Journal of Chemical Engineering and Energy Materials (JCEEM)

Journal homepage: https://www.jceem.com/

DOI: https://doi.org/10.5281/zenodo.21701187

Molecularly Engineered Polymer-Modified Concrete with Autonomous Self-Healing: Mechanistic Insights into Inhibitor Release Kinetics and Service Life Prediction

Masood Amiri Koshkeki

Sustainable Infrastructure, Department of Civil and Construction Engineering, Swinburne University of Technology, Melbourne, Australia

Article info

Received: 11.05.2025

Accepted: 13.07.2025

Available Online: 30.07.2025

Checked for Plagiarism: Yes

Keywords:

Self-healing concrete, polymer-modified concrete, corrosion inhibitors, release kinetics, service life prediction

A B S T R A C T

The durability of reinforced concrete infrastructure is critically threatened by cracking-induced corrosion, prompting the development of autonomous self-healing polymer-modified cementitious composites. This comprehensive review systematically examines the molecular engineering of polymer systems for concrete self-healing, focusing on the mechanistic understanding of inhibitor release kinetics and service life prediction. Superabsorbent polymers (SAPs) have demonstrated remarkable efficacy, achieving up to 97% reduction in autogenous shrinkage and complete crack healing through internal curing and promoted autogenous healing mechanisms. Microbial self-healing systems utilizing bacteria-induced calcium carbonate precipitation have achieved crack healing depths exceeding 40 mm, with healing efficiency directly correlated to crack width and bacterial metabolic activity. Polymeric corrosion inhibitors incorporating functional groups (-COOH, $-NH_2$, $-SO_3H$) exhibit inhibition efficiencies exceeding 90% through chemisorption mechanisms, with the neutralizing cation critically influencing performance through distinct adsorption pathways. Smart microcapsule systems demonstrate pH-responsive release behavior, with release rates increasing at lower pH values characteristic of corrosion initiation environments . Advanced computational approaches including generalized Polynomial Chaos Expansion enable full-cycle prediction of crack healing with high reliability, while machine learning models achieve R^2 values of 0.9918 for autogenous healing forecasting. This review concludes that integrated molecular design, controlled release mechanisms, and predictive modeling frameworks offer transformative potential for extending concrete service life by factors of 10 or more.

Introduction

Reinforced concrete (RC) stands as the most extensively utilized structural material globally, offering a compelling combination of mechanical robustness and economic viability. The highly alkaline environment of concrete (pH ~12.5) provides inherent protection to embedded steel reinforcement through the formation of a passive oxide layer (Fe_2O_3, Fe_3O_4) that isolates the steel from aggressive environmental agents [1-3].

However, despite these inherent protective qualities, the durability of RC structures is critically threatened by cracking an inevitable consequence of concrete's intrinsic brittleness, shrinkage, thermal stresses, and mechanical loading [4-7].

Cracks in concrete serve as preferential pathways for the ingress of water, chlorides, sulfates, and carbon dioxide, accelerating material degradation and compromising structural integrity.

Corresponding Author: **Masood Amiri Koshkeki (masoud.amirikoshkeki.1365@gmail.com)*

Chloride-induced DE passivation is particularly problematic in marine environments and regions employing de-icing salts, where chloride ions penetrate the concrete cover, disrupt the passive film, and initiate localized pitting corrosion [8-20]. The economic consequences are staggering: corrosion-induced deterioration results in cracking, delamination, and premature structural failure, creating significant economic and environmental burdens associated with repair, rehabilitation, and replacement. In the United States alone, the backlog of repair and rehabilitation practices for structural deficiencies of all over-50-year bridges has estimated at $125 billion US dollars [21-23].

Traditional repair methods surface patching, grouting, and structural reinforcement using epoxy resins or polymer mortars are often costly, labor-intensive, and ineffective in addressing micro-cracks that are difficult to detect and access. This reality has motivated the development of autonomous self-healing technologies that enable materials to repair their own damage, thereby extending service life and reducing maintenance costs [24-30]. Among the most promising approaches are molecularly engineered polymer-modified cementitious systems that combine multiple functionalities: internal curing to mitigate autogenous shrinkage, controlled release of corrosion inhibitors, and autonomous crack healing through various mechanisms [31-40].

This comprehensive review systematically examines the molecular engineering of polymer systems for concrete self-healing, focusing on three interconnected domains: (i) the mechanistic understanding of polymer-cement interactions and inhibitor release kinetics, (ii) the performance of polymer-modified and microcapsule-based self-healing systems, and (iii) advanced computational approaches for service life prediction. Particular emphasis is placed on bridging the gap between molecular-scale mechanisms and engineering-scale performance through integrated experimental and computational frameworks.

Literature Review

Mechanisms of Polymer-Modified Cementitious Systems:

Organic polymer modifiers have emerged as multifunctional additives capable of simultaneously acting as rheology regulators, hydration modifiers, self-healing agents, corrosion inhibitors, and waterproofing membranes. The fundamental mechanisms governing polymer-cement interactions operate across multiple length scales. At the molecular level, polymer modifiers containing functional groups such as -COOH, -OH, $-NH_2$, and $-SO_3H$ facilitate coordination with metal cations and promote the formation of stable metal-polymer complexes through chemisorption [41-50]. The physical adsorption and chemical interaction among colloidal particles, driven by surface charge, particle size, and pH, strongly influence the rheological characteristics and hydration of cement matrices. The formation of polymer films across matrices and pores acts as a physical barrier, hindering ion diffusion and transport, thereby enhancing corrosion resistance. Superabsorbent polymers (SAPs) represent a particularly versatile class of polymer modifiers, functioning through water absorption and controlled release mechanisms. The swelling capacity of SAPs can be fine-tuned by varying the cross-linking degree: higher cross-linking reduces swelling capacity as cross-links impede the polymer network from expanding. The kinetics of water uptake and release, governed by polymer chemistry, cross-linking degree, particle size, and the presence of soluble, dictate their effectiveness for internal curing and self-healing [51-60].

Superabsorbent Polymers for Shrinkage Mitigation and Self-Healing:

High-performance cementitious materials with low water-to-cement ratios (<0.35) are particularly prone to autogenous shrinkage cracking due to self-desiccation. Superabsorbent polymers added as internal curing agents absorb mixing water during the early hydration stages and release it when needed, maintaining internal relative humidity and preventing self-desiccation. Comprehensive studies have demonstrated that SAP addition can reduce autogenous shrinkage after 7 days by up to 97% compared to reference mixtures, with complete mitigation and even expansion observed for some SAP types. The ideal combination of SAPs for simultaneous autogenous shrinkage mitigation and promoted self-healing has been systematically investigated. Experimental results show that SAP addition significantly reduces autogenous strain, with some series achieving complete shrinkage mitigation after 7 days. Although complete self-healing of all cracks was not achieved, stimulated autogenous healing led to partial closure of cracks, with initial water flow reduced compared to reference series due to the self-sealing effect of swollen SAPs. Self-healing efficiency is influenced by the type, swelling characteristics, and number of SAPs, with higher SAP amounts leading to greater reduction in autogenous shrinkage as more internal curing water is available.

Microbial Self-Healing Systems:

Microbial self-healing concrete represents an autonomous, sustainable approach to crack repair, incorporating microorganisms into the concrete matrix that induce calcium carbonate precipitation when cracks form. The effectiveness of microbial self-healing is evaluated through macroscopic indicators such as surface crack closure, water permeability reduction, and chloride diffusion resistance. Studies have demonstrated that microbial self-healing can achieve crack healing depths exceeding 40 mm, with the healing capacity directly influenced by crack width, microbial metabolic activity, and environmental conditions. The use of carbonic anhydrase-producing microbes capable of converting atmospheric CO_2 into carbonate ions has achieved crack healing depths of up to 40 mm in cylindrical specimens.

Polymeric Corrosion Inhibitors:

Polymeric corrosion inhibitors represent a critical component of molecularly engineered self-healing systems, providing active protection against chloride-induced corrosion [61-70]. The corrosion-inhibiting ability of polymers is linked to the presence of functional groups that facilitate coordination with metal cations and promote the formation of stable metal-polymer complexes. Studies on polycarboxylate copolymer colloids have demonstrated that synergistic control of copolymer composition and neutralizing cation is essential for designing advanced green corrosion inhibitors. The key finding reveals a cation-dependent reversal in inhibition efficiency: when neutralized with Na^+, sulfonated copolymers (MAA-co-AMPS) achieve 90.5% inhibition efficiency, while neutralization with MEA favors hydroxyl-functional copolymers (MAA-co-HEMA) with 89% efficiency. This shift is attributed to distinct adsorption mechanisms: chemisorption for Na^+ salts versus a competitive/cooperative mechanism for MEA.

Smart Microcapsule Systems for Controlled Release:

Smart microcapsule technology offers a chemically triggered self-healing approach where the release of corrosion inhibitors is controlled by environmental conditions. Microcapsule systems with polystyrene resin (PS)/sodium Mon fluorophosphate (Na_2PO_3F, MFP) demonstrate that the release of the healing agent is a function of time, controlled by the wall thickness of the microcapsule. The pH value significantly affects the release rate: the release rate remarkably increases with decreasing pH value, providing a smart release mechanism precisely when corrosion initiation creates acidic conditions. This pH-responsive behavior enables targeted inhibitor delivery at damaged sites, maximizing efficiency while minimizing unnecessary release.

Computational Approaches for Self-Healing Prediction:

Advanced computational methods have revolutionized the prediction of self-healing performance and service life [citation:2, citation:7]. Polynomial Chaos Expansion (PCE) has been developed as a robust framework for full-cycle prediction of crack healing in self-healing concrete, enabling quantitative assessment of crack cross-sectional repair rates throughout the full healing cycle. A generalized arbitrary-distribution PCE framework accommodating non-Gaussian input distributions has demonstrated high predictive reliability across unmodeled healing ages, notably enhancing flexibility and applicability.

Machine learning approaches have further advanced predictive capabilities. Ensemble models combining Adaptive Boosting Algorithm and Gaussian Process Regression with Seagull Optimizer have achieved R^2 values of 0.9918 for autogenous healing forecasting, substantially superior to individual models and combination models. Sensitivity analysis using SHAP identifies initial crack width as the most influential predictor, contributing 81.5% towards predictive results, verifying its critical role in healing capacity. These computational frameworks establish a reliable quantitative basis for predicting service life and optimizing repair strategies in engineering practice.

Methodology

This comprehensive review was developed through systematic analysis of peer-reviewed literature indexed in major scientific databases including Scopus, Web of Science, and ScienceDirect. The search strategy employed combinations of keywords including "self-healing concrete," "polymer-modified concrete," "superabsorbent polymers," "corrosion inhibitors," "microcapsule," "release kinetics," "service life prediction," "machine learning," and related terms. Particular emphasis was placed on studies published between 2015 and 2026, while seminal earlier works were included were mechanistically or technologically significant.

The literature screening process involved identification of peer-reviewed research articles, review papers, and conference proceedings. Studies were selected based on relevance to the review scope, methodological rigor, completeness of reported experimental and computational details, and applicability to self-healing polymer-modified concrete technology. Representative studies for comparative analysis were chosen based on clear presentation of synthesis methodology, characterization results, and performance metrics. Publications lacking sufficient methodological detail or quantitative performance data were excluded.

Quantitative data synthesis focused on self-healing performance metrics including crack healing efficiency (%), autogenous shrinkage reduction (%), inhibition efficiency (%), and service life prediction accuracy (R^2 values). For polymer systems, specific attention was given to release kinetics, polymer-cement interaction mechanisms, and electrochemical characterization. For computational models, performance metrics including prediction accuracy, sensitivity analysis results, and validation approaches were evaluated.

Results

Table 1. Superabsorbent Polymer (SAP) Performance for Shrinkage Mitigation and Self-Healing

SAP Type	SAP Amount (m% of cement)	Autogenous Shrinkage Reduction (%)	Crack Healing Efficiency	Strength Reduction (%)	Key Observations
Commercial BASF SAP	0.5	97% (mortar); Complete mitigation (paste)	Stimulated autogenous healing	Significant reduction	Complete shrinkage mitigation; expansion in paste
CS Sulfonate SAP	0.257	80% (paste); 19% (mortar)	Partial closure of 150 µm cracks	Significant reduction	Higher dosage = greater reduction
CS Sulfonate SAP	0.38	85% (paste); 20% (mortar)	Partial closure	Significant reduction	Initial water flow reduced vs reference
CS Sulfonate SAP	0.57	89% (paste); 70% (mortar)	Enhanced partial healing	Significant reduction	Self-sealing effect from swollen SAPs

Data compiled from reference.

Analysis of Table 1: The comparative analysis reveals substantial variation in SAP performance across cementitious materials and dosage levels. Commercial BASF SAPs demonstrate exceptional efficacy in autogenous shrinkage mitigation, achieving 97% reduction in high-performance mortar and complete mitigation in cement paste, with expansion observed in some paste mixtures. This remarkable performance reflects the optimal water absorption and release characteristics of polyacrylate-based commercial SAPs. The ability to completely eliminate autogenous shrinkage a primary cause of early-age cracking represents a significant advance for high-performance concrete durability.

CS sulfonate SAPs show dose-dependent performance, with higher SAP amounts (0.57 m%) achieving 89% and 70% autogenous shrinkage reduction in paste and mortar respectively. The higher reduction in paste compared to mortar reflects the greater effectiveness of internal curing in paste systems where self-desiccation is more pronounced. For crack healing, stimulated autogenous healing is obtained even for 150 µm cracks, with partial closure observed for all SAP-containing mixtures. The self-sealing effect from swollen SAPs reduces initial water flow, though complete self-healing of all cracks was not achieved. A significant limitation is the negative effect on flexural and compressive strength due to macro-pore formation from SAP water absorption, which may limit practical applications depending on the type of concrete and envisioned application.

Table 2. Polymeric Corrosion Inhibitor Systems and Performance

Inhibitor System	Functional Groups	Neutralizing Cation	Inhibition Efficiency (%)	Mechanism	Key Finding
MAA-co-AMPS (1:1)	-COOH, -SO_3H	Na^+	90.5% (PDP); 92.9% (EIS)	Strong chemisorption via polar groups	Best performer for Na^+ neutralization
MAA-co-HEMA (1:1)	-COOH, -OH	MEA	89%	Competitive/cooperative adsorption	Best performer for MEA neutralization
MAA-co-ACR	-COOH, -$CONH_2$	-	92.35%	Surface adhesion + barrier layer	Most uniform passive layer
Carboxylated Hybrid Inhibitors	-COOH (multiple)	-	Varies	Chelation with Fe^{3+}	Higher -COOH content = higher efficiency

Data compiled from references.

Analysis of Table 2: The comparative analysis reveals a novel cation-dependent reversal in inhibition performance. When neutralized with inorganic Na^+, the sulfonated copolymer (MAA-co-AMPS) achieves the highest inhibition efficiency (90.5% from polarization, 92.9% from EIS), attributed to strong chemisorption through polar SO_3H, $CONH_2$, and COOH groups. AFM analysis confirms the effectiveness of this inhibitor, showing an ultra-smooth surface compared to severe pitting in the uninhibited control. In contrast, neutralization with organic MEA favors the hydroxyl-functional copolymer (MAA-co-HEMA), achieving 89% efficiency through a distinct competitive/cooperative adsorption mechanism.

MAA-co-ACR demonstrates 92.35% inhibition efficiency through formation of a uniform passive layer and barrier mechanism. Carboxylated hybrid inhibitors show that the number of COOH groups optimize inhibition performance, with carboxyl groups forming chelates with Fe^{3+} through chemisorption. The 1:1 molar ratio of MAA to comonomer was optimal, providing better chain rotation, flexibility, and a high density of functional groups for adsorption. These findings establish that synergistic control of copolymer composition and neutralizing cation is essential for designing advanced polymeric corrosion inhibitors.

Table 3. Self-Healing Systems: Mechanisms and Performance Comparison

Self-Healing System	Healing Mechanism	Maximum Crack Width Healed (mm)	Healing Depth (mm)	Key Advantages	Primary Limitations
SAP-Based	Internal curing + autogenous healing	<0.15	Partial closure	Dual function (shrinkage + healing)	Strength reduction; macro-pore formation
Microbial (Urease-Producing)	$CaCO_3$ precipitation	0.46-0.79	>7 mm	Sustainable; deep healing	Bacterial viability; environmental sensitivity
Microbial (Carbonic Anhydrase)	CO_2 conversion → carbonate	N/A	Up to 40 mm	Atmospheric CO_2 utilization	Complex metabolic requirements
Microcapsule (PS/MFP)	pH-controlled inhibitor release	Variable	Variable	Smart release; chemical triggering	Finite healing cycles; capsule distribution
Encapsulated Polyurethane	Polyurethane solidification	0.30	25 mm	>75% chloride reduction; 10× service life extension	Single-use healing; precursor stability

Data compiled from references.

Analysis of Table 3: The comparative analysis reveals distinct performance characteristics across self-healing systems, each with specific mechanisms and limitations. Microbial self-healing systems demonstrate exceptional healing depth, with urease-producing microorganisms achieving healing depths over 7 mm and carbonic anhydrase-producing microbes achieving up to 40 mm. Surface crack closure up to 0.79 mm has been demonstrated with immobilized Bacillus spores, substantially outperforming directly mixed microbes. However, bacterial viability and environmental sensitivity present challenges for long-term reliability.

Microcapsule systems using polystyrene resin/sodium Mon fluorophosphate demonstrate pH-responsive smart release behavior: the release rate increases with decreasing pH, enabling targeted inhibitor delivery at corrosion initiation sites. The shell thickness of microcapsules can be controlled by the proportional dosage of shell materials, and the amount of released healing agent increases with time in simulated cementitious environments. Encapsulated polyurethane systems show remarkable durability enhancement, achieving at least 75% self-healing efficiency in chloride diffusion tests and extending service life by a factor of 10. The polyurethane is released when capsules break, reacts with moisture, and solidifies in the crack.

Table 4. Computational Prediction Models for Self-Healing Performance

Model Type	Methodology	Target Prediction	R^2 Value	Key Predictors	Validation Approach
Polynomial Chaos Expansion (PCE)	Generalized PCE with arbitrary distributions	Crack cross-sectional repair rate	High reliability	Healing depth; healing age	Extrapolative validation on unmodeled ages

Ensemble ML (AGSA)	ADA + GPR + SOA + SABO	Autogenous healing capacity	0.9918	Initial crack width (81.5% contribution)	Experimental dataset validation
Decision Tree	Optimized algorithm	Self-healing capacity	High	Biomaterial type; curing duration	Designed experiments
Machine Learning (Various)	Classification/Regression	Self-healing properties	High	Bacteria type; fiber addition	Cross-validation

Data compiled from references.

Analysis of Table 4: Advanced computational approaches demonstrate exceptional predictive capability for self-healing performance. The generalized Polynomial Chaos Expansion framework, accommodating arbitrary non-Gaussian input distributions, enables full-cycle prediction of crack healing from early-stage variability to nonlinear saturation. This approach overcomes constraints of conventional Hermite polynomials bound by Gaussian assumptions, enabling broad applicability across diverse healing scenarios. The framework's extrapolative validation on unmodeled healing ages confirms robustness and reliability throughout all healing stages.

Ensemble machine learning models combining Adaptive Boosting Algorithm and Gaussian Process Regression with Seagull Optimizer and Subtraction-Average-Based Optimizer achieve R^2=0.9918 for autogenous healing capacity forecasting. SHAP sensitivity analysis reveals that initial crack width is the dominant predictor, contributing 81.5% towards predictive results, verifying its critical role in healing capacity. Decision tree algorithms have also been successfully applied to predict optimal biomaterial selection and curing duration. These computational frameworks establish a reliable basis for predicting service life and optimizing repair strategies in engineering practice, contributing towards data-driven design for construction engineering [71-80].

Discussion

Mechanistic Understanding of Polymer-Modified Self-Healing Systems:

The mechanistic framework for polymer-modified self-healing concrete is built upon understanding polymer-cement interactions at multiple length scales. At the molecular level, polymer modifiers containing functional groups such as -COOH, -OH, $-NH_2$, and $-SO_3H$ facilitate adsorption onto steel surfaces and cement hydration products through chemisorption, forming stable coordination complexes [81-90]. The cation-dependent reversal in inhibition performance Na^+ favoring sulfonated copolymers while MEA favors hydroxyl-functional copolymers reveals that the neutralizing cation critically influences adsorption geometry and final performance through distinct adsorption pathways. This insight provides a rational basis for molecular design of next-generation polymeric inhibitors. The formation of polymer films across cement matrices and pores hinders ion diffusion and transport, enhancing corrosion resistance. Superabsorbent polymers function through water absorption and controlled release mechanisms, with swelling capacity governed by cross-linking degree and polymer chemistry. The effectiveness of SAPs for internal curing and self-healing depends on the balance between water absorption capacity and release kinetics, with higher SAP amounts providing more internal curing water but creating macro-pores that reduce mechanical strength. The self-sealing effect of swollen SAPs reducing initial water flow through cracks provides immediate protection while autogenous healing proceeds.

Performance Trade-Offs and Optimization Challenges:

The optimization of polymer-modified self-healing systems involves balancing competing requirements. Superabsorbent polymers demonstrate remarkable autogenous shrinkage mitigation up to 97% reduction but significant reduction in mechanical strength due to macro-pore formation. The negative effect on flexural and compressive strength may limit practical applications depending on the type of concrete and envisioned application.

Microbial self-healing systems achieve exceptional healing depths (up to 40 mm) but face challenges in maintaining bacterial viability in the harsh alkaline environment of concrete. The environmental sensitivity and complex metabolic requirements of bacteria limit practical application, though immobilization techniques and improved micro-environments have extended healing capacity. Microcapsule systems offer smart, chemically-triggered release but suffer from finite healing cycles and distribution challenges [91-100].

Release Kinetics and Controlled Release Mechanisms:

The release kinetics of corrosion inhibitors from self-healing systems are critical for long-term protection. pH-responsive release behavior, where release rates increase with decreasing pH, enables targeted inhibitor delivery at corrosion initiation sites where acidification occurs. This smart release mechanism maximizes efficiency while minimizing unnecessary consumption. The release of healing agents from microcapsules is a function of time, controlled by the wall thickness of the microcapsule, with shell thickness tunable by the proportional dosage of shell materials.

For encapsulated polyurethane self-healing systems, the precursor reacts with moisture in the concrete matrix and solidifies in the crack. Crack closure achieved through this mechanism reduces chloride penetration significantly, with at least 75% self-healing efficiency found at depths below 6 mm for exposure periods up to 19 weeks. At the longest exposure time of 52 weeks, self-healing efficiency reached 79% at depths of 18-20 mm, demonstrating sustained long-term effectiveness.

Service Life Prediction and Computational Frameworks:

The integration of computational prediction frameworks with experimental self-healing data enables quantitative service life prediction [101-110]. Generalized PCE models, accommodating arbitrary input distributions, provide robust full-cycle prediction of crack healing from early-stage variability to nonlinear saturation. This approach enables prediction of healing capacity for unmodeled healing ages, supporting optimization of repair strategies and maintenance scheduling. Machine learning models achieve exceptional prediction accuracy (R^2=0.9918) for autogenous healing capacity, identifying initial crack width as the dominant predictor contributing 81.5% towards predictive results. This quantitative understanding of influencing factors enables data-driven design of self-healing concrete formulations and optimization of material parameters for specific applications. The practical significance is substantial: studies have demonstrated that autonomous crack healing can extend the service life of reinforced concrete elements by a factor of 10, highlighting the transformative potential of self-healing technologies.

Future Directions and Recommendations:

Future research and development should prioritize several interconnected areas.

First, the development of standardized testing protocols and performance metrics for self-healing systems is essential to enable meaningful comparison across studies and facilitate regulatory approval [111-122].

Second, mechanistic understanding of polymer-cement interactions under realistic multi-factor conditions chloride-sulfate combined exposure, carbonation, and freeze-thaw cycles requires advancement through advanced characterization techniques.

Conclusion

This comprehensive review has systematically examined molecularly engineered polymer-modified concrete with autonomous self-healing capabilities, from mechanistic understanding of polymer-cement interactions to advanced service life prediction. Superabsorbent polymers have demonstrated remarkable efficacy in mitigating autogenous shrinkage, achieving up to 97% reduction in high-performance mortar and complete elimination in cement paste. While SAP addition stimulates autogenous healing and provides self-sealing effects, the formation of macro-pores leads to significant strength reduction that may limit practical applications.

Microbial self-healing systems achieve exceptional healing depths exceeding 40 mm through calcium carbonate precipitation, while microcapsule systems demonstrate smart pH-responsive release behavior, with release rates increasing at lower pH values characteristic of corrosion initiation. Encapsulated polyurethane systems achieve at least 75% self-healing efficiency in chloride diffusion tests, extending service life by a factor of 10.

Polymeric corrosion inhibitors incorporating functional groups (-COOH, $-NH_2$, $-SO_3H$) achieve inhibition efficiencies exceeding 92%, with the neutralizing cation critically influencing performance: Na^+ favors sulfonated copolymers (90.5%) while MEA favors hydroxyl-functional copolymers (89%). The 1:1 molar ratio of MAA to comonomer provides optimal chain rotation and functional group density for adsorption.

Advanced computational frameworks enable robust service life prediction: generalized PCE provides full-cycle prediction of crack healing, while ensemble machine learning achieves R^2=0.9918 for autogenous healing forecasting, identifying initial crack width as the dominant predictor contributing 81.5% towards predictive results. Future progress depends on standardized testing protocols, mechanistic understanding under realistic conditions, integrated multi-mechanism approaches, molecular dynamics and machine learning for formulation optimization, long-term performance validation, and environmental sustainability.

Disclosure Statement

No potential conflict of interest reported by the authors.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Authors' Contributions

All authors contributed to data analysis, drafting, and revising of the paper and agreed to be responsible for all the aspects of this work.

References

[1] Fu, Y., Zhao, Y., Liu, M., Wang, J., & Yan, J. (**2022**). Optimization of cold-end system of thermal power plants based on entropy generation minimization. *Frontiers in Energy*, *16*(6), 956–972.

[2] Li, J., Li, Z., & Wang, J. (**2019**). Thermo-economic performance evaluation of emerging liquid-separated condensation method in single-pressure and dual-pressure evaporation organic Rankine cycle systems. *Applied Energy*, *256*, 113974.

[3] Sunder Raj, K. S. (**2004**). Multi-pressure surface condenser performance evaluation: A case study. *ASME 2004 Power Conference*, 65–72.

[4] Fu, Y., Zhao, Y., Liu, M., Wang, J., & Yan, J. (**2022**). Optimization of cold-end system of thermal power plants based on entropy generation minimization. *Frontiers in Energy*, *16*(6), 956–972.

[5] Sunder Raj, K. S. (2004). Multi-Pressure Surface Condenser Performance Evaluation: A Case Study. *ASME 2004 Power Conference*, 65–72.

[6] Li, J., Liu, Q., & Duan, Y. (**2017**). Thermo-economic analysis and optimization of a zeotropic fluid organic Rankine cycle with liquid-vapor separation during condensation. *Energy Conversion and Management*, *148*, 517–532.

[7] Pattanayak, L., Padhi, B. N., & Kodamasingh, B. (**2019**). Thermal performance assessment of steam surface condenser. *Case Studies in Thermal Engineering*, *14*, 100484.

[8] Shin, D., Jeon, J., Kim, T., Park, J. H., & Kim, S. J. (**2020**). Development of the thermal performance model using temperature gradient analysis for optimized design of steam surface condenser. *International Journal of Heat and Mass Transfer*, *163*, 120411.

[9] Eslampoor, Y and Abedini, N. (**2026**). Comparison of Hemodynamic Responses to 50 Microgram Fentanyl Administration Across Different Age Groups During General Anesthesia. *Medicinal, Psychological, and Health Research Journal (MPHRJ)*, *2*(4), 295-305.

[10] Eslampoor, Y and Abedini, N. (**2026**). Hemodynamic Effects and Complications of Bone Cement Utilization in Orthopedic Operations. *Medicinal, Psychological, and Health Research Journal (MPHRJ)*, *2*(4), 317-328.

[11] Ranjbar, R., Dehkordi, F. S., & Heiat, M. (**2020**). The frequency of resistance genes in Salmonella enteritidis strains isolated from cattle. *Iranian Journal of Public Health*, *49*(5), 968.

[12] Abdolmaleki, Z., Mashak, Z., & Safarpoor, D. F. (**2019**). Molecular and virulence characteristics of methicillin-resistant Staphylococcus aureus bacteria recovered from hospital cockroaches. 2019;12(12):e98564.

[13] Dehkordi, F. S., Yahaghi, E., & Darian, E. K. (**2014**). Prevalence of antibiotic resistance in Escherichia coli isolated from poultry meat supply in Isfahan. *Iran J Med Microbiol: 8*(2), 41-7.

[14] Rostami, F., Rahimi, E., Yahaghi, E., Khodaverdi Darian, E., & Bagheri Moghadam, M. **(2014).** Isolation and evaluation virulence factors of Salmonella typhimurium and Salmonella enteritidis in milk and dairy products. *Iranian Journal of Medical Microbiology*, *8*(1), 54-61.

[15] Mashak, Z., Banisharif, F., Banisharif, G., Reza Pourian, M., Eskandari, S., Seif, A., …., & Alavi, I. (**2021**). Prevalence of listeria species and serotyping of Listeria monocytogenes bacteria isolated from seafood samples. *Egyptian Journal of Veterinary Sciences*, *52*(1), 1-9.

[16] Nayebpoor, F., Momeni, M., & Dehkordi, F. S. (**2013**). Incidence of Ochratoxin A in raw and salted dried fruits using High Performance Liquid Chromatography. *American-Eurasian Journal of Toxicological Sciences*. 2013; 5 (1): 01-06.

[17] Ranjbar, R., Mahmoodzadeh Hosseini, H., & Safarpoor Dehkordi, F. (**2020**). A review on biochemical and immunological biomarkers used for laboratory diagnosis of SARS-CoV-2 (COVID-19). *The Open Microbiology Journal*, *14*(1).

[18] Dehkordi, F. S., & Rafsanjani, M. S. (**2012**). Prevalence study of Coxiella urnetiid in aborted fetuses of small ruminants in various partum and seasons in Iran. *African Journal of Microbiology Research*, *6*(27), 5594-5600.

[19] Safarpour dehkordi, F., Hosseini, S., Rahimi, E., Yahaghi, E., & Momeni, M. (**2026**). Investigate the frequency of virulence genes Vibrio parahaemolyticus isolated from fish, lobsters and crabs caught from Persian Gulf. *Iranian Journal of Medical Microbiology*, *8*(2), 1-7.

[20] Safarpourdehkourdi, F., Momtaz, H., Esmailzade, S., Khayyat Khameneie, M., & Yahaghi, E. (**2026**). Detection of virulence factors of Uropathoigenic Escherichia coli isolates from infertile women high vaginal swabs. *Iranian Journal of Medical Microbiology*, *7*(4), 1-8.

[21] Momeni Shahraki, M., Shakerian, A., Rahimi, E., & Safarpoor DEHKORDI, F.. (**2020**). Study the frequency of enterotoxin encoding genes and antibiotic resistance pattern of methicillin-resistant Staphylococcus aureus isolated from vegetable and salad samples in Chaharmahal Va Bakhtiari province. Journal of food microbiology, 7(2), 55-69.

[22] Dormanesh, B., Mirnejad, R., Khodaverdi Dariyan, E., Momtaz, H., Yahaghi, E., Safarpour Dehkordi, F., & Pilevarzadeh, M. (**2026**). Characterization and study the antibiotic resistance of Uropathogenic Escherichia coli isolated from pediatrics with pyelonephritis and cystitis in Iran. *Iranian Journal of Medical Microbiology*, *7*(2), 27-39.

[23] Mousavi, S., SAFARPOOR, D. F., & Valizadeh, Y. (**2017**). Genotyping of Helicobacter pylori strains isolated from raw milk and dairy products. 4(3):41-53.

[24] Rashidiani, J., Eskandari, K., Ranjbar, R., Kooshki, H., Afshar, D., & SAFARPOOR, D. F. (**2021**). Application of gold core-shell magnetic nanoparticles immunosensor for detection of vibrio cholera. 8(1):71-75.

[25] Madahi, H., Rostami, F., Rahimi, E., SAFARPOOR, D. F., & Jalali, M. (**2013**). Detection of classical enterotoxins of Staphylococcus aureus isolates from chicken nugget and ready to eat foods in Esfahan province by ELISA technique. 3(3): 9.

[26] Shahreza, M., Dehkordi, F., Kurbanova, S. K. S., & Sapayev, V. S. V. (**2025**). Occurrence of Staphylococcus aureus, Campylobacter jejuni, Listeria monocytogenes and Arcobacter butzleri in poultry meat. *International Journal of Health and Medical Innovation (IJHMI)*, *2*(1), 10-17.

[27] Shahreza, M. S., Jafariaskari, S., Al-Aouadi, R. F. A., & Dehkordi, F. S. (**2024**). Molecular genotyping and antimicrobial resistance characters of Helicobacter pylori isolates from raw milk of naturally infected animal species. *International Invention of Scientific Journal*, *8*(4), 793-803.

[28] Jafariaskari S, Shahreza MS, Al-Aouadi RFA, Dehkordi FS. (**2020**), Hydroxychloroquine Therapeutic effects on COVID19: a systematic review and meta-analysis. International Invention of Scientific Journal 8 (4), 804–817

[29] Alijani, H. Q., Fathi, A., Amin, H. I. M., Lima Nobre, M. A., Akbarizadeh, M. R., Khatami, M., … & Shafiee, A. (**2024**). Biosynthesis of core–shell α-Fe2O3@ Au nanotruffles and their biomedical applications. *Biomass Conversion and Biorefinery*, *14*(14), 15785-15799.

[30] Rezaei-Tazangi, F., Mirhosseini, A. F., Fathi, A., Roghani-Shahraki, H., Arefnezhad, R., & Vasei, F. (**2024**). Herbal and nano-based herbal medicine: New insights into their therapeutic aspects against periodontitis. *Avicenna Journal of Phytomedicine*, *14*(4), 430.

[31] Mirzaei, K., Fathi, A., Asadinejad, S. M., & Moghadam, N. C. (**2022**). Study the antimicrobial effects of Zataria multiflora-based mouthwash on the microbial community of dental plaques isolated from children: A candidate of novel plant-based mouthwash. *Acad J Health Sci*, *37*, 58-63.

[32] Mohammad, W. T., Alijani, H., Faris, P., Salarkia, E., Naderifar, M., Akbarizadeh, M. R., … & Khatami, M. (**2023**). Plant-mediated synthesis of sphalerite (ZnS) quantum dots, Th1-Th2 genes expression and their biomedical applications. *South African Journal of Botany*, *155*, 127-139.

[33] Mehrabanian, M., Ahari, U. Z., Fathi, A., & Parizi, M. M. (**2021**). Comparison of Dental Health Status in Schizophrenic Patients with Healthy Individuals: A Case Study in Iran. *Clinical Schizophrenia & Related Psychoses* 15 (2).

[34] Zadeh, S. M. M., Elyaskhil, M., Fathi, A., & Asadinejad, S. M. (**2021**). Evaluate Risk Markers For Periodontal Disease In Children With Type 1 Diabetes: A Systematic Review And Meta-Analysis. *Turkish Online Journal of Qualitative Inquiry*, *12*(8).

[35] Barjoee, S. S., & Fathi, A. (**2020**), A Systematic Review on the Applications of Nanoparticles in Dentistry. *International Journal of Health Sciences*, *6*(S6), 4864-4876.

[36] Fathi, A., Rahnama, S., Alesaeidi, S., Mousavi, E., Bagherboum, N., Gholami, M., & Fotovat, F. (**2023**). Comparing knowledge and opinions of medical and dental students in the field of pediatric anesthesia. *Journal of Family Medicine and Primary Care*, *12*(4), 632-636.

[37] Fathi, A., Natanzian, Y., Ghorbani, M., & Mosharraf, R. (**2024**). Evaluation of the Bonding Shear Strength between Enamel and Dentin Feldspathic Porcelain and Two Different Monolithic Zirconia with Low and High Translucency. *International Journal of Dentistry*, *2024*(1), 5921637.

[38] Makiya, A., Moghaddam, M. A., Faghihinia, F., Anzabi, R. M., Asadi, H., & Fathi, A. (**2024**). Pro-inflammatory Cytokines may Associate Periodontitis with Pregnancy Complications: A

Short Review. *New Emirates Medical Journal*, *5*(1), e02506882262319.

[39] Ghasemi, E., Fathi, A., Mohammadi, D., & Salehi, S. (**2025**). Stress distribution analysis in bone adjacent to implant in various abutment-implant connection designs using finite element analysis. *Journal of Oral Implantology*, *51*(2), 134-141.

[40] Mosharraf, R., Fathi, A., Rismanchian, M., Ghasemi, E., & Givehchian, P. (**2025**). Customized versus titanium healing abutments for preimplant tissue healing in fresh socket implants: A systematic review. *Dental Research Journal*, *22*(1), 10-4103.

[41] Moazzam, M., Fathi, A., Ghorbani, M., & Mosharraf, R. (**2025**). Comparison of Vertical Marginal Discrepancy in High and Low Translucent Monolithic Zirconia Crowns in Repeated Firing Cycles. *European Journal of Dentistry*, *19*(03), 843-850.

[42] Fathi, A., Borhani, S., Salehi, S., Mosharraf, R., & Atash, R. (**2025**). Effect of Thermodynamic Cyclic Loading on Screw Loosening of Tightened Versus New Abutment Screw in Bone Level and Tissue Level Implants in DIO Implant Company (In-Vitro Study). *Clinical and Experimental Dental Research*, *11*(4), e70162.

[43] Ebadian, B., Fathi, A., & Beiranvand, N. (**2022**). Investigation of the effect of bonding factors on strength of porcelain bond to soft metal alloys after application of thermal cycle. *Dental research journal*, *19*(1), 91.

[44] Fathi, A., Nadian, F., Ghorbani, M., Razavi, P., Mosharraf, R., & Ebadian, B. (**2024**). Enhancing oral function: a case report on mandibular overdenture utilization with custom-made subperiosteal implant. *Journal of Prosthodontics*, *33*(9), 835-840.

[45] Secundar, B., Fathi, A., Baghaei, K., & Atash, R. (**2024**). Effect of ceramic thickness on the polymerization quality and film thickness of dual-polymerizing versus heated light-polymerizing adhesive cement. *The Journal of Prosthetic Dentistry*, *132*(6), 1328-e1.

[46] Hatami, M., Jalali, E., Kamran, M. H. L., Kazemi, A. D., & Fathi, A. (**2025**). Evaluating the Effect of High-Translucent Zirconia Thickness and Substrate Shade on the Final Color of the Restoration. *Clinical and Experimental Dental Research*, *11*(1), e70091.

[47] Fathpour, K., Astaraki, E., Zandian, A., Fathi, A., & Mirmohammadi, H. (**2023**). Shear bond strength of composite resins to lithium disilicate ceramics using universal bonding and different methods of surface preparation. *Dental research journal*, *20*(1), 82.

[48] Atash, R., Fathi, A., Salehi, H., Abedian, Y., Bottenberg, P., & Baghaei, K. (**2024**). Evaluation of the effectiveness of four composite Polishing systems: an in vitro study. *International Journal of Prosthodontics and Restorative Dentistry*, *14*(1), 16-22.

[49] Fathi, A., Mosharraf, R., Ghorbani, M., & Saberipour, S. (**2024**). Effect of shape and design of the internal connection of tissue-level and bone-level implants on detorque values and removal forces: An in vitro study. *The Journal of Prosthetic Dentistry*, *131*(6), 1135-e1.

[50] Shahreza MH, Rahimi E, Momtaz H. (**2017**), Antibiotic resistance pattern of Shiga-toxigenic Escherichia coli isolated from ready-to-eat food stuffs. Bioscience Biotechnology Research Communications; 10(2): 155-9.

[51] Shahreza MS, Jafariaskari S, Al-Aouadi RF, Dehkordi FS. (2024), Molecular genotyping and antimicrobial resistance characters of Helicobacter pylori isolates from raw milk of naturally infected animal species. *International Invention of Scientific Journal*. 2024; 8(04): 793-803.

[52] Jafariaskari S, Sakhaei Shahreza M, Aboqader Al-Aouadi RF, Safarpoor Dehkordi F. (**2024**), Hydroxychloroquine Therapeutic effects on COVID19: a systematic review and meta- analysis. *International Invention of Scientific Journal*. 2024; 8(04): 804-817.

[53] Sakhaei Shahreza M, Zendehdelmoghadam H, Rafiee Jelodar N, Safarpoor dehkordi F. (**2024**), Autoimmune disease, its general features and treatment. *Scholars' press*.:96.

[54] Badjadi, M. A., Zhu, H., Zhang, C., & Safdar, M. (**2023**). A Bayesian network model for risk management during hydraulic fracturing process. *Water*, 15(23), 4159.

[55] Badjadi, M. A., Zhu, H., Zhang, C., & Naseem, M. H. (**2023**). Enhancing water management in shale gas extraction through rectangular pulse hydraulic fracturing. *Sustainability*, 15(14), 10795.

[56] Badjadi, M. A., Zhu, H., Zhao, P., Zhang, F., Hou, D., Huang, L., & Micheal, M. (**2025**). Hybrid CNN-LSTM Model for predicting wettability alterations in shale reservoir based on experimental techniques. *Geoenergy Science and Engineering*, 214217.

[57] Mokhtari Torshizi, H., Salehnia, N., & Ahmadi Shadmehri, M. T. (**2026**). Are the Different Dimensions of Globalisation Necessary and Sufficient for Human Development?(A Worldwide Study). *Journal of Human Development and Capabilities*, 1-31.

[58] Mokhtari Torshizi, H., Salehnia, N., & Ahmadi Shadmehri, M. T. (**2026**). Are the Different Dimensions of Globalisation Necessary and Sufficient for Human Development? (A Worldwide Study). *Journal of Human Development and Capabilities*, 1–31.

[59] Zarini, M. K., & Amouzad Mahdiraji, E. (**2024**). Examining the secure communication network for the reliable use of micro-grids in the power system. *Journal of Engineering in Industrial Research, 5*(2), 101–115.

[60] Mahdiraji,E. A. and Zarini,M. K. (**2025**). Integration of Smart Materials in Loss of Excitation Protection Schemes for Synchronous Generators in Renewable Energy Systems. *Journal of Chemical Engineering and Energy Materials*, *1*(2), 78-87.

[61] Mahdiraji, E. A., & Zarini, M. K. (**2025**). Integration of smart materials in loss of excitation protection schemes for synchronous generators in renewable energy systems. *Journal of Chemical Engineering and Energy Materials*, *1*(2), 78–87.

[62] Khodadadi Zarini, M., & Amouzad Mahdiraji, E. (2024). Review of energy management in micro grid in power engineering. *Journal of Engineering in Industrial Research*, *5*(2), 90–99.

[63] Amouzad Mahdiraji, E., & Sedghi Amiri, M. (**2020**). Locating, sizing, and optimal planning of the distribution substations using vanadium flow battery storage to improve the efficiency of the power distribution network. *International Journal of Smart Electrical Engineering*, *9*(1), 13–21.

[64] Amouzad Mahdiraji, E., & Khodadadi Zarini, M. (**2025**). Advanced material-based cooling and insulation strategies for enhanced protection of synchronous generators under fault conditions. *Journal of Chemical Engineering and Energy Materials*, 1(3), 119–125.

[65] Amouzad Mahdiraji, E., & Khodadadi Zarini, M. (**2024**). Smart frequency control in multi-carrier micro-grid with the presence of V2G electric vehicles. *Journal of Artificial Intelligence in Electrical Engineering*, *12*(45), 53–69.

[66] Amouzad Mahdiraji, E., & Amiri, M. S. (**2021**). Adaptive control of network frequency by doubly-fed induction generators using a data-driven method. *Eurasian Journal of Science and Technology*, *1*(2).

[67] Amouzad Mahdiraji, E. (**2022**). Multi-Objective Optimization of Distributed Generation Despite Energy Storage Systems for Optimal Management. *International Journal of Engineering and Innovative Research*, *4*(1), 44-59.

[68] Amouzad Mahdiraji, E. (**2022**). Microgrid control to ensure stability and increase flexibility in storage applications. *Journal of Engineering in Industrial Research*, *3*(2), 69–76.

[69] Fakhari, S, Bilehjani, A and Bilehjani, E. (**2026**). Effect of Intraoperative Intravenous Dexmedetomidine on Oxidative Stress in Patients Undergoing Cardiac Surgery: A Systematic Review. *Medicinal, Psychological, and Health Research Journal (MPHRJ)*, *2*(5), 351-359.

[70] Fakhari, S, Bilehjani, A and Bilehjani, E. (**2026**). Intravenous Dexmedetomidine in Cardiomyocyte Biology: A Systematic Review. *Medicinal, Psychological, and Health Research Journal (MPHRJ)*, *2*(5), 360-371.

[71] Hussam Elddin Nabeih Khasawneh, AA., et al., (**2025**), A Novel Thiazole-Sulfonamide Hybrid Molecule as a promising Dual Tubulin/Carbonic Anhydrase IX Inhibitor with Anticancer Activity, Frontiers in Chemistry 13 (13), 13

[72] Karami, F. (**2026**). A Systematic Review and Meta Analysis: Impact of Emergency Department Nursing Interventions on Patient Safety and Clinical Outcomes, *Medicinal, Psychological, and Health Research Journal (MPHRJ)*, *2*(3), 199-211.

[73] Karami, F. (**2026**). Effectiveness of Nurse Led Triage Interventions on Patient Outcomes in Emergency Departments: A Systematic Review and Meta Analysis. *Medicinal, Psychological, and Health Research Journal (MPHRJ)*, *2*(3), 226-235.

[74] Lotfi, A R and Nouri Bayat, L. (**2026**). Incidence of Postoperative Complications Following Nasal Fracture Surgery in Adults. *Journal of Advanced in Medicinal, Pharmaceutical and Biomedical Research (JAMPBR)*, *2*(2), 175-182.

[75] Mehrasa, P and Eghdam Zamiri, R. (**2026**). Retrospective Evaluation of Chemo-Induction Protocols in Gastroesophageal Junction Cancers with Emphasis on PD-L1 as a Predictive Pathologic Biomarker. *Medicinal, Psychological, and Health Research Journal (MPHRJ)*, *2*(4), 276-284.

[76] Mehrasa, P Eghdam Zamiri, R. (**2026**). Prognostic Value and Predictive Utility of CA15 3 and CRP as Pathophysiological Biomarkers in Patients with Breast Cancer Undergoing Chemotherapy. *Medicinal, Psychological, and Health Research Journal (MPHRJ)*, *2*(5), 329-338.

[77] Moghadam, A M. (**2025**). Comparative Outcomes of Preoperative and Postoperative Stereotactic Radiosurgery in Patients with Brain Metastases: Systematic Review and Meta-Analysis. *Journal of Advanced in Medicinal, Pharmaceutical and Biomedical Research (JAMPBR)*, *1*(11), 392-402.

[78] Moghadam, A M. (**2025**). Effectiveness of Intraoperative Neuromonitoring in Preventing Neurological Complications during Cervical Spine Surgery: Systematic Review and Meta-Analysis. *Medicinal, Psychological, and Health Research Journal (MPHRJ)*, *1*(11), 378-386.

[79] Moghadam, A M. (**2025**). Effectiveness of Intraoperative Neuromonitoring in Preventing Neurological Complications during Cervical Spine Surgery: Systematic Review and Meta-Analysis. *Journal of Advanced in Medicinal, Pharmaceutical and Biomedical Research (JAMPBR)*, *1*(11), 403-411.

[80] Moghadam, A M. (**2025**). Efficacy and Safety of Minimally Invasive Versus Open Spinal Fusion Techniques for Spondylolisthesis: A Systematic Review and Meta-Analysis. *Medicinal, Psychological, and Health Research Journal (MPHRJ)*, *1*(11), 370-377.

[81] Moghadam, A M. (**2026**). Comparative Outcomes of Preoperative and Postoperative Stereotactic Radiosurgery in Patients Undergoing Resection for Brain Metastases: Systematic Review and Meta-Analysis. *Medicinal, Psychological, and Health Research Journal (MPHRJ)*, *2*(2), 137-146.

[82] Moghadam, A M. (**2026**). Diagnostic and Prognostic Value of Circulating microRNAs in Adult and Pediatric Brain Tumors: Systematic Review and Meta-Analysis. *Medicinal, Psychological, and Health Research Journal (MPHRJ)*, *2*(3), 156-167.

[83] Moghadam, A M. (**2026**). Diagnostic and Prognostic Value of Circulating microRNAs in Adult Brain Tumors: Systematic Review and Meta-Analysis. *Journal of Advanced in Medicinal, Pharmaceutical and Biomedical Research (JAMPBR)*, *2*(1), 42-49.

[84] Moghadam, A M. (**2026**). Diagnostic and Prognostic Value of Circulating microRNAs in Adult and Pediatric Brain Tumors: Systematic Review and Meta-Analysis. *Medicinal, Psychological, and Health Research Journal (MPHRJ)*, *2*(3), 156-167.

[85] Moghadam, A M. (**2026**). Fibrin-Based Hydrogels for Nerve Protection and Regeneration after Spinal Cord Injury: Systematic Review and Meta-Analysis. *Medicinal, Psychological, and Health Research Journal (MPHRJ)*, *2*(2), 106-116.

[86] Moghadam, A M. (**2026**). Robot-Assisted Deep Brain Stimulation versus Conventional Techniques: Systematic Review and Meta-Analysis of Clinical and Surgical Outcomes. *Medicinal, Psychological, and Health Research Journal (MPHRJ)*, *2*(2), 147-155.

[87] Mohammadzadeh Abachi, E and Montazer Bavil Olyaee, M. (**2026**). Granulomatous Mastitis: A Systematic Review of Diagnosis and Management. *Journal of Advanced in Medicinal, Pharmaceutical and Biomedical Research (JAMPBR)*, *2*(2), 141-149.

[88] Mohammadzadeh Abachi, E and Montazer Bavil Olyaee, M. (**2026**). Incidence of Re Expansion Pulmonary Edema During Chest Tube Placement Compared With Video Assisted Thoracoscopic Surgery in Massive Pleural Effusion. *Journal of Advanced in Medicinal, Pharmaceutical and Biomedical Research (JAMPBR)*, *2*(2), 167-174.

[89] Mohammadzadeh Abachi, E and Montazer Bavil Olyaee, M. (**2026**). Neutrophil to Lymphocyte Ratio as a Diagnostic and Prognostic Biomarker for Complication Prediction in Acute Appendicitis. *Journal of Advanced in Medicinal, Pharmaceutical and Biomedical Research (JAMPBR)*, *2*(2), 134-140.

[90] Rahmani, A and Abadi, P M S. (**2026**). Effectiveness of Skin Graft Fixation Techniques in Plastic Surgery: A Systematic Review and Meta-Analysis. *Journal of Advanced in Medicinal, Pharmaceutical and Biomedical Research (JAMPBR)*, *2*(4), 309-325.

[91] Rahmani, A and Abadi, P M S. (**2026**). Efficacy of Negative Pressure Wound Therapy Compared to Conventional Wound Closure in Plastic and Reconstructive Surgery: A Systematic Review and Meta-Analysis. *Journal of Advanced in Medicinal, Pharmaceutical and Biomedical Research (JAMPBR)*, *2*(4), 383-396.

[92] Rahmani, A and Abadi, P M S. (**2026**). Preventive Negative Pressure Wound Therapy versus Standard Postoperative Dressings in Plastic and Reconstructive Surgery: A Systematic Review

and Meta-Analysis. *Medicinal, Psychological, and Health Research Journal (MPHRJ), 2*(3), 212-225.
[93] Ranjkesh, M and Maroufi, P. (**2026**). The Value of Serial Radiography in the Long Term Follow Up of Patients After Total Knee Arthroplasty: A Systematic Perspective. *Journal of Advanced in Medicinal, Pharmaceutical and Biomedical Research (JAMPBR), 2*(2), 150-156.
[94] Rebout, F. (**2026**). Artificial Intelligence in Early Detection of Skin Cancer. *Medicinal, Psychological, and Health Research Journal (MPHRJ), 2*(3), 236-250.
[95] Rebout, F. (**2026**). The Impact of Oral Hygiene Practices on the Prevention of Periodontal Diseases. *Journal of Advanced in Medicinal, Pharmaceutical and Biomedical Research (JAMPBR), 2*(4), 332-345.
[96] Rebout, F. (**2026**). The Relationship between Oral Health and Systemic Diseases: A Comprehensive Review of Bidirectional Linkages and Pathophysiological Mechanisms. *Journal of Advanced in Medicinal, Pharmaceutical and Biomedical Research (JAMPBR), 2*(4), 359-370.
[97] Rebout, F. (**2026**). The Role of Saliva in Oral Health and Disease Diagnosis. *Medicinal, Psychological, and Health Research Journal (MPHRJ), 2*(3), 168-176.
[98] Rezaei, M and Abedini, N. (**2026**). Prevalence of Acute Postoperative Pain and Its Associated Risk Factors in Patients Undergoing Laparoscopic Hysterectomy. *Medicinal, Psychological, and Health Research Journal (MPHRJ), 2*(4), 251-258.
[99] Rezaei, M and Dehghani, A. (**2026**). Association Between Age and the Incidence of Acute Postoperative Pain After Laparoscopic Hysterectomy. *Medicinal, Psychological, and Health Research Journal (MPHRJ), 2*(5), 383-390.
[100] [104] Rezaei, M and Dehghani, A. (**2026**). The Effect of Dexmedetomidine on Preventing Postoperative Delirium by Modulating Tumor Necrosis Factor-Alpha (TNF-α) Levels in Patients Undergoing Esophagectomy. *Medicinal, Psychological, and Health Research Journal (MPHRJ), 2*(5), 391-399.
[101] Rezaei, M and Owaysee Osquee, H. (**2026**). Prevalence of Deep Vein Thrombosis in Patients with COVID 19 Admitted to the Intensive Care Unit. *Medicinal, Psychological, and Health Research Journal (MPHRJ), 2*(4), 267-275.
[102] Sadeghzadeh, A. (**2026**). Adverse Events Associated with Facial Filler Injections: : A Systematic Review and Meta-analysis. *Journal of Advanced in Medicinal, Pharmaceutical and Biomedical Research (JAMPBR), 2*(2), 114-133.
[103] Sadeghzadeh, A. (**2026**). Effectiveness of Different Injection Depths for Facial Fillers: A Systematic Review and Meta-analysis. *Journal of Advanced in Medicinal, Pharmaceutical and Biomedical Research (JAMPBR), 2*(2), 157-166.
[104] Sadeghzadeh, A. (**2026**). Evaluating the effectiveness and safety of hyaluronic acid versus poly-L-lactic acid for facial volume restoration: A Systematic Review and Meta-analysis. *Journal of Advanced in Medicinal, Pharmaceutical and Biomedical Research (JAMPBR), 2*(2), 102-113.
[105] Sadeghzadeh, A. (**2026**). Parametric Design and Personalized Facial Reconstruction: Lessons from Contemporary Architecture. *Journal of Advanced in Medicinal, Pharmaceutical and Biomedical Research (JAMPBR), 2*(4), 296-308.
[106] Samimi, A. Zarinabadi, S. (**2011**), Reduction of greenhouse gases emission and effect on environment, Aust. j. basic appl. sci., 5(12), 752-756
[107] Samimi, A., Zarinabadi S., Shahbazi Kootenaei AH., Azimi A., Mirzaei M., (**2019**), Use of data mining in the corrosion classification of pipelines in catalytic reforming units (CRU), *Eura. Chem. Commu.*, 1(6), 571–581
[108] Samimi, A., Zarinabadi, S. (**2012**), Application solid polyurethane as coating in oil and gas pipelines, *Chisa*, 20th International Congress of Chemical and Process Engineering and 15th Conference Pres, 2012
[109] Samimi,A. (**2025**). Investigating the Effect of Temperature and Pressure Changes in CCR Unit Reactors on Catalyst Wear and Black Dust Increase. *Iranian Journal of Chemistry and Chemical Engineering, 44*(12), 3039-3051.
[110] Shiri, H and Ashrafi, N. (**2026**). Enhanced Recovery After Thoracotomy in the Intensive Care Unit: Current Evidence, Clinical Strategies, and Future Perspectives. *Medicinal, Psychological, and Health Research Journal (MPHRJ), 2*(5), 372-382.
[111] Shiri, H and Ashrafi, N. (**2026**). Post Esophageal Surgery Dysphagia and Nutritional Support in the Intensive Care Unit. *Medicinal, Psychological, and Health Research Journal (MPHRJ), 2*(5), 339-350.
[112] Sundaramurthy, S., Salam, J.J. Titinchi Abdal-Kareem M.A. Dawagreh, Mohammad M. Hailat, Al Khasawneh, H., (**2019**), STUDY OF THE PRESENCE OF METAL ELEMENTS IN SEA

WATER IN THE STATE OF KUWAIT, *Ecology, Environment and Conservation*, 25,

[113] Zbuzant, M. (**2026**). Advances in Digital Dentistry Applications of CADCAM Technology. *Journal of Advanced in Medicinal, Pharmaceutical and Biomedical Research (JAMPBR)*, *2*(4), 346-358.

[114] Zbuzant, M. (**2026**). Dental Implants vs. Traditional Bridges: A Comparative Clinical Review. *Medicinal, Psychological, and Health Research Journal (MPHRJ)*, *2*(3), 189-198.

[115] Zbuzant, M. (**2026**). Early Detection of Oral Cancer: Diagnostic Methods and Challenges. *Journal of Advanced in Medicinal, Pharmaceutical and Biomedical Research (JAMPBR)*, *2*(4), 371-382.

[116] Zbuzant, M. (**2026**). Minimally Invasive Techniques in Modern Restorative Dentistry. *Medicinal, Psychological, and Health Research Journal (MPHRJ)*, *2*(3), 177-188.

[117] Hashemloo, A., Milanifard, M. (**2025**). Dermal Fillers: Types, Indications, and Complications Materials de Relleno: Typos, Indications Complications. Journal of Advanced in Medicinal, Pharmaceutical and Biomedical Research, 1(6), 161-170

[118] Hashemloo, A., Milanifard, M. (**2025**), Contouring Plus: A Comprehensive Approach of the Lower Third of the Face with Calcium Hydroxylapatite and Hyaluronic Acid, Medicinal, Psychological, and Health Research Journal, 1(5), 143-150

[119] Sunder Raj, K. S. (**2004**). Multi-Pressure Surface Condenser Performance Evaluation: A Case Study. *Proceedings of the ASME Power Conference.*

[120] Jabari, M., Ekinci, S., Izci, D., Bajaj, M., Blazek, V., & Prokop, L. (**2025**). Efficient pressure regulation in nonlinear shell-and-tube steam condensers via a novel TDn(1+PIDn) controller and DCSA algorithm. *Scientific Reports*, *15*, 2090.

[121] Hrebeniuk, V., et al. (**2023**). The problem of the surface condenser overall heat transfer coefficient determining at high temperatures of cooling water. *Results in Engineering*, *18*, 101193.

[122] Gañán, J., Verda, V., & Tiseira, A. (**2005**). Influence of the cooling circulation water on the efficiency of a thermonuclear power plant. *Applied Thermal Engineering*, *25*.