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Membrane Fabrication Using Green Chemistry Principles: A Comprehensive Review of Microwave Irradiation, Sonochemical, and Continuous Flow Methodologies

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Abstract

Membrane-based separation technologies have emerged as indispensable tools in water purification, biomedical engineering, pharmaceutical processing, and environmental protection. However, conventional membrane fabrication processes often rely on hazardous organic solvents, energy-intensive steps, and environmentally taxing conditions. In response to increasing global emphasis on sustainability and regulatory pressures, green chemistry strategies have gained attention for enabling safer, energy-efficient, and eco-friendly membrane production. This review provides a comprehensive and structured analysis of three prominent green methodologies – microwave-assisted fabrication, sonochemical techniques, and continuous flow membrane synthesis. Each method is examined with respect to its principles, physicochemical mechanisms, operational parameters, material suitability, environmental benefits, and scalability potential. Furthermore, accompanying diagrams, tables, and mechanistic illustrations strengthen conceptual clarity. The review consolidates current advancements, research gaps, and future opportunities for integrating green chemistry principles in membrane engineering with a focus on pharmaceutical, bioprocessing, and environmental applications. By offering an in-depth understanding of sustainable membrane fabrication routes, this article aims to support researchers, industries, and academia in adopting greener technologies for next-generation membrane systems.

Keywords: Continuous flow methodology, eco-friendly polymer processing, energy-efficient membrane production, green chemistry, microwave irradiation, novel membrane technologies, pharmaceutical separations, sonochemical synthesis, sustainable membrane fabrication

INTRODUCTION

Membrane technology plays a pivotal role across diverse domains including water treatment, gas separation, bioprocessing, pharmaceutical manufacturing, and energy devices. Membranes offer several advantages such as modular design, low chemical consumption, selective separation, and operational flexibility. The global membrane market continues to expand due to growing demands for high-purity water, controlled drug release systems, and industrial effluent treatment. Traditionally, polymeric membranes are prepared predominantly through techniques such as phase inversion, interfacial polymerization, electrospinning, and stretching methods. Although these processes have been optimized over decades, they rely heavily on toxic organic solvents like N,N-dimethylformamide (DMF), tetrahydrofuran (THF), or N-methyl-2-pyrrolidone (NMP), and often require long reaction times or high energy input [1].

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THE EMERGENCE OF GREEN CHEMISTRY IN MEMBRANE ENGINEERING

Green chemistry, defined by the 12 Principles proposed by Anastas and Warner, emphasizes waste reduction, safer solvents, and improved energy efficiency. As sustainability becomes an essential criterion for materials science, the polymer and membrane industries face increasing pressure to minimize environmental impact. This shift has resulted in exploration of greener solvents (e.g., ionic liquids, deep eutectic solvents), alternative energy sources (microwaves, ultrasound), and continuous processing systems that reduce waste and improve reproducibility [2].

Three methodologies – microwave irradiation, sonochemical processing, and continuous flow fabrication – are particularly promising because they offer.

- Reduced reaction time.
- Decreased solvent consumption.
- Enhanced membrane morphology and performance.
- Improved scalability.
- Minimized environmental hazard.
- Better control over polymer–solvent interaction.

These attributes align strongly with green chemistry principles, making them significant for modern membrane science.

Rationale for Sustainable Membrane Fabrication

Membrane fabrication is conventionally associated with energy-intensive, batch-based, and solvent-heavy processes that generate substantial waste. In contrast, greener fabrication approaches use alternative energy inputs or intensification strategies to achieve:

- *Lower Carbon Footprint:* Shorter process durations minimize electricity usage.
- *Cleaner Production:* Avoidance or reduction of hazardous solvents ensures safer occupational environments.
- *Enhanced Efficiency:* Non-conventional energy sources often improve polymer dissolution kinetics and membrane porosity.
- *Regulatory Compliance:* Stricter guidelines on organic solvent disposal necessitate greener methodologies.
- *Better Material Performance:* Some green methods produce membranes with superior permeability, hydrophilicity, or mechanical stability (Figure 1) [3].

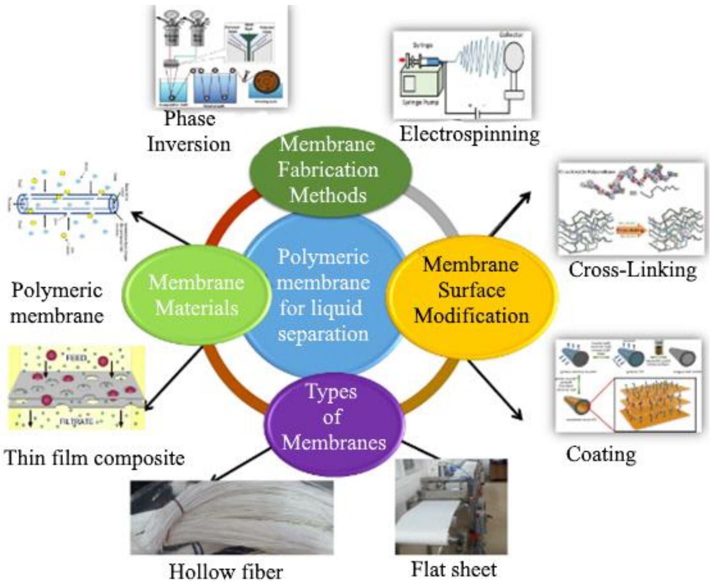

Figure 1. Conceptual overview of sustainable membrane fabrication approaches.

THE NEED FOR THIS REVIEW

Although numerous studies discuss individual green methods in membrane fabrication, a comprehensive comparative review combining microwave, sonochemical, and continuous flow approaches is lacking. This article fills that gap by:

- Integrating mechanistic understanding.
- Comparing fabrication efficiency and environmental impact.
- Highlighting applications in pharmaceutical and environmental domain.
- Presenting diagrams, tables, and systematic classification.
- Identifying challenges and future research direction.

This review aims to serve as a valuable resource for postgraduate research scholars, membrane scientists, chemical engineers, and industrial professionals exploring sustainable alternatives for membrane production (Table 1) [4].

Table 1. Comparison of conventional vs. green membrane fabrication approaches.

Parameter	**Conventional Methods**	**Green Methods (Microwave / Sonochemical / Continuous Flow)**
Energy Input	High	Low to moderate.
Solvent Consumption	High (often toxic)	Reduced, eco-friendly options.
Process Duration	Long	Significantly shortened.
Scalability	Moderate	High (especially continuous flow).
Environmental Impact	High	Low.
Control over Morphology	Variable	Significantly improved.
Safety	Moderate (toxic solvents)	Higher (reduced exposure).

Conventional Membrane Fabrication: Limitations and Environmental Challenges

Polymeric membrane fabrication historically relies on processing techniques such as phase inversion, thermally induced phase separation (TIPS), interfacial polymerization, and electrospinning. While these techniques have provided robust, high-performing membranes, their environmental and operational drawbacks are significant.

- *High Solvent Burden:* Solvents like DMF, DMAc, NMP, and THF pose toxicity, flammability, and disposal issues
- *Long Extraction and Drying Times:* Phase inversion often requires prolonged leaching steps and thermal drying
- *Batch-to-Batch Variability:* Particularly in interfacial polymerization and electrospinning
- *High Energy Demand:* Thermal processing and solvent evaporation contribute to carbon emissions
- *Environmental Regulations:* Stringent standards for emissions and waste disposal challenge industry-scale adoption

These limitations highlight the urgent need for sustainable, controlled, and energy-efficient fabrication methodologies [5].

Transition Toward Greener Technologies

Recent advancements in green engineering have shifted membrane research towards minimizing environmental impact while improving membrane performance. Innovations such as:

- Microwave-assisted polymer dissolution and membrane casting.
- Ultrasound-driven phase inversion and nanoparticle integration.
- Continuous flow reactors for consistent, scalable polymer film formation.

These offer transformative potential to membrane science. These approaches collectively support the principles of green chemistry.

- Prevention of waste.
- Safer solvents and auxiliaries.
- Energy efficiency.
- Reduced derivative.
- Process intensification.
- Enhanced safety and reduced emission.

Thus, green methodologies represent the evolution of membrane fabrication towards sustainability, reduced footprint, and improved operational control [6].

BACKGROUND / LITERATURE REVIEW

Development of Green Chemistry in Materials Science

Green chemistry emerged in the late 1990s as a scientific framework to minimize chemical hazards. Initially applied in organic synthesis, advancements soon extended to materials engineering, polymer processing, and nanotechnology. Membrane science adopted green chemistry later, and the first reports of microwave-assisted membrane fabrication appeared in early 2010s. By mid-2010s, the scientific community began exploring:

- Solvent-free polymer activation.
- Non-conventional heat source.
- Alternative solvents such as ionic liquids, deep eutectic solvents (DES).
- Bio-based polymers (cellulose acetate, chitosan, alginate, polylactic acid.

Green Membrane Fabrication: Research Progress

Research in sustainable membrane fabrication can be categorized into three waves.

Wave 1 (Early 2000–2010): Green Solvents

- Exploration of bio-based solvents for polymer dissolution.
- Replacement of NMP/DMF with less toxic alternative.
- Development of water-based phase inversion.
- Initial challenges with solubility and membrane mechanical stability.

Wave 2 (2010–2018): Alternative Energy Sources

- Emergence of microwave irradiation for polymer activation.
- Introduction of sonochemical (ultrasound-driven) membrane modification.
- Enhanced pore formation is due to cavitation.
- Improvement in blending of polymers and fillers.

Wave 3 (2018–Present): Continuous Flow & Process Intensification

- Integration of continuous flow microreactor.
- High consistency and reproducibility.
- Industrial-level scalability.
- Inline monitoring of viscosity, polymer mixing, and phase inversion kinetic.

These progressive developments form the backbone of current sustainable membrane fabrication strategies [7, 8].

Current Research on Microwave-Assisted Membrane Fabrication

Studies report that microwaves accelerate polymer dissolution through dipolar rotation and ionic conduction. Membranes fabricated using microwaves often show:

- Higher porosity.
- Reduced defects.

- Enhanced hydrophilicity.
- Faster processing.

Microwave-induced phase inversion also improves polymer–solvent interactions, enabling lower solvent use.

Advances in Sonochemical Membrane Engineering

Ultrasound processing induces acoustic cavitation, producing localized hotspots, shockwaves, and microjets that enhance.

- Polymer blending.
- Pore structure development.
- Nanoparticle dispersion.
- Surface functionalization.

Sonochemical modification is particularly effective for mixed matrix membranes (MMMs) where uniform filler dispersion is critical (Figure 2) [9].

Continuous Flow Systems in Membrane Fabrication

Continuous flow reactors represent the most industrially scalable approach, enabling:

- Automated, reproducible membrane casting.
- Inline temperature and flow control.
- Lower energy consumption.
- Minimal waste generation.

Flow-based casting and cross-linking of membranes offer better uniformity compared to batch processes (Table 2).

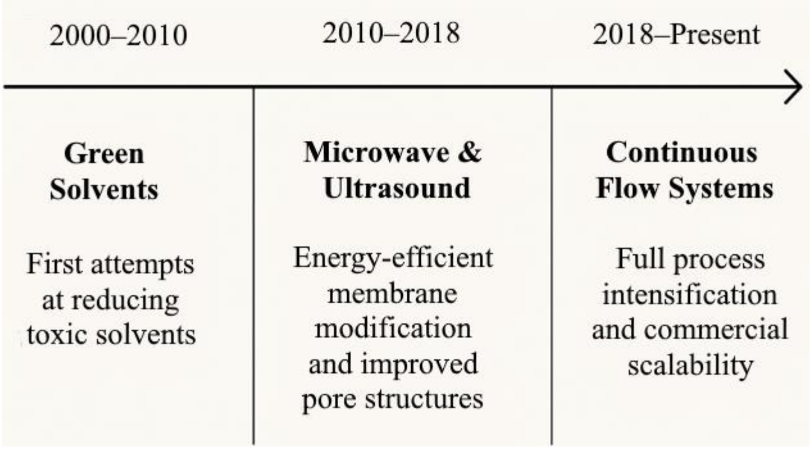

Figure 2. Evolution timeline of sustainable membrane fabrication methods.

Table 2. Summary of key literature developments in green membrane fabrication.

Method	Major researchers / Groups	Key findings	Limitations reported
Microwave-Assisted	Various polymer science groups (2010–2020)	Faster dissolution, improved porosity, reduced energy	Uneven heating in large batches.
Sonochemical	Nanotechnology & membrane labs worldwide	Enhanced mixing, improved MMM performance	Potential polymer degradation at high power.
Continuous Flow	Chemical & industrial engineering groups	Scalability, uniformity, reduced waste	High equipment cost, initial setup complexity.
Green Solvents	Environmental polymer labs	Safer processing conditions	Limited polymer compatibility.

CLASSIFICATION / TYPES OF SUSTAINABLE MEMBRANE FABRICATION METHODS

Sustainable membrane fabrication approaches following green chemistry principles can be broadly classified into three main categories based on the nature of energy input, process dynamics, and solvent utilization. These include.

- Microwave-Assisted Membrane Fabrication.
- Sonochemical (Ultrasound-Assisted) Membrane Fabrication.
- Continuous Flow Membrane Fabrication.

Within each category, multiple subtypes or process variations exist depending on polymer type, solvent system, and membrane architecture (flat sheet, hollow fiber, nanofibrous, thin-film composite) [10].

Microwave-Assisted Membrane Fabrication

Microwave-based membrane production is categorized into:

Direct Microwave Heating of Polymer Solution

- Applied during polymer dissolution stage.
- Speeds up solubilization due to dipolar rotation and ionic conduction.

Microwave-Induced Phase Inversion

- Heating polymer–solvent mixtures just before casting.
- Enhances pore formation during coagulation bath immersion.

Microwave-Assisted Cross-Linking

- Used for hydrogel membranes or polymer networks (e.g., PVA, chitosan).
- Provides rapid cross-linking without thermal degradation [11].

Sonochemical (Ultrasound-Assisted) Membrane Fabrication

Ultrasound-based membrane engineering can be classified into:

Direct Sonication of Polymer Solutions

- Improves dissolution.
- Prevents agglomeration of fillers in mixed matrix membranes (MMMs).

Indirect Sonication During Phase Inversion

- Ultrasonic waves are applied to coagulation medium.
- Generates uniform pore structures.

Sonochemical Surface Modification

- Functionalization using ultrasound to graft nano-additives.
- Enhance hydrophilicity, antifouling properties, or catalytic activity.

Acoustic Cavitation-Assisted Nanocomposite Membranes

- Formation of microjets and shockwaves improves dispersion of nanoparticles (TiO_2, graphene, AgNPs).

Continuous Flow Membrane Fabrication

Continuous flow approaches represent a shift from batch-based to automated, scalable systems.

Continuous Flow Polymer Doping Solutions

- Controlled polymer mixing in microreactors.
- Achieves consistent viscosity and morphology.

Continuous Flow Film Casting

- Steady-state extrusion of membrane-forming solutions onto support.
- Inline monitoring prevents defects.

Continuous Interfacial Polymerization

- *Used in thin-film composite (TFC) membranes.*
- *Facilitates constant monomer addition and reaction control.*

Continuous Flow Nanofiber Spinning

- Aligned nanofibers produced reduced solvent waste.
- Highly suitable for biomedical and filtration membranes [12].

MECHANISTIC BASIS OF GREEN MEMBRANE FABRICATION METHODS

Understanding the mechanistic principles of each green method is essential for optimizing membrane morphology, pore size distribution, and performance parameters such as permeance, selectivity, and fouling resistance (Table 3).

Mechanism of Microwave-Assisted Fabrication

Microwave heating operates on dielectric heating principles, involving.

Dipolar Rotation

- Polar molecules (e.g., solvents, polymers) rotate in alternating electromagnetic fields.
- Generates instantaneous volumetric heating.
- It leads to uniform polymer dissolution.

Ionic Conduction

- Ionic species oscillate, producing molecular friction and heat [13].
- Accelerates mixing and reduces dissolution time.

Polymer–Solvent Interaction Enhancement

- Microwaves disrupt intermolecular forces.
- Creates finer pore structures during coagulation.

Mechanistic Outcomes

- Reduced solvent usage.
- Faster phase inversion.
- Enhanced porosity and membrane uniformity.
- Lower thermal degradation compared to conventional heating.

Mechanism of Sonochemical Membrane Fabrication

Ultrasound irradiation (20–40 kHz) drives membrane fabrication through acoustic cavitation.

Acoustic Cavitation

Formation, growth, and collapse of microbubbles generate:

- Shockwave.
- Microjet.
- Local hotspots (up to 5000 K, though transient.
- High-pressure gradient.

Mixing and Polymer Activation

- Cavitation enhances polymer chain mobility.

- Breaks agglomerates of nanoparticles.
- Reduces solution viscosity locally.

Surface and Structural Modification

- Improves interfacial bonding in mixed matrix membranes.
- Generates microchannels that enhance permeability.

Mechanistic Outcomes

- Superior nanoparticle dispersion.
- More homogeneous pore architecture.
- Enhanced hydrophilicity and antifouling behavior.
- Reduced fabrication time.

Mechanism of Continuous Flow Fabrication

Continuous flow methodology is based on process intensification.

Controlled Mixing in Microreactors

- Laminar flow channels ensure precise solution blending.
- Temperature remains consistent throughout the process.

Steady-State Film Formation

- Polymer dope is pumped continuously onto a moving substrate.
- Facilitates uniform membrane thickness.

Inline Coagulation and Monitoring

- Real-time control of
  - Flow rate.
  - Temperature.
  - Phase inversion kinetic.
  - Solvent exchange rate.

Lower Environmental Impact

- Avoiding batch waste.
- Allows solvent recycling.
- Requires less energy per unit membrane.

Mechanistic Outcomes

- High reproducibility.
- Optimal membrane consistency.
- Scalability is suitable for industrial deployment.

Table 3. Mechanistic comparison of green fabrication methods.

Parameter	Microwave	Sonochemical	Continuous flow
Energy Source	Electromagnetic waves	Ultrasound waves	Mechanical/automated flow.
Key Phenomena	Dipolar rotation, ionic conduction	Cavitation, shockwaves	Controlled laminar flow.
Heating Pattern	Volumetric, uniform	Localized hotspots	Minimal heating.
Major Benefits	Rapid dissolution, uniform porosity	Enhanced dispersion, pore formation	Scalability, reproducibility.
Typical Applications	Polymeric membranes, hydrogels	MMMs, surface modification	TFC membranes, nanofibers

FABRICATION / DEVELOPMENT / PREPARATION METHODS

Sustainable membrane fabrication methods utilize non-conventional energy sources and intensified processes to reduce solvent usage, shorten processing times, and improve environmental compatibility. This section provides detailed stepwise methodologies for microwave-assisted, sonochemical, and continuous flow membrane fabrication, with emphasis on polymeric membranes commonly used in pharmaceutical and environmental applications (e.g., polysulfone [PSf], polyvinylidene fluoride [PVDF], cellulose acetate, chitosan, polylactic acid) [14].

Microwave-Assisted Membrane Fabrication Methods

Microwave-based membrane fabrication typically involves two major stages.

- Polymer Dissolution under Microwave Irradiation
- Microwave-Driven Phase Inversion or Cross-Linking

Microwave-Assisted Polymer Dissolution

Microwave-assisted polymer dissolution is faster and more energy-efficient compared to conventional thermal stirring [15].

STEP-BY-STEP METHOD

Selection of Polymer and Solvent

- *Polymer:* PSf, PVDF, PES, cellulose derivatives, chitosan.
- *Solvent:* Green options include water, ethanol-water mixtures, ionic liquids, or DES.

Weighing and Mixing

- Polymer and solvent are mixed in a microwave-safe vessel.
- Optional addition of fillers (graphene oxide, TiO_2, silica nanoparticles).

Microwave Irradiation

- Expose mixture to microwave radiation (100–600 W).
- Stirring is applied intermittently to avoid hot spots.
- *Duration:* 1–5 minutes depending on polymer viscosity.

Removal of Bubbles

Degassing under vacuum for 5–10 minutes.

Key Advantages

- Faster dissolution.
- Uniform heating.
- Less solvent requirement.
- Reduced polymer degradation compared to prolonged heating.

Microwave-Induced Phase Inversion

Microwave energy used immediately before casting enhances pore formation in the membrane.

Procedure

- Heat polymer dope solution using microwave irradiation to activate polymer chains.
- Immediately cast the viscous solution onto a glass plate using a casting knife.
- Expose cast film to microwave for 20–40 seconds to accelerate initial phase separation steps.
- Transfer film to coagulation bath (water/ethanol/water-miscible solvents).
- Wash and store membranes until characterization.

Sonochemical (Ultrasound-Assisted) Membrane Fabrication Methods

Ultrasound-assisted methods exploit acoustic cavitation to improve polymer dissolution, blending, and pore structure.

Direct Sonication for Polymer Solution Preparation

Method

Polymer Dissolution

- Polymer is dispersed in solvent and placed in a sonication bath or probe sonicator.

Ultrasound Treatment

- *Frequency:* 20–40 kH.
- *Power:* 100–300 W depending on polymer and solution volume.
- *Duration:* 5–30 minute.

Cavitation-Driven Mixing

- Breaks polymer aggregate.
- Enhances molecular diffusion.
- Allows uniform dispersion of nanofiller.

Sonochemical Phase Inversion Technique

Procedure

- Cast polymer film on glass substrate.
- Place substrate in an ultrasonic bath during the initial 10–60 seconds of immersion in coagulation bath.
- Cavitation accelerates solvent–non-solvent exchange, creating uniform pores.
- Rinse and store formed membrane.

Sonochemical Surface Functionalization

Used to graft nanoparticles or modify the surface chemistry of membranes.

Process

- Membrane placed in aqueous/nonaqueous medium containing functionalizing agent.
- Ultrasound applied to trigger cavitation and promoted grafting.
- Surface becomes more hydrophilic, antifouling, or catalytic.

Continuous Flow Membrane Fabrication Methods

Continuous flow methodologies involve automated, scalable processes that provide reproducible membrane characteristics.

Continuous-Flow Dope Solution Preparation

Procedure

- Polymer and solvent introduced through precision pumps into a microreactor channel.
- Laminar mixing ensures consistent polymer chain dispersion.
- Temperature is controlled by using jacketed flow reactors.
- Final dope solution collected continuously for casting.

Continuous Film Casting

Method

- Dope solution pumped steadily onto a moving support substrate
- Film thickness controlled by adjustable doctor blade or slit-die.
- Immediately passed into coagulation bath in continuous fashion.
- Further washing and drying occur on a conveyor system.

Continuous Interfacial Polymerization for TFC Membranes

Used in desalination and nanofiltration membranes.

Procedure

- Flow of aqueous monomer solution (e.g., m-phenylenediamine).
- Followed by controlled flow of organic phase (e.g., trimesoyl chloride in hexane substitute).
- Thin-film layer forms instantly at interface in controlled flow.
- Heat curing and washing performed in-line (Table 4) [16].

Table 4. Comparison of fabrication method parameters.

Parameter	Microwave	Sonochemical	Continuous flow
Typical Processing Time	Very short	Moderate	Continuous.
Energy Mechanism	EM radiation	Acoustic cavitation	Flow dynamics.
Ideal For	Rapid dissolution, hydrogels	MMMs, pore tuning	Large-scale membrane production.
Solvent Use	Low	Moderate	Very low (recyclable).
Scalability	Medium	Medium	Very high.

EVALUATION / CHARACTERIZATION OF GREEN-FABRICATED MEMBRANES

Characterization of membranes fabricated using microwave, sonochemical, and continuous flow methods is essential to establish their physicochemical attributes, separation efficiency, mechanical robustness, and long-term performance. Sustainable fabrication may alter membrane properties, necessitating standardized evaluation.

Membrane characterization is generally categorized into:

- Physicochemical characterization.
- Structural and morphological evaluation.
- Mechanical performance test.
- Transport/separation performance.
- Surface chemistry and wettability assessment.
- Thermal stability studies.

Physicochemical Characterization

Viscosity Analysis of Dope Solution

- Important for predicting membrane thickness and pore morphology.
- Measured using a Brookfield viscometer or rheometer.
- Microwave and ultrasound processing typically reduce viscosity due to enhanced polymer chain mobility.

Density and Conductivity

- Continuous flow systems often exhibit improved uniformity in polymer–solvent mixing.
- Conductivity changes reflect ionic content influenced by microwave or ultrasound exposure.

Structural & Morphological Characterization

Scanning Electron Microscopy (SEM)

SEM provides insights into:

- Cross-sectional pore structure.
- Surface porosity.
- Macrovoid formation.
- Skin layer thickness.

Microwave-Treated Membranes Often Show

- Thin, uniform skin layer.
- Increased microporosity.

Sonochemically Prepared Membranes Show

- Uniform pore distribution due to cavitation.
- Better nanofiller dispersion.

Atomic Force Microscopy (AFM)

Evaluations

- Surface roughness (Ra value).
- Topographical uniformity.

Ultrasound tends to reduce roughness, improving antifouling properties.

X-Ray Diffraction (XRD)

Determines

- Polymer crystallinity.
- Effect of microwave acceleration on crystal domain.
- Sonication-induced microstructural change.

Fourier Transform Infrared Spectroscopy (FTIR)

Used to Detect

- Chemical modification.
- Functional group interaction.
- Cross-linking changes after microwave exposure.

Mechanical Characterization

Tensile Strength

- Evaluated using a universal testing machine (UTM).
- Continuous flow membranes often exhibit superior mechanical properties due to controlled casting.

Young's Modulus and Elongation at Break

- Sonicated membranes may show slightly lower modulus due to microstructural softening.
- Microwave cross-linked hydrogels often demonstrate increased tensile strength.

Burst Pressure Test

- Essential for hollow fiber membranes.

Transport and Separation Performance

Pure Water Flux (PWF)

Measured using a dead-end or crossflow filtration setup.

Green fabrication influences flux as follows:

- *Microwave → increased hydrophilicity & porosity → higher flu.*
- *Sonochemical → improved pore uniformity → stable flu.*
- *Continuous flow → consistent flux across large batches.*

Solute Rejection Studies

Performed for

- Salts (nanofiltration).
- Dye.
- Protein.
- Drugs (pharmaceutical processing).

Permeability & Selectivity

Determined Using Standard Permeation Equations

- Hydraulic permeability (L/m2·h·bar).
- Selectivity ratios for multi-solute system.

Surface Properties Evaluation

Contact Angle Measurement

- Indicates surface hydrophilicity.
- Lower contact angle = improved antifouling (Table 5).

Sonochemical Modification Generally Results in

- 10–20° reduction in contact angle due to grafting or improved nanofiller distribution.

Zeta Potential

Evaluates Surface Charge, Affecting:

- Fouling behavior.
- Protein adhesion.
- Drug loading efficiency.

Thermal Characterization

Thermogravimetric Analysis (TGA)

Assesses

- Polymer thermal stability.
- Decomposition temperature.
- Residual solvent presence.

Differential Scanning Calorimetry (DSC)

Provides

- Glass transition temperature (Tg).
- Crystallinity modification.
- Effect of microwave heating on polymer ordering.

Table 5. Summary of characterization techniques and outputs.

Characterization type	Technique	Key outputs	Relevance
Morphology	SEM, AFM	Pores, roughness	Performance prediction.
Surface Chemistry	FTIR, XPS	Functional groups	Fouling resistance.
Mechanical	UTM	Strength, modulus	Durability.
Transport	Flux, Rejection tests	Permeability	Application suitability.
Thermal	TGA, DSC	Stability	Processing & storage.

APPLICATIONS OF GREEN-FABRICATED MEMBRANES

Sustainably fabricated membranes are increasingly being utilized across scientific, industrial, environmental, and pharmaceutical sectors. The adoption of microwave-assisted, sonochemical, and continuous flow techniques has broadened the scope of membrane technology while reducing environmental and operational burdens.

Water Treatment and Environmental Applications

Membranes fabricated using green methodologies exhibit improved porosity, hydrophilicity, and fouling resistance – key features for water purification [17].

Applications Include

- *Microfiltration and Ultrafiltration:* Removal of microorganisms, turbidity, and macromolecules.

- *Nanofiltration:* Selective removal of dyes, divalent ions, and endocrine-disrupting chemicals.
- *Wastewater treatment:* Treatment of textile, pharmaceutical, and industrial effluents.
- *Membrane Bioreactors (MBRs):* Enhanced biofouling resistance due to hydrophilic surfaces achieved via sonochemical modification.

Green-fabricated membranes reduce chemical usage during production, contributing to overall sustainability in water purification infrastructure.

Pharmaceutical and Bioprocessing Applications

Membranes are extensively used in downstream processing, sterile filtration, and drug purification. Sustainable fabrication enhances safety and minimizes solvent residues – critical for pharmaceutical compliance.

Applications Include

- Protein purification and concentration.
- Sterile filtration in formulation unit.
- Separation of APIs during synthesis.
- Encapsulation and controlled release in drug delivery system.
- Biomolecule fractionation (e.g., peptides, enzymes).

Microwave-assisted polymer hydration is particularly useful in preparing hydrogel membranes for transdermal and targeted drug delivery [13].

Food, Nutraceutical, and Biotechnological Applications

Green membranes offer improved safety for processes involving consumables.

Applications

- Concentration of fruit juices, polyphenols, and herbal extract.
- Removal of pathogens and spoilage organisms.
- Enzymatic bioprocessing requires sterile barrier membrane.
- Extraction of nutritional compounds using continuous-flow system.

Energy and Fuel Cell Applications

Green-fabricated polymer electrolyte membranes (PEMs) are important in renewable energy systems.

Use Cases

- Proton exchange membranes in fuel cells.
- Gas separation (CO_2/N_2, O_2/N_2).
- Hydrogen purification.
- Batteries and supercapacitors require ion-selective membrane.

Microwave-induced cross-linking accelerates PEM formation and improves ionic conductivity.

Biomedical and Tissue Engineering Applications

Chitosan, cellulose acetate, and PLA membranes prepared using sustainable methods have gained momentum in biomedical fields.

Applications Include

- Wound dressing.
- Tissue scaffold.
- Hemodialysis membrane.

- Transdermal patches.
- Artificial organs and implantable devices.

Sonochemical fabrication helps incorporate bioactive nanoparticles (ZnO, Ag) for antimicrobial properties.

ADVANTAGES OF GREEN MEMBRANE FABRICATION METHODS

Green fabrication approaches offer distinct advantages aligned with the goals of sustainability, process intensification, and environmentally conscious engineering.

Advantages of Microwave-Assisted Methods

- Rapid polymer dissolution (up to 5–10× faster).
- Uniform heating minimizes thermal gradient.
- Reduced solvent consumption.
- Improved membrane morphology with fewer macrovoids.
- Enhanced polymer–solvent interaction for better porosity.
- Energy-efficient due to volumetric heating.
- Suitable for hydrogels and cross-linked system.

Advantages of Sonochemical Methods

- Superior nanoparticle dispersion for mixed matrix membrane.
- Enhanced porosity and uniform pore size due to cavitation.
- Improved hydrophilicity → better antifouling properties.
- Accelerated reaction kinetic.
- Lower energy input compared to high-temperature treatment.
- Simple equipment requirements (ultrasonic bath/probe).

Advantages of Continuous Flow Methods

- High scalability is suitable for industrial manufacturing.
- Reduced batch-to-batch variation.
- Minimal waste and solvent recycling.
- Precise control over membrane thickness and morphology.
- Energy savings due to steady-state operation.
- Integration with inline monitoring tool.
- Enhanced worker safety due to closed-loop system.

LIMITATIONS OF GREEN MEMBRANE FABRICATION TECHNIQUES

Despite their benefits, sustainable membrane fabrication methods face challenges that must be addressed for widespread adoption [11].

Limitations of Microwave-Assisted Fabrication

- Non-uniform heating in large volumes (scaling challenges).
- Limited compatibility with non-polar solvent.
- Risk of localized overheating.
- Requirement of microwave-transparent processing vessel.

Limitations of Sonochemical Methods

- Potential polymer degradation at high ultrasound power.
- Formation of undesired microcracks in brittle polymer.
- Difficulty in controlling cavitation intensity.
- Not ideal for very viscous polymer dope.

Limitations of Continuous Flow Processes

- High initial equipment and setup cost.
- Requires precise flow control technology.
- Complex maintenance.
- Potential clogging or fouling in microreactor channel.
- Limited flexibility when producing diverse membrane types.

CONCLUSION

Sustainable membrane fabrication represents a pivotal advancement in materials science, driven by global environmental concerns, regulatory pressures, and the growing need for safer and energy-efficient manufacturing technologies. This review systematically examined three major green chemistry-based methodologies – microwave-assisted fabrication, sonochemical processing, and continuous flow membrane production – highlighting their mechanistic principles, fabrication workflows, structural characteristics, application potential, and existing challenges.

Microwave-assisted fabrication offers rapid polymer dissolution and enhanced pore structure through volumetric heating and improved polymer–solvent interactions. Sonochemical methods exploit acoustic cavitation to create highly uniform morphologies, superior nanofiller dispersion, and enhanced hydrophilicity, making them valuable for mixed matrix membranes and functionalized surfaces. Continuous flow approaches stand out for their scalability, reproducibility, and industrial relevance, providing precise control over film formation, solvent exchange, and membrane morphology while minimizing waste and operational hazards.

Despite notable advantages, limitations still exist. Microwave processing faces scale-up issues due to uneven heating in large batches; sonication may induce polymer degradation at high intensities; and continuous flow systems demand high capital investment and stringent maintenance. However, ongoing innovations in reactor design, solvent substitution, nanoparticle integration, and hybrid energy systems continue to mitigate these challenges.

Overall, sustainable membrane fabrication technologies embody the core principles of green chemistry by reducing solvent consumption, energy usage, toxic emissions, and waste generation. They offer tremendous promises for next-generation membrane systems used in water purification, pharmaceutical processing, biomedicine, energy applications, and environmental remediation. Continued interdisciplinary research, combining materials engineering, green chemistry, and process intensification, will be crucial for transitioning these green methods from laboratory-scale demonstrations to industrial-scale implementation.

REFERENCES

1. Anastas PT, Warner JC. Green chemistry: Theory and practice. Oxford: Oxford University Press; 2000.
2. Baker RW. Membrane technology and applications. 3rd ed. Hoboken (NJ): Wiley; 2012.
3. Basu S, Omole I, Ahmad A. Recent advances in green polymer solvents for sustainable membrane fabrication. J Membr Sci. 2020;604:118015.
4. Cheng L, Fang J. Microwave-assisted polymer processing for advanced materials. Polym Eng Sci. 2018;58(4):567–581.
5. Deen WM. Analysis of transport phenomena. 2nd ed. Oxford: Oxford University Press; 2019.
6. Ezugbe EO, Rathilal S. Membrane technologies in wastewater treatment: A review. Environ Chem Lett. 2020;18(3):1169–1193.
7. Ghasemian M, Albadarin A. Sonochemical synthesis and modification of polymeric membranes: mechanisms and applications. Ultrason Sonochem. 2021;73:105506.
8. Guo H, Li Y, Kim J. Continuous flow membrane fabrication: Emerging technologies and industrial perspectives. Chem Eng J. 2017;328:567–590.

9. Hasan Z, Jhaveri J. Mixed matrix membranes: Advances in sustainable fabrication techniques. Sep Purif Technol. 2022;301:122050.
10. Li X, Lau CH, Chung TS. High-performance polymers for membrane fabrication. Prog Polym Sci. 2016;57:76–125.
11. Mauter MS, Elimelech M. Environmental applications of membrane technologies: Current challenges and future trends. Nat Sustain. 2020;3:19–27.
12. Nandan A, Singh R, Yadav S. Microwave-induced phase inversion for sustainable membrane preparation. J Appl Polym Sci. 2021;138(45):51204.
13. Patel M, Rastogi N. Ultrasound-assisted nanocomposite membrane preparation. Mater Chem Phys. 2019;223:435–445.
14. Qin J, et al. Energy-efficient membrane manufacturing technologies. Chem Eng Res Des. 2019;152:256–272.
15. Sánchez M, Blanco A. Green chemistry approaches in polymer membrane engineering. Mater Today Sustain. 2020;7:100040.
16. Xu Z, Huang H. Continuous-flow interfacial polymerization for thin-film composite membranes: Progress and prospects. Adv Mater Interfaces. 2022;9(14):2200154.
17. Zhao Y, Wang R. Advances in ultrasound-assisted fabrication of polymeric membranes. J Membr Sci. 2021;635:119533.