles, providing direct confirmation of their elemental composition and highlighting silicon and oxygen as the main constituents.

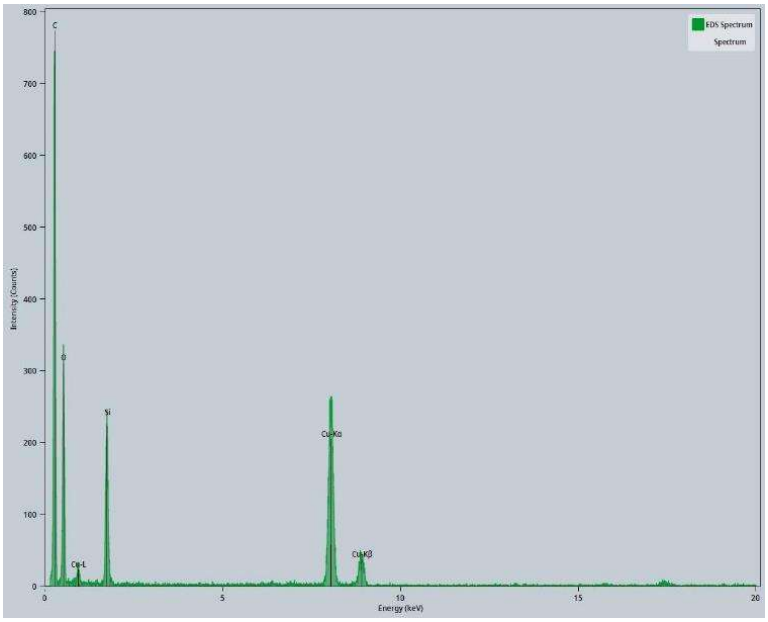

Fig.4. EDS Spectrum of Synthesized SiO_2 Nanoparticles.

The EDS results clearly confirm the silicon–oxygen composition of the nanoparticles, with strong Si and O peaks consistent with stoichiometric SiO_2 within instrumental uncertainty. Small carbon (C) and copper (Cu) signals are also present, which originate from the carbon-coated TEM grid and the copper sample holder, respectively, rather than from the nanoparticles themselves. Importantly, no additional elements were detected above the instrumental detection limit, demonstrating the high chemical purity of the synthesized SiO_2.

Together with the TEM observations, the EDS analysis verifies that the nanoparticles consist of chemically pure SiO_2 with well-defined nanoscale features. This level of purity is particularly important for membrane modification, as unwanted impurities can negatively affect membrane structure and performance. The confirmed Si–O composition, combined with the small particle size and branched aggregate morphology, suggests that these nanoparticles are well suited for use as hydrophilizing and antifouling additives in reverse osmosis membranes.

Based on their structural and chemical characteristics, the SiO_2 nanoparticles are expected to reduce membrane surface contact angle, enhance flow recovery rate (FRR), and improve resistance to organic fouling, while maintaining high salt rejection at optimal loadings (typically around 0.1–0.3 wt.% relative to the polyamide selective layer). To further clarify the relationship between nanoparticle structure and membrane performance, additional analyses such as SAED or HR-TEM (to examine Si–O–Si network organization), XPS (to confirm surface silanol groups, –Si–OH), and Raman spectroscopy (characteristic band near ~1080 cm^{-1}) are recommended to assess the degree of silica condensation and its potential impact on membrane properties.

Conclusion

Detailed structural and compositional analyses revealed that the synthesized SiO_2 nanoparticles consist mainly of quasi-spherical primary particles forming branched aggregates. TEM observations showed primary particle sizes predominantly between 10 and 25 nm, with aggregate dimensions extending to approximately 150 nm. Quantitative image analysis confirmed that nanoscale particles dominate the sample, with more than 60% below 15 nm and nearly 71% below 20 nm, resulting in an average diameter of 18.4 ± 14.7 nm. Statistical fitting indicated that while the Gaussian model captures the central size population, the log-normal distribution more accurately reflects the asymmetric tail caused by aggregation, consistent with nucleation–growth processes followed by partial clustering.

EDS measurements verified the high chemical purity of the nanoparticles, with strong silicon and oxygen signals corresponding to stoichiometric SiO_2 and no detectable impurities. The combination of small particle size, hierarchical morphology, and chemical integrity highlights the suitability of these nanoparticles for membrane modification.

Taken together, these features are expected to enhance membrane wettability, improve flow recovery, and increase resistance to organic fouling while maintaining salt rejection at optimized nanoparticle loadings. The results provide a strong structural foundation for future membrane performance studies and support the potential of SiO_2 nanoparticles in advanced nanocomposite reverse osmosis membranes.

Future Outlook

Future efforts will focus on directly linking nanoparticle structure to membrane performance through systematic evaluation of contact angle, water flux, salt rejection, and fouling resistance. Advanced techniques such as HR-TEM and SAED will be used to further examine Si–O–Si network organization, while XPS and Raman spectroscopy will help clarify surface chemistry, including the presence of silanol groups and the degree of silica condensation. In parallel, optimization of nanoparticle loading and dispersion within the polyamide layer will be explored to achieve the best balance between permeability and selectivity. Long-term filtration tests under realistic water conditions will also be conducted to assess membrane stability and practical applicability. These studies will help translate laboratory-scale findings into scalable nanocomposite RO systems for sustainable water treatment.

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