

Wastewater Treatment Technologies: Advancements in Membrane Filtration Systems

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ABSTRACT

The growing demand for efficient wastewater treatment has spurred significant advancements in membrane filtration systems, which are increasingly recognized for their effectiveness in removing contaminants and enhancing water quality. This paper reviews recent developments in membrane technologies, focusing on innovations in materials, design, and operational processes. Key advancements, including the integration of nanomaterials, the use of biomimetic membranes, and improvements in fouling resistance, are discussed in relation to their impact on performance and sustainability. The paper also explores various applications of membrane filtration in municipal and industrial wastewater treatment, highlighting case studies that demonstrate enhanced efficiency and cost-effectiveness. Furthermore, the challenges associated with membrane technologies, such as maintenance, lifespan, and energy consumption, are analyzed, along with potential solutions to overcome these barriers. Ultimately, this review underscores the role of membrane filtration systems as a pivotal component in the future of wastewater treatment, paving the way for more sustainable practices in water resource management.

Keywords: Membrane Filtration, Wastewater Treatment, Nanomaterials, Fouling Resistance, Sustainability

INTRODUCTION

The increasing pressure on global water resources, driven by rapid urbanization, industrialization, and climate change, has intensified the need for effective wastewater treatment solutions. Traditional treatment methods often struggle to meet stringent regulatory requirements and are limited in their ability to remove emerging contaminants. In this context, membrane filtration technologies have emerged as a promising alternative, offering superior performance in separating pollutants from water.

Membrane filtration encompasses a range of processes, including microfiltration, ultrafiltration, nanofiltration, and reverse osmosis, each with distinct capabilities for removing particulate matter, bacteria, viruses, and dissolved substances. Recent advancements in membrane materials and designs, such as the incorporation of nanomaterials and biomimetic structures, have significantly enhanced their efficiency and longevity. Moreover, innovations aimed at mitigating fouling—a primary challenge in membrane systems—are crucial for improving operational sustainability and reducing maintenance costs.

This paper aims to provide a comprehensive overview of the current state of membrane filtration technologies in wastewater treatment. We will explore recent advancements, assess their implications for practical applications, and discuss the challenges that remain in the adoption and implementation of these systems. By highlighting successful case studies and innovative approaches, this review seeks to underscore the vital role of membrane filtration in advancing sustainable water management practices and addressing the global water crisis.

LITERATURE REVIEW

The literature on membrane filtration technologies for wastewater treatment has expanded significantly in recent years, reflecting ongoing research and development aimed at improving performance and sustainability. This review synthesizes key findings from various studies, focusing on material innovations, operational advancements, and case studies demonstrating practical applications.

- 1. Material Innovations:** Recent studies have highlighted the development of novel membrane materials that enhance filtration efficiency and reduce fouling. For example, the incorporation of nanomaterials, such as graphene oxide and

carbon nanotubes, has been shown to improve the mechanical strength and hydrophilicity of membranes, leading to increased permeability and reduced resistance to flow (Zhang et al., 2021; Wang et al., 2022). Biomimetic membranes, inspired by natural filtration processes, have also gained attention for their ability to selectively filter contaminants while minimizing fouling (Yuan et al., 2020).

- 2. Operational Advancements:** Innovations in operational strategies have played a crucial role in optimizing membrane filtration systems. Techniques such as periodic backwashing, chemical cleaning, and the use of integrated membrane bioreactors (MBRs) have been shown to enhance the lifespan and efficiency of membranes (Li et al., 2019; Chen et al., 2023). Additionally, advancements in process automation and monitoring technologies facilitate real-time assessments of membrane performance, enabling timely interventions to prevent fouling and maintain optimal operation.
- 3. Case Studies and Applications:** Numerous case studies demonstrate the successful implementation of membrane filtration technologies in various settings. For instance, a study conducted in a municipal wastewater treatment plant showcased a significant reduction in total suspended solids and nutrient levels when integrating membrane filtration with conventional treatment processes (Smith et al., 2021). In industrial applications, membrane filtration has been employed to treat wastewater from textile and food processing industries, yielding high-quality effluents suitable for reuse (Patel et al., 2022).
- 4. Challenges and Future Directions:** Despite the advancements in membrane filtration technologies, several challenges persist. Fouling remains a critical issue, necessitating ongoing research into novel anti-fouling coatings and operational strategies (Deng et al., 2023). Additionally, the energy consumption associated with high-pressure systems, particularly reverse osmosis, raises concerns about the sustainability of these technologies (Gomez et al., 2022). Future research should focus on developing energy-efficient processes and exploring hybrid systems that combine membrane filtration with other treatment methods to enhance overall efficiency.

In summary, the literature indicates that membrane filtration technologies hold significant promise for advancing wastewater treatment practices. Continued innovation in materials and operational strategies, coupled with successful real-world applications, positions these technologies as vital components in addressing global water challenges.

THEORETICAL FRAMEWORK

The theoretical framework for this study is grounded in the principles of membrane filtration technologies, encompassing various scientific concepts and engineering theories that underpin their operation and performance in wastewater treatment. This framework integrates multiple disciplines, including materials science, fluid dynamics, and environmental engineering, to provide a comprehensive understanding of membrane systems.

1. Membrane Filtration Principles: Membrane filtration operates on the principle of selective permeability, where membranes act as barriers to separate contaminants from water based on size, charge, or chemical properties. The fundamental processes involved include:

Microfiltration (MF) and Ultrafiltration (UF): These processes utilize porous membranes to remove suspended solids, bacteria, and large organic molecules. The theoretical basis for these techniques relies on size exclusion and the dynamics of particle movement through porous media.

Nanofiltration (NF) and Reverse Osmosis (RO): NF and RO are more advanced filtration methods that leverage pressure-driven processes to separate smaller solutes and dissolved contaminants, including ions and small organic molecules. The theoretical principles of osmotic pressure and concentration polarization are essential for understanding their operation.

2. Fouling Mechanisms: Fouling is a major challenge in membrane filtration, significantly impacting performance and lifespan. Theoretical models of fouling mechanisms—such as cake layer formation, pore blocking, and gel layer development—help elucidate how various factors, including feed water characteristics, operational conditions, and membrane properties, influence fouling rates. Understanding these mechanisms is critical for developing effective anti-fouling strategies and optimizing cleaning protocols.

3. Transport Phenomena: The behavior of solutes and solvents in membrane systems can be described using transport phenomena, which encompasses the principles of mass transfer, momentum transfer, and energy transfer. Models such as the Nernst-Planck equation and Darcy's law are applied to predict flux rates, concentration gradients, and the impact of pressure differentials on filtration performance.

5. Thermodynamics and Energy Considerations: The energy requirements for membrane processes, particularly in high-pressure applications like RO, are assessed through thermodynamic principles. Theoretical models help evaluate energy consumption, identify opportunities for energy recovery, and explore the environmental implications of different filtration technologies.

6. Sustainability and Lifecycle Assessment: As wastewater treatment technologies evolve, it is crucial to consider their sustainability. Theoretical frameworks for lifecycle assessment (LCA) are employed to evaluate the environmental impacts associated with membrane production, operation, and disposal. This approach integrates ecological, economic, and social factors, guiding the development of more sustainable membrane technologies.

In summary, this theoretical framework provides a comprehensive foundation for understanding the mechanisms, challenges, and innovations associated with membrane filtration technologies in wastewater treatment. By integrating these diverse theoretical perspectives, the framework informs the analysis and discussion of advancements in membrane systems and their role in promoting sustainable water management practices.

RESULTS AND ANALYSIS

This section presents the findings from recent studies and analyses concerning advancements in membrane filtration technologies for wastewater treatment. The results are categorized based on key themes: membrane performance, fouling mitigation, and case studies highlighting practical applications.

1. Membrane Performance:

Recent advancements in membrane materials and design have significantly enhanced filtration performance. Studies indicate that membranes incorporating nanomaterials, such as graphene oxide and titanium dioxide, exhibit improved permeability and selectivity. For instance, a comparative analysis revealed that graphene oxide membranes achieved flux rates exceeding 50 L/m²/h while effectively rejecting contaminants up to 99% (Zhang et al., 2021).

In addition, biomimetic membranes demonstrated remarkable filtration capabilities, with one study reporting a reduction in energy consumption by 30% compared to traditional polymeric membranes due to their lower resistance to flow (Yuan et al., 2020). These results underscore the potential for innovative materials to enhance both efficiency and sustainability in wastewater treatment processes.

2. Fouling Mitigation:

Fouling remains a significant challenge in membrane filtration. Recent research has focused on understanding fouling mechanisms and developing strategies to mitigate their effects. A comprehensive study evaluated various anti-fouling coatings, revealing that membranes treated with hydrophilic polymers exhibited up to a 40% reduction in fouling rates compared to untreated membranes (Li et al., 2019).

Additionally, operational strategies such as periodic backwashing and the implementation of integrated membrane bioreactors (MBRs) were shown to effectively minimize fouling. In one case, a MBR system demonstrated a sustained flux of 30 L/m²/h over six months of operation, significantly outperforming conventional systems (Chen et al., 2023). These findings highlight the importance of both material innovations and operational adjustments in managing fouling.

3. Case Studies: Practical Applications

Several case studies illustrate the successful application of advanced membrane filtration technologies in diverse wastewater treatment scenarios. In a municipal treatment facility, the integration of an ultrafiltration system achieved a total suspended solids removal efficiency of 95%, significantly enhancing effluent quality and enabling water reuse (Smith et al., 2021).

In industrial applications, membrane filtration has been effectively utilized to treat wastewater from textile manufacturing. A pilot study demonstrated that a combined UF and RO system reduced chemical oxygen demand (COD) levels by over 80%, making the treated water suitable for discharge or reuse (Patel et al., 2022). These real-world applications underscore the effectiveness of membrane technologies in addressing specific treatment challenges.

4. Energy Consumption Analysis:

Energy consumption associated with membrane filtration processes, particularly in RO systems, was analyzed to assess sustainability. The energy requirements were found to vary significantly based on operational pressures and feed water characteristics. For example, energy audits revealed that optimizing operational pressure could reduce energy costs by up to 25% without compromising effluent quality (Gomez et al., 2022).

Furthermore, integrating energy recovery devices within RO systems has shown promise, potentially recovering up to 90% of the energy used during operation. These insights are critical for evaluating the environmental footprint of membrane technologies.

Conclusion of Results and Analysis:

Overall, the results indicate that advancements in membrane filtration technologies are paving the way for more efficient and sustainable wastewater treatment solutions. Innovations in materials, strategies for fouling mitigation, and successful case studies collectively demonstrate the effectiveness of these systems. However, challenges remain, particularly regarding energy consumption and long-term operational sustainability, highlighting the need for ongoing research and development in this field.

COMPARATIVE ANALYSIS IN TABULAR FORM

Here’s a comparative analysis of various membrane filtration technologies in tabular form, highlighting key features, advantages, challenges, and applications:

Technology	Filtration Range	Advantages	Challenges	Applications
Microfiltration (MF)	0.1 - 10 µm	- Low energy consumption - Effective for bacteria and suspended solids	- Limited removal of dissolved substances - Potential for fouling	- Municipal water treatment - Dairy processing
Ultrafiltration (UF)	1 - 100 nm	- Higher rejection of larger organics and viruses - Moderate energy use	- Still limited for small solutes - Fouling issues can arise	- Wastewater treatment - Food and beverage industry
Nanofiltration (NF)	1 - 10 nm	- Effective for divalent ions and larger organics - Lower pressure requirements than RO	- Moderate energy consumption - Fouling can be significant	- Water softening - Textile wastewater treatment
Reverse Osmosis (RO)	0.001 - 1 nm	- High rejection rates for dissolved salts and small molecules - Produces high-quality water	- High energy consumption - Membrane fouling and scaling	- Desalination - Industrial wastewater treatment
Biomimetic Membranes	Varies (targeted)	- Enhanced flux and selectivity - Lower energy requirements	- Development costs - Limited commercial availability	- Advanced water treatment applications - Potential for resource recovery
Integrated Membrane Bioreactors (MBR)	Varies	- Combines biological treatment and membrane filtration - High quality effluent	- High operational complexity - Membrane fouling	- Municipal wastewater treatment - Industrial effluent treatment

This table summarizes the key aspects of different membrane filtration technologies, aiding in the understanding of their comparative strengths and weaknesses in wastewater treatment contexts.

SIGNIFICANCE OF THE TOPIC

The significance of advancements in membrane filtration technologies for wastewater treatment is multifaceted, encompassing environmental, economic, and societal dimensions:

Environmental Protection:

Pollution Reduction: Membrane filtration systems are highly effective in removing a wide range of contaminants, including pathogens, heavy metals, and organic pollutants. This capability helps to mitigate the adverse effects of wastewater discharge on ecosystems and water bodies.

Resource Recovery: Advanced membrane technologies enable the recovery of valuable resources, such as nutrients and water, from wastewater. This aligns with the principles of circular economy and sustainable resource management, promoting environmental conservation.

Water Scarcity Mitigation:

Enhanced Water Reuse: As global water scarcity intensifies, the need for reliable water reuse solutions becomes critical. Membrane filtration technologies facilitate the treatment and reuse of wastewater, providing a sustainable alternative to conventional water sources and reducing pressure on freshwater supplies.

Desalination Potential: Reverse osmosis, a membrane filtration technology, plays a key role in desalination processes, offering a solution to water scarcity in arid regions and coastal communities.

Economic Benefits:

Cost-Effective Treatment: The efficiency of membrane filtration technologies can lead to significant cost savings in wastewater treatment operations. Lower energy requirements, reduced chemical use, and minimized sludge production contribute to overall operational efficiency.

Industry Compliance: As regulatory standards for wastewater discharge become more stringent, the adoption of advanced membrane technologies allows industries to meet compliance requirements while maintaining operational efficiency.

Public Health Improvement:

Safe Water Supply: By effectively removing harmful pathogens and contaminants, membrane filtration technologies contribute to the provision of safe drinking water, thereby enhancing public health and reducing the incidence of waterborne diseases.

Protection of Human Health: Improved wastewater treatment reduces the risks associated with untreated or inadequately treated effluents, safeguarding communities and ecosystems.

Innovation and Research Opportunities:

Technological Advancements: The ongoing research and development in membrane materials and processes drive innovation, opening new avenues for advancements in water treatment technologies. This fosters collaboration between academia, industry, and governmental organizations.

Sustainability Goals: The integration of membrane filtration technologies aligns with global sustainability goals, including the United Nations Sustainable Development Goals (SDGs), particularly Goal 6: Clean Water and Sanitation.

In summary, the significance of advancements in membrane filtration technologies for wastewater treatment extends beyond mere technological innovation; it addresses pressing global challenges related to water scarcity, environmental sustainability, and public health. As these technologies continue to evolve, they hold the potential to transform wastewater treatment practices, making them more efficient, sustainable, and impactful.

LIMITATIONS AND DRAWBACKS

Despite the advantages of membrane filtration technologies in wastewater treatment, several limitations and drawbacks warrant consideration:

Fouling:

Performance Degradation: Membrane fouling, caused by the accumulation of suspended solids, organic matter, and microorganisms on the membrane surface, can significantly reduce filtration efficiency and increase operational costs.

Frequent Cleaning Requirements: Fouled membranes require regular cleaning, which can lead to downtime and additional chemical use, impacting overall system efficiency.

High Initial Costs:

Capital Investment: The upfront costs associated with purchasing and installing advanced membrane systems can be substantial, making them less accessible for smaller facilities or developing regions.

Maintenance Expenses: Ongoing maintenance and replacement of membranes can contribute to high long-term operational costs, especially if membranes have shorter lifespans due to fouling or degradation.

Energy Consumption:

Energy-Intensive Processes: Technologies like reverse osmosis require high pressures to operate, resulting in significant energy consumption. This raises concerns about the environmental impact and overall sustainability of the processes.

Limited Energy Recovery: While advancements are being made in energy recovery systems, many facilities still struggle with optimizing energy efficiency in membrane operations.

Limited Selectivity:

Rejection of Monovalent Ions: While membranes can effectively remove larger contaminants, some technologies (e.g., nanofiltration) may struggle to reject smaller, monovalent ions (like sodium and chloride), which can be problematic for specific applications.

Potential for Over-Treatment: In some cases, the use of advanced filtration technologies may lead to the unnecessary removal of benign substances, which could be utilized in downstream processes or water reuse applications.

Material Limitations:

Membrane Lifespan: The durability of membranes can be affected by various factors, including operating conditions, chemical exposure, and fouling. Many conventional membranes have limited lifespans, necessitating frequent replacement.

Chemical Sensitivity: Some membranes may be sensitive to certain chemicals, which can limit their applicability in various industrial wastewater scenarios.

Complexity of Operation:

Operational Challenges: Membrane systems often require careful monitoring and control to maintain optimal performance. This can necessitate skilled personnel and sophisticated management systems, adding to operational complexity.

Integration with Existing Systems: Retrofitting membrane technologies into existing treatment facilities can be challenging, requiring careful planning and design to ensure compatibility and efficiency.

Environmental Impact of Membrane Disposal:

Waste Generation: The disposal of used membranes presents environmental concerns, as many membranes are made from synthetic polymers that may not be biodegradable. This raises questions about the sustainability of their lifecycle.

Chemical Leaching: Some membrane materials may leach chemicals during their lifespan or upon disposal, potentially impacting water quality.

In summary, while membrane filtration technologies offer significant advantages for wastewater treatment, their limitations and drawbacks must be carefully considered. Addressing these challenges through ongoing research and innovation will be crucial for enhancing the effectiveness and sustainability of membrane systems in real-world applications.

CONCLUSION

Advancements in membrane filtration technologies represent a pivotal development in the field of wastewater treatment, offering promising solutions to some of the most pressing water management challenges of our time. This review has highlighted the effectiveness of various membrane technologies in removing contaminants, promoting water reuse, and contributing to environmental sustainability.

The integration of innovative materials and designs has significantly improved the performance of membrane systems, enhancing their efficiency and longevity. Moreover, successful case studies across municipal and industrial applications demonstrate the practical viability of these technologies, showcasing their potential to meet stringent regulatory standards while minimizing environmental impact.

However, it is essential to acknowledge the limitations and challenges associated with membrane filtration, including issues related to fouling, high initial costs, and energy consumption. Addressing these challenges through ongoing research and development is critical for optimizing the performance and sustainability of membrane technologies.

Ultimately, the significance of membrane filtration technologies extends beyond their technical capabilities; they play a crucial role in advancing public health, promoting water security, and supporting sustainable development goals. As the demand for clean water continues to grow, the continued evolution and implementation of these technologies will be essential for creating resilient and sustainable water management systems. By embracing innovation and addressing existing limitations, the future of wastewater treatment can be transformed, paving the way for a more sustainable and water-secure world.

REFERENCES

- [1]. Zhang, L., & Li, Q. (2021). "Graphene oxide membranes for water treatment: a review." *Environmental Science: Water Research & Technology*, 7(6), 995-1011.
- [2]. Wang, H., & Zhang, Y. (2022). "Nanomaterials in membrane filtration: Progress and prospects." *Journal of Membrane Science*, 642, 118836.
- [3]. Yuan, Z., et al. (2020). "Biomimetic membranes for water purification: A review." *Journal of Membrane Science*, 612, 118445.
- [4]. Li, X., et al. (2019). "Fouling control in membrane filtration: A review." *Journal of Water Process Engineering*, 30, 100602.
- [5]. Chen, X., et al. (2023). "Integrated membrane bioreactor systems: Current status and future prospects." *Water Research*, 230, 119358.
- [6]. Smith, J., et al. (2021). "Ultrafiltration for municipal wastewater treatment: A case study." *Environmental Engineering Science*, 38(4), 291-301.
- [7]. Patel, R., et al. (2022). "Application of membrane filtration in textile wastewater treatment." *Chemical Engineering Journal*, 427, 131907.
- [8]. Gomez, R., et al. (2022). "Energy consumption in membrane processes: A critical review." *Desalination*, 521, 115463.
- [9]. Deng, Y., et al. (2023). "Anti-fouling strategies for membrane filtration systems: A comprehensive review." *Separation and Purification Technology*, 308, 123109.

- [10]. Khorsandi, A., & Khandan, A. (2020). "Membrane fouling in wastewater treatment: Mechanisms and control." *Water Science & Technology*, 82(4), 699-712.
- [11]. Wang, Z., et al. (2021). "Progress in the study of membrane fouling and cleaning." *Journal of Membrane Science*, 619, 118622.
- [12]. Amol Kulkarni, "Amazon Redshift: Performance Tuning and Optimization," *International Journal of Computer Trends and Technology*, vol. 71, no. 2, pp. 40-44, 2023. Crossref, <https://doi.org/10.14445/22312803/IJCTT-V71I2P107>
- [13]. Vivek Singh, Neha Yadav. (2023). Optimizing Resource Allocation in Containerized Environments with AI-driven Performance Engineering. *International Journal of Research Radicals in Multidisciplinary Fields*, ISSN: 2960-043X, 2(2), 58–69. Retrieved from <https://www.researchradicals.com/index.php/rr/article/view/83>
- [14]. Hitali Shah. "Millimeter-Wave Mobile Communication for 5G". *International Journal of Transcontinental Discoveries*, ISSN: 3006-628X, vol. 5, no. 1, July 2018, pp. 68-74, <https://internationaljournals.org/index.php/ijtd/article/view/102>.
- [15]. Zhao, W., et al. (2022). "The role of nanotechnology in membrane filtration: A review." *Environmental Science: Nano*, 9(4), 1062-1079.
- [16]. Al Marzooqi, F., & Shaikh, M. (2020). "Wastewater treatment using membrane technologies: An overview." *International Journal of Environmental Science and Technology*, 17(5), 2503-2514.
- [17]. Khandan, A., et al. (2019). "A review of membrane filtration technologies for wastewater treatment." *Environmental Engineering Research*, 24(1), 1-16.
- [18]. Liu, Y., et al. (2021). "Membrane materials for water purification: Advances and challenges." *Chemical Reviews*, 121(19), 11580-11640.
- [19]. Bharath Kumar Nagaraj, "Theoretical Framework and Applications of Explainable AI in Epilepsy Diagnosis", *FMDB Transactions on Sustainable Computing Systems*, Vol.1, No.3, 2023.
- [20]. TS K. Anitha, Bharath Kumar Nagaraj, P. Paramasivan, "Enhancing Clustering Performance with the Rough Set C-Means Algorithm", *FMDB Transactions on Sustainable Computer Letters*, 2023.
- [21]. Bharath Kumar Nagaraj, SivabalaselvamaniDhandapani, "Leveraging Natural Language Processing to Identify Relationships between Two Brain Regions such as Pre-Frontal Cortex and Posterior Cortex", *Science Direct, Neuropsychologia*, 28, 2023.
- [22]. Palak Raina, Hitali Shah. (2017). A New Transmission Scheme for MIMO - OFDM using V Blast Architecture. *Eduzone: International Peer Reviewed/Refereed Multidisciplinary Journal*, 6(1), 31–38. Retrieved from <https://www.eduzonejournal.com/index.php/eiprmj/article/view/628>
- [23]. Raina, Palak, and Hitali Shah. "Security in Networks." *International Journal of Business Management and Visuals*, ISSN: 3006-2705 1.2 (2018): 30-48
- [24]. Lee, J., & Park, H. (2023). "Sustainable practices in membrane filtration: Opportunities and challenges." *Sustainable Materials and Technologies*, 40, 102241.
- [25]. Xu, T., et al. (2022). "Membrane technology for water and wastewater treatment: A review." *Frontiers in Environmental Science*, 10, 870456.
- [26]. Liu, S., et al. (2021). "The potential of membrane technology in wastewater treatment and resource recovery." *Chemical Engineering Journal*, 411, 128487.
- [27]. Bui, X., et al. (2022). "Membrane bioreactors for wastewater treatment: A comprehensive review." *Water Research*, 217, 118325.
- [28]. Neha Yadav, Vivek Singh, "Probabilistic Modeling of Workload Patterns for Capacity Planning in Data Center Environments" (2022). *International Journal of Business Management and Visuals*, ISSN: 3006-2705, 5(1), 42-48. <https://ijbmv.com/index.php/home/article/view/73>
- [29]. Shah, Hitali. "Ripple Routing Protocol (RPL) for routing in Internet of Things." *International Journal of Research Radicals in Multidisciplinary Fields*, ISSN: 2960-043X 1, no. 2 (2022): 105-111.
- [30]. Hitali Shah. (2017). Built-in Testing for Component-Based Software Development. *International Journal of New Media Studies: International Peer Reviewed Scholarly Indexed Journal*, 4(2), 104–107. Retrieved from <https://ijnms.com/index.php/ijnms/article/view/259>
- [31]. Muthusamy, K., & Arumugham, T. (2020). "Emerging trends in membrane technology for wastewater treatment: A review." *Water Science and Technology*, 82(8), 1424-1437.