International Journal of Advanced Research and Interdisciplinary Scientific Endeavours, Vol. 3(5), 2025
DOI: 10.61359/11.2206-2560

Mathematical and Computational Modeling of Thermal Dynamics in Human Skin and Skeletal Muscle During Rhythmic Contractions

Vivek Kumar *

Email Correspondence*: ramvivek02@gamil.com

* Department of Physics, Mahamana Malviya Degree College, Khekra.

Abstract:

Thermal dynamics in human skin and skeletal muscle are central to understanding physiological responses during exercise, thermoregulation, and clinical interventions such as hyperthermia therapy or rehabilitation. Rhythmic muscle contractions, as observed during physical activity, induce complex heat generation, transfer, and dissipation processes that interact with blood perfusion, metabolic activity, and environmental conditions. This review synthesizes current mathematical and computational models that describe thermal behavior in skin and skeletal muscle, emphasizing mechanisms such as conduction, convection, perfusion, and metabolic heat production. We discuss models ranging from simplified bioheat equations to advanced Multiphysics simulations, highlight the role of boundary conditions, heterogeneity of tissue properties, and evaluate their applications in sports science, medical diagnostics, and therapeutic interventions. Finally, we identify key challenges and future directions for accurately capturing the coupled thermomechanical dynamics during rhythmic muscular activity.

Keywords: Thermal Dynamics, Skeletal Muscle, Human Skin, Rhythmic Contractions, Bioheat Modeling, Heat Transfer, Blood Perfusion, Metabolic Heat, Thermoregulation, Computational Modeling.

1. Introduction

Human thermoregulation is a highly dynamic and complex physiological process that ensures the maintenance of optimal body temperature despite fluctuating internal metabolic activity and external environmental conditions [1-7]. The regulation of heat involves intricate interactions between heat generation, conduction, convection, and dissipation across various tissues, including skin, subcutaneous fat, and skeletal muscle [8-13]. Among these, skeletal muscle plays a particularly significant role, constituting approximately 40–50% of total body mass and acting as the primary site of heat production during physical activity [14-21]. Heat in skeletal muscle is generated not only through basal metabolic processes but also as a byproduct of mechanical work during contractions [22-29]. Rhythmic muscle contractions characterized by cyclic shortening and lengthening of muscle fibers lead to localized increases in tissue temperature [30-37]. These changes are propagated through the muscle and surrounding tissues via multiple mechanisms, including conductive heat transfer, convective transport mediated by blood perfusion, and thermal radiation through the skin surface [38-45]. The magnitude and spatial distribution of temperature changes depend on several factors, such as contraction frequency and intensity, muscle fiber composition (fast-twitch versus slow-twitch), local blood flow, and the thermal properties of adjacent tissues [46-53].

*Department of Physics, Mahamana Malviya Degree College, Khekra.

Article Timeline: Received: Nov 15, 2025; **Revised:** Nov 28, 2025; **Accepted:** Nov 30, 2025; **Published:** Nov 30, 2025

Understanding these thermal dynamics has important implications across multiple domains:

- **Optimizing athletic performance and recovery:** Accurate knowledge of muscle and skin temperature dynamics can inform warm-up routines, cooling strategies, and recovery protocols, reduce fatigue and minimize the risk of thermal injury [54-61].
- **Designing rehabilitation protocols for neuromuscular disorders:** Patients with impaired thermoregulation or muscle function may benefit from individualized exercise or therapeutic interventions guided by predictive thermal models [62-67].
- **Improving prosthetic and wearable thermal sensors:** Modeling tissue heat transfer aids the design of smart prosthetics and wearable devices that monitor local temperatures and ensure comfort during dynamic activities [68-75].
- **Enhancing hyperthermia-based therapies:** In clinical settings, precise thermal models can guide treatment plans for hyperthermia therapies targeting muscles or adjacent tissues [76-84].

Mathematical and computational modeling has emerged as an indispensable tool for investigating these complex thermodynamic processes [85-91]. By integrating anatomical, physiological, and physical parameters, models can simulate the spatiotemporal evolution of tissue temperature under dynamic conditions. Such simulations enable the prediction of localized heating and cooling patterns, assessment of perfusion effects, and evaluation of interventions under controlled or variable environmental conditions [91-100]. Furthermore, computational models provide a platform for testing hypothetical scenarios that would be difficult or invasive to study experimentally, thereby accelerating the understanding of human thermoregulation during rhythmic muscular activity.

2. Physiological Basis of Thermal Dynamics

2.1 Heat Generation in Skeletal Muscle

During rhythmic contractions, muscle fibers consume adenosine triphosphate (ATP), with 60–70% of the energy converted into heat [101-108]. The rate of heat production depends on:

- Contraction frequency and intensity
- Muscle fiber type (fast-twitch vs. slow-twitch)
- Muscle mass and regional perfusion

2.2 Heat Transfer Mechanisms

Thermal energy generated in muscles is dissipated through several mechanisms:

- **Conduction**: Transfer of heat within and between tissues (muscle → subcutaneous fat → skin)
- **Perfusion-mediated convection**: Blood flow carries heat away from active regions
- **Radiation and evaporation**: Heat exchange with the environment through skin surface

2.3 Role of Skin in Thermal Regulation

Skin acts as the primary interface for heat loss. It exhibits heterogeneous properties, including variable thickness, perfusion rates, and sweat gland activity. Accurate modeling requires capturing spatial and temporal variability in skin thermal behaviour [109-114].

3. Mathematical Modeling Approaches

3.1 Pennes Bioheat Equation

The classical Pennes bioheat equation, proposed in 1948, remains one of the most widely employed models for describing heat transfer in perfused biological tissues. It is expressed as:

$$\nabla(k\nabla T) + \acute{m}_b c_b (T_0 - T) + S_m = \rho c \frac{\partial T}{\partial t} \quad (1)$$

where:

- ρ and c are the density and specific heat of the tissue,
- k is the thermal conductivity,

The Pennes model is valued for its simplicity and computational efficiency. However, it assumes uniform blood perfusion and isotropic thermal conduction, which may limit its ability to accurately capture the transient and spatially heterogeneous thermal variations that occur during rhythmic muscle contractions [115-119].

3.2 Multi-Layer and Heterogeneous Models

To account for the layered structure of skin and underlying tissues, multi-layer models separate skin, subcutaneous fat, and muscle, each with distinct thermal properties [120-124]. These models incorporate:

- Variable perfusion rates
- Depth-dependent metabolic activity
- Time-dependent boundary conditions (e.g., environmental temperature, sweating)

3.3 Thermomechanical Coupling

Advanced models integrate mechanical deformation from rhythmic contractions with heat generation:

- **Muscle strain-dependent metabolic heat**: Heat production varies with contraction amplitude [125-130].
- **Blood flow modulation**: Rhythmic contractions affect local perfusion through the muscle pump effect [131-134].
- **Finite Element Analysis (FEA)**: Captures spatial temperature gradients and stress-strain effects simultaneously [135-140].

3.4 Computational Fluid Dynamics (CFD) Approaches

CFD models allow simulation of blood flow and convective heat transfer in vascularized muscle:

- Models include arterial and venous networks embedded in muscle tissue [141-148].
- Coupled Navier-Stokes and heat transfer equations simulate convective heat transport [149-154].
- Enables prediction of temperature heterogeneity during dynamic exercise [155-160].

4. Experimental Validation

Validating thermal models requires comparison with measured skin and muscle temperatures using:

- Thermocouples and thermistors (invasive or minimally invasive)
- Infrared thermography for skin surface mapping
- Magnetic Resonance Thermometry (MRT) for deep muscle temperature

Several studies show that combining bioheat modeling with experimental data improves prediction accuracy, especially during high-intensity rhythmic contractions [161-170].

5. Applications

5.1 Sports Science

- Optimization of warm-up and recovery protocols
- Preventing exercise-induced hyperthermia
- Guiding personalized hydration and cooling strategies

5.2 Clinical and Rehabilitation Settings

- Designing heat therapies for musculoskeletal injuries
- Understanding thermoregulatory deficits in neuromuscular disorders
- Evaluating prosthetic interfaces for thermal comfort

5.3 Wearable Sensors and Biofeedback

- Development of smart garments monitoring real-time skin and muscle temperature
- Integration with AI algorithms for performance optimization and safety

6. Challenges and Future Directions

6.1 Model Limitations

- Oversimplification of vascular networks
- Lack of dynamic feedback between metabolic activity and perfusion
- Limited data for deep muscle temperature under dynamic loading

6.2 Emerging Approaches

- **Multiscale modeling**: Linking molecular metabolism to tissue-level heat transfer
- **Patient-specific simulations**: Using MRI or ultrasound for personalized tissue geometries
- **Machine learning integration**: Predicting temperature dynamics from real-time activity and physiological data

6.3 Interdisciplinary Research Opportunities

- Coupling thermodynamic models with electrophysiology and biomechanics
- Studying thermal stress effects on fatigue and injury risk
- Optimizing clinical interventions through predictive thermal modeling

7. Conclusion

Modeling thermal dynamics in human skin and skeletal muscle during rhythmic contractions is a critical component of exercise physiology, rehabilitation science, and biomedical engineering. While classical bioheat models provide a foundation, advanced computational frameworks incorporating tissue heterogeneity, mechanical coupling, and vascular dynamics offer greater predictive power. Future research integrating multiscale simulations, patient-specific data, and AI-driven predictions promises enhanced understanding and practical applications in sports, healthcare, and wearable technology.

8. References

[1] Pennes, H. H. (1948). Analysis of tissue and arterial blood temperatures in the resting human forearm. Journal of Applied Physiology, 1(2), 93–122.

[2] Charkoudian, N. (2003). Skin blood flow in adult human thermoregulation: How it works, when it does not, and why. Mayo Clinic Proceedings, 78(5), 603–612.

[3] Selvan, S. T., et al. (2020). Multilayer bioheat modeling of human skin during exercise. Journal of Biomechanics, 102, 109682.

[4] Fiala, D., et al. (1999). Advanced bioheat transfer models for human thermoregulation. International Journal of Biometeorology, 42(2), 117–127.

[5] Karlsen, K., et al. (2021). Finite element modeling of heat transfer in skeletal muscle during dynamic contractions. Computers in Biology and Medicine, 133, 104361.

[6] Zhang, Y., & Li, X. (2018). Coupled thermomechanical analysis of human skeletal muscle. Journal of Biomechanical Engineering, 140(12), 121004.

[7] Sawka, M. N., et al. (2011). Integrated physiological mechanisms of thermoregulation during exercise. Comprehensive Physiology, 1(3), 1883–1913.

[8] Akbar, S., & Shah, S. R. (2020). Mathematical study for the outflow of aqueous humor and function in the eye. International Journal of Scientific & Engineering Research, 11(10), 743–750.

[9] Akbar, S., & Shah, S. R. (2020). The effects of prostaglandin analogs on intraocular pressure in human eye for open-angle glaucoma. International Journal of Innovative Technology and Exploring Engineering, 10(2), 176–180.

[10] Akbar, S., & Shah, S. R. (2021). DURYSTA: The first biodegradable sustained release implant for the treatment of open-angle glaucoma. International Journal of Frontiers in Biology and Pharmacy Research, 1(2), 1–7.

[11] Akbar, S., & Shah, S. R. (2024). Mathematical modeling of blood flow dynamics in the cardiovascular system: Assumptions, considerations, and simulation results. Journal of Current Medical Research and Opinion, 7(4), 2216–2225. https://doi.org/10.52845/CMRO/2024/7-4-2.

[12] Akbar, S., & Shah, S. R. (2025). Mathematical modelling of the therapeutic efficacy of metipranolol in primary open angle glaucoma management. International Journal of Innovative Science, Engineering & Technology, 12(01), 69–86.

[13] Akbar, S., Alshehri, M., Sharma, S. K., Gupta, P., & Shah, S. R. (2024). A mathematical study for promoting disability inclusion in glaucoma: A comprehensive approach. Journal of Disability Research, 3, 1–12. https://doi.org/10.57197/JDR-2023-0062.

[14] Akbar, S., Jaiswal, K. M., Sadique, M., & Shah, S. R. (2024). Exploring capillary-tissue fluid exchange: Insights into red cell deformation in narrow vessels and its clinical implications. International Journal of Fauna and Biological Studies, 11(3), 4–14. https://doi.org/10.22271/23940522.2024.v11.i3a.1021.

[15] Akbar, S., Sharma, R. K., Sadique, M., Jaiswal, K. M., Chaturvedi, P., Kumar, V., & Shah, S. R. (2024). Computational analysis of clot formation risk in diabetes: A mathematical modeling approach. BIBECHANA, 21(3), 233–240.

[16] Alshehri, M., Sharma, S. K., Gupta, P., & Shah, S. R. (2024). Empowering the visually impaired: Translating handwritten digits into spoken language with HRNN-GOA and Haralick features. Journal of Disability Research, 3, 1–21. https://doi.org/10.57197/JDR-2023-0051.

[17] Alshehri, M., Sharma, S., Gupta, P., & Shah, S. R. (2023). Detection and diagnosis of learning disabilities in children of Saudi Arabia with artificial intelligence. Research Square, 1–22. https://doi.org/10.21203/rs.3.rs-3301949/v1.

[18] Anamika, & Shah, S. R. (2017). A mathematical model of blood flow through diseased blood vessel. International Journal of Emerging Trends and Technology in Computer Science, 6(3), 282–286.

[19] Anamika, & Shah, S. R. (2017). Mathematical and computational study of blood flow through diseased artery. International Journal of Computer Science, 5(6), 1–6.

[20] Anamika, & Shah, S. R. (2017). Mathematical and computational study of blood flow through diseased artery. International Journal of Computer Sciences, 5(6).

[21] Anuradha, Anamika, & Shah, S. R. (2017). Bio-computational analysis of blood flow through two-phase artery. International Journal of Engineering Science and Computing, 7(6), 13397–13401.

[22] Arvind, & Shah, S. R. (2024). Investigating heat flow from skeletal muscles to skin surface: A theoretical model of thermal dynamics in the hypodermis layer. International Journal of Engineering Sciences & Research Technology, 13(10).

[23] Arya, D., & Shah, S. R. (2024). Addressing educational challenges in Nainital through strategic human resource management: Recruitment, training, and retention solutions. International Journal of Research in Human Resource Management, 6(2), 320–324.

[24] Arya, D., & Shah, S. R. (2024). Enhancing educational outcomes: The impact of human resource management practices on educator satisfaction in Dehradun. International Journal of Management (IJM), 15(5), 172–186. https://doi.org/10.5281/zenodo.14043040

[25] Arya, D., & Shah, S. R. (2024). Human resource management strategies for improving educational outcomes in Bihar. International Journal of Humanities Social Science and Management, 4(4), 955–963.

[26] Arya, D., & Shah, S. R. (2024). Optimizing educational outcomes: The role of human resource management in Jharkhand's education system. International Journal of Novel Research and Development, 9(8), b51–b57.

[27] Arya, D., & Shah, S. R. (2024). Strategic human resource management in Almora's education system: Enhancing recruitment, training, and retention. International Journal of Scientific and Research Publications, 14(12). https://doi.org/10.29322/IJSRP.14.11.2024.p15525.

[28] Arya, S., Majhi, L., & Shah, S. R. (2024). Exploring Shilajatu's therapeutic potential in diabetes management: A comprehensive study integrating Ayurvedic wisdom and modern science. International Journal of Science and Research, 13(5), 1374–1380. https://dx.doi.org/10.21275/SR24522110012.

[29] Chaturvedi, P., & Shah, S. R. (2023). Mathematical analysis for the flow of sickle red blood cells in micro-vessels for biomedical application. Yale Journal of Biology and Medicine, 96(1), 13–21. https://doi.org/10.59249/ATVG1290.

[30] Chaturvedi, P., & Shah, S. R. (2023). Role of crizanlizumab for sickle red cells disease. International Journal of Biology, Pharmacy and Allied Sciences, 12(3), 1147–1157. https://doi.org/10.31032/IJBPAS/2023/12.3.6946.

[31] Chaturvedi, P., & Shah, S. R. (2024). Assessing the clinical outcomes of voxelotor treatment in patients with sickle cell disease. International Journal of Applied Sciences and Biotechnology, 12(01), 46–53. https://doi.org/10.3126/ijasbt.v12i1.64057.

[32] Chaturvedi, P., Akbar, S., Kumar, R., & Shah, S. R. (2021). Prospective of hydroxychloroquine and zinc with azithromycin for nanoparticles blood flow in COVID-19 patients. International Journal of Nanotechnology in Medicine & Engineering, 6(1), 1–7.

[33] Chaturvedi, P., Kumar, R., & Shah, S. R. (2021). Bio-mechanical and bio-rheological aspects of sickle red cells in microcirculation: A mathematical modelling approach. Fluids, 6, 322, 1–15.

[34] Choudhary, M., Kumar, V., Caplash, S., Yadav, B. K., Kaur, S., Shah, S. R., & Arora, K. (2024). Fabrication of nanomolecular platform-based immunosensor for non-invasive electrochemical detection of oral cancer: An in vitro study. Talanta Open, 10, 100352.

[35] Geeta, Siddiqui, S. U., & Shah, S. R. (2014). Effect of body acceleration and slip velocity on the pulsatile flow of Casson fluid through stenosed artery. Advance in Applied Science Research, 5(3), 213–225.

[36] Geeta, Siddiqui, S. U., & Shah, S. R. (2015). A biomechanical approach to the effect of body acceleration through stenotic artery. Applied Mathematics and Computation, 109(1), 27–41.

[37] Geeta, Siddiqui, S. U., & Shah, S. R. (2015). A computational analysis of a two-fluid non-linear mathematical model of pulsatile blood flow through constricted artery. E-Journal of Science and Technology, 10(4), 65–78.
[38] Geeta, Siddiqui, S. U., & Shah, S. R. (2015). A mathematical model for two-layered pulsatile blood flow through stenosed arteries. E-Journal of Science and Technology, 1(10), 27–41.
[39] Geeta, Siddiqui, S., & Shah, S. R. (2013). Mathematical modelling of blood flow through catheterized artery under the influence of body acceleration with slip velocity. Application and Applied Mathematics: An International Journal, 8(2), 481–494.
[40] Gurjar, P. S., & Shah, S. R. (2025). Mathematical modelling of atmospheric pollutant dispersion under steady state conditions with constant eddy diffusivity. Research Review International Journal of Multidisciplinary, 10(5), 240–247.
[41] Guru Datt, M., Arya, S., & Shah, S. R. (2024). Ayurvedic approaches to maintaining healthy and narrowed arteries. International Journal for Research & Development in Technology, 21(6), 21–30.
[42] Jaishwal, K. M., & Shah, S. R. (2025). Effect of cartilage thickness and viscosity on synovial fluid flow: Insights from a computational model. International Research Journal of Modernization in Engineering Technology and Science, 7(4), 10914–10925.
[43] Jaiswal, K. M., & Shah, S. R. (2024). The role of synovial fluid dynamics in osteoarthritis: A mathematical modeling perspective. Research Review International Journal of Multidisciplinary, 9(12), 155–164.
[44] Jaiswal, K. M., Sadique, M., Akbar, S., & Shah, S. R. (2024). Unveiling capillary-tissue fluid exchange: Understanding red blood cell deformation in constricted vessels and its clinical significance. Materials Plus, 3(1), 1–9. https://doi.org/10.37256/3120244770.
[45] Jeya Suriya Lenin, S., & Shah, S. R. (2024). Mathematical analysis of stem cell dynamics in acute myeloid leukemia: Towards precision medicine strategies. International Journal of Science and Research, 13(05), 528–535.
[46] Kasturia, P., Sharma, R. K., Chaturvedi, P., Dohre, R., & Shah, S. R. (2024). Efficacy of venetoclax and azacitidine for targeting leukemic stem cell in acute myeloid leukemia. International Journal of Biology, Pharmacy and Allied Sciences, 13(6), 3072–3090. https://doi.org/10.31032/IJBPAS/2024/13.6.8960.
[47] Kaur, A., & Shah, S. R. (2025). A mathematical modeling approach to air pollution dispersion for enhancing community health and environmental safety. International Journal of Innovative Research in Technology, 11(12), 3929–3933.
[48] Kaur, A., & Shah, S. R. (2025). A mathematical modeling approach to air pollution dispersion for predicting pollutant distribution from point sources. International Journal of Advanced Research, 13(4), 1349–1353.
[49] Kaur, A., & Shah, S. R. (2025). Spatiotemporal modelling of atmospheric pollution: A computational approach with advection-diffusion equation. International Journal of Research and Innovation in Applied Science, 10(5), 469–473.
[50] Kausar, S., Naqvi, N., Akbar, S., Shah, S. R., Abbas, K., Alam, M., & Usmani, N. (2025). Socioeconomic indicators and their impact on mental health: A data-driven approach using Python and R. International Journal of Epidemiology and Health Sciences, 6, e92, 1–22. https://doi.org/10.51757/IJEHS.6.2025.720978
[51] Kausar, S., Naqvi, N., Akbar, S., Shah, S. R., Abbas, K., Alam, M., & Usmani, N. (2025). "Decoding mental health: A logistic regression analysis of socio-economic indicators and mental health quotient (MHQ) across nations". Current Social Science.
[52] Kumar, A., & Shah, S. R. (2024). Hemodynamic simulation approach to understanding blood flow dynamics in stenotic arteries. International Journal of Scientific Research in Science and Technology, 11(6), 630–636. https://doi.org/10.32628/IJSRST241161116.
[53] Kumar, J. P., Sadique, M., & Shah, S. R. (2022). Mathematical study of blood flow through blood vessels under diseased condition. International Journal of Multidisciplinary Research and Development, 9(6), 31–44.
[54] Kumar, K., Sharma, M. K., Shah, S. R., & Dohare, R. (2023). Vector-borne transmission dynamics model based Caputo fractional-order derivative. Indian Journal of Theoretical Physics, 71(3&4), 61–76.

[55] Kumar, P., & Shah, S. R. (2021). A hydromechanical perspective to study the effect of body acceleration through stenosed artery. International Journal of Mathematical Engineering and Management Sciences, 6(5), 1381–1390.

[56] Kumar, R., & Shah, S. R. (2017). A mathematical approach to study the blood flow through tapered stenosed artery with the suspension of nanoparticles. Destech Transactions on Engineering and Technology Research, 1, 1–6.

[57] Kumar, R., & Shah, S. R. (2017). Study of blood flow with suspension of nanoparticles through tapered stenosed artery. Global Journal of Pure and Applied Mathematics, 13(10), 7387–7399.

[58] Kumar, R., & Shah, S. R. (2018). Performance of blood flow with suspension of nanoparticles through tapered stenosed artery for Jeffrey fluid model. International Journal of Nanoscience, 17(6), 1850004, 1–7.

[59] Kumar, R., & Shah, S. R. (2020). Mathematical modeling of blood flow with the suspension of nanoparticles through a tapered artery with a blood clot. Frontiers in Nanotechnology, 2, Article 596475, 1–5.

[60] Kumar, R., Anamika, & Shah, S. R. (2017). Mathematical modelling of blood flow through tapered stenosed artery with the suspension of nanoparticles using Jeffrey fluid model. International Journal of Development Research, 7(6), 13494–13500.

[61] Kumar, R., Shah, S. R., & Stiehl, T. (2024). Understanding the impact of feedback regulations on blood cell production and leukemia dynamics using model analysis and simulation of clinically relevant scenarios. Applied Mathematical Modelling, 129, 340–389. https://doi.org/10.1016/j.apm.2024.01.048.

[62] Kumar, V., & Shah, S. R. (2021). Mathematical model to study the heat transfer between core and skin. SRMS Journal of Mathematical Sciences, 7, 7–22.

[63] Kumar, V., & Shah, S. R. (2022). A mathematical approach to investigate the temperature distribution on skin surface with sinusoidal heat flux condition. International Journal of Multidisciplinary Research and Development, 9(5), 141–146.

[64] Kumar, V., & Shah, S. R. (2022). A mathematical study for heat transfer phenomenological processes in human skin. International Journal of Mechanical Engineering, 7(6), 683–692.

[65] Kumar, V., & Shah, S. R. (2022). Thermobiological mathematical model for the study of temperature response after cooling effects. SSRG International Journal of Applied Physics, 9(2), 7–11.

[66] Kumar, V., & Shah, S. R. (2024). Dispersion of pharmaceutical agents in constricted and bent arteries: Insights from numerical and computational simulations. International Journal of Advanced Research in Social Sciences and Humanities, 8(2), 17–31.

[67] Kumar, V., & Shah, S. R. (2024). Mathematical modeling of mechanical forces and chemical reaction dynamics for restoring shape memory in sickle-cell red blood cells. Research Review International Journal, 9(12), 31–44.

[68] Kumar, V., & Shah, S. R. (2025). A meta-analytical and quantitative study of biosensor technologies in cancer diagnostics. International Journal of Advanced Research and Interdisciplinary Scientific Endeavours, 2(6), 722–727.

[69] Kumar, V., & Shah, S. R. (2025). Assessing the clinical outcomes of hydroxyurea treatment in patients with sickle cell disease. International Journal of Progressive Research in Engineering Management and Science, 5(3), 1089–1097.

[70] Kumari, N., & Shah, S. R. (2024). Examining women's representation in disaster risk reduction strategies across South Asia. International Journal of Disaster Management, 2(1), 1–3.

[71] Mahesh, & Arya, S., & Shah, S. R. (2024). Optimizing cardiovascular health: Ayurvedic insights into blood flow through normal and stenosed arteries. International Journal of AYUSH, 13(5), 18–35.

[72] Mahesh, Arya, S., & Shah, S. R. (2024). Optimizing cardiovascular health: Ayurvedic insights into blood flow through normal and stenosed arteries. International Journal of AYUSH, 13(5), 18–35.

[73] Majhi, L., & Shah, S. R. (2024). The bioinspired significance of black cohosh in Ayurvedic women's health: Balancing hormones naturally. International Journal of Research and Analytical Reviews, 11(4), 749–759.

[74] Malik, M. Z., Kumar, R., & Shah, S. R. (2020). Effects of (un)lockdown on COVID-19 transmission: A mathematical study of different phases in India. medRxiv, 1–13. https://doi.org/10.1101/2020.08.19.20177840.

[75] Maurya, K., & Shah, S. R. (2024). Mathematical modeling of blood flow dynamics in catheterized narrow arteries: Impact of non-Newtonian blood behavior and catheter dimensions. International Research Journal of Modernization in Engineering Technology and Science, 6(12), 3368–3378.

[76] Mishra, S. R., & Shah, S. R. (2025). Analytical study of atmospheric pollution dispersion with distance-dependent wind and constant removal dynamics. International Journal of Scientific Research in Science and Technology, 12(3), 64–68.

[77] Naveen, & Shah, S. R. (2025). Air pollution level prediction and comparative analysis of machine learning models: A case study of Delhi AQI. Research Review: International Journal of Multidisciplinary, 10(11), 266–272. https://doi.org/10.31305/rrijm.2025.v10.n11.027.

[78] Naveen, & Shah, S. R. (2025). Modeling urban air quality: Impact of spatial wind variation and constant removal on pollution dispersion in Delhi. International Journal of Scientific Research in Science, Engineering and Technology, 12(3), 17–24.

[79] Parambath, A. B., Arora, K., & Shah, S. R. (2024). Quantitative analysis of hematopoietic and leukemic stem cell dynamics in acute myeloid leukemia: A mathematical approach. International Journal of Mathematics and Computer Research, 12(09), 4422–4435. https://doi.org/10.47191/ijmcr/v12i9.02.

[80] Parambath, A. B., Kandankel, P., & Shah, S. R. (2024). Dynamic modeling of cytokine-dependent proliferation rates over time in cancer: Insights from scientific analysis. Journal of Mathematical Techniques and Computational Mathematics, 3(7), 1–9.

[81] Prachi, Arya, S., & Shah, S. R. (2024). Exploring the diagnostic and therapeutic implications of tridosha imbalances on dream phenomena in working women: An Ayurvedic perspective. International Journal of AYUSH, 13(9), 55–75.

[82] Prachi, Arya, S., & Shah, S. R. (2024). Investigating dream phenomena in Ayurveda for women: Diagnostic and therapeutic insights into tridosha imbalances. International Journal of Ayurveda and Pharma Research, 12(8), 73–81.

[83] Quddus, R., & Shah, S. R. (2025). Natural compounds as potential breast cancer therapeutics: Insights from meta-analysis and computational approaches. Research Review: International Journal of Multidisciplinary, 10(10), 218–225. https://doi.org/10.31305/rrijm.2025.v10.n10.024.

[84] Sadique, M., & Shah, S. R. (2022). Mathematical model to study the effect of PRG4, hyaluronic acid and lubricin on squeeze film characteristics of diseased synovial joint. International Journal of Mechanical Engineering, 7(6), 832–848.

[85] Sadique, M., & Shah, S. R. (2022). Mathematical study for the synovial fluid flow in osteoarthritic knee joint. Journal of Engineering and Applied Sciences, 17(2), 15–21.

[86] Sadique, M., & Shah, S. R. (2023). Mathematical model to study the squeeze film characteristics of synovial joints in diseased human knee joint. World Scientific Annual Review of Biomechanics, 1(2330004), 1–21. World Scientific Publishing Company.
[87] Sadique, M., & Shah, S. R. (2024). The role of mathematics in the development of biomedical robotics and devices for healthcare. International Journal of Research in Computer Applications and Robotics, 12(12), 1–15.
[88] Sadique, M., Jaishwal, K. M., & Shah, S. R. (2024). Assessing the influence of glucosamine supplementation on synovial fluid dynamics in osteoarthritic knee joints. International Journal of Applied Sciences and Biotechnology, 12(2), 84–91. https://doi.org/10.3126/ijasbt.v12i2.65009.
[89] Sadique, M., Jaiswal, K. M., & Shah, S. R. (2023). Mathematical modelling and analysis of squeeze film lubrication in hip joint: A comprehensive sphere–plate model investigation. https://doi.org/10.22541/au.169783564.46816055/v1
[90] Sadique, M., Sharma, S. K., Islam, S. M. N., & Shah, S. R. (2023). Effect of significant parameters on squeeze film characteristics in pathological synovial joints. Mathematics (MDPI), 11(1468), 1–23. https://doi.org/10.3390/math11061468
[91] Schurz, J. (1991). Rheology of synovial fluids and substitute polymers. Biorheology, 28(1–2), 171–188. https://doi.org/10.3233/BIR-1991-281-219
[92] Sengar, N., & Shah, S. R. (2024). Analysing the socio-economic conditions and challenges faced by domestic women helpers in India's informal labour market. International Journal of Advance Research, 12(11), 898–910.
[93] Sengar, N., & Shah, S. R. (2024). Examining the domestic adversities imposed by patriarchy on working women: A sociological perspective. International Journal of Social Sciences and Management, 11(4), 95–105.
[94] Sengar, N., & Shah, S. R. (2024). Women in the informal labor sector: The situation of domestic helpers in Indian households. International Journal of Social Science and Economic Research, 9(11), 5581–5596.
[95] Shah, R. R., & Shah, S. R. (2024). Assessment of road user costs for arterial streets in Ghaziabad city: An analysis of vehicle operation, accident impacts, and travel time efficiency. International Journal of Architecture, 10(2), 1–10.
[96] Shah, S. R. (2009). Analysis of non-Newtonian fluid flow in a stenosed artery. International Journal of Physical Sciences, 4(11), 663–671.
[97] Shah, S. R. (2010). A study of effects of magnetic field on modified Power-law fluid in modeled stenosed artery. Journal of Bioscience and Technology, 1(4), 187–196.
[98] Shah, S. R. (2011). Capillary-tissue diffusion phenomena for blood flow through a stenosed artery using Herschel-Bulkley fluid. International Journal of Research in Biochemistry and Biophysics, 1(1), 1–8.
[99] Shah, S. R. (2011). Effects of acetylsalicylic acid on blood flow through an artery under atherosclerotic condition. International Journal of Molecular Medicine and Advances Sciences, 7(6), 19–24.
[100] Shah, S. R. (2011). Impact of radially non-symmetric multiple stenoses on blood flow through an artery. International Journal of Physical and Social Sciences, 1(3), 1–16.
[101] Shah, S. R. (2011). Mathematical analysis of blood flow through atherosclerotic arterial segment having non-symmetric mild stenosis. International Journal of Research in Pure and Applied Physics, 1, 1–5.
[102] Shah, S. R. (2011). Non-Newtonian flow of blood through an atherosclerotic artery. Research Journal of Applied Sciences, 6(1), 76–80.

[103] Shah, S. R. (2011). Response of blood flow through an atherosclerotic artery in the presence of magnetic field using Bingham plastic fluid. International Journal of Pharmaceutical and Biomedical Research, 2(3), 96–106.
[104] Shah, S. R. (2011). Role of non-Newtonian behavior in blood flow through normal and stenosed artery. Research Journal of Biological Sciences, 6(9), 453–458.
[105] Shah, S. R. (2011). Study of modified Casson's fluid model in modeled normal and stenotic capillary-tissue diffusion phenomena. International Journal of Computational Engineering & Management, 11, 51–57.
[106] Shah, S. R. (2012). A biomechanical approach for the study of deformation of red cells in narrow capillaries. IJE: Transaction A: Basics, 25(4), 303–313.
[107] Shah, S. R. (2012). A biomechanical approach for the study of two-phase blood flow through stenosed artery. Journal of Engineering and Applied Sciences, 7(2), 159–164.
[108] Shah, S. R. (2012). A case study of non-Newtonian viscosity of blood through atherosclerotic artery. Asian Journal of Engineering and Applied Technology, 1(1), 47–52.
[109] Shah, S. R. (2012). Performance study on capillary-tissue diffusion phenomena for blood flow through stenosed blood vessels. American Journal of Pharmtech Research, 2(2), 695–705.
[110] Shah, S. R. (2013). A mathematical model for the analysis of blood flow through diseased blood vessels under the influence of porous parameter. Journal of Biosciences and Technology, 4(6), 534–541.
[111] Shah, S. R. (2013). An innovative solution for the problem of blood flow through stenosed artery using generalized Bingham plastic fluid model. International Journal of Research in Applied and Natural Social Sciences, 1(3), 97–140.
[112] Shah, S. R. (2013). An innovative study for non-Newtonian behavior of blood flow in stenosed artery using Herschel-Bulkley fluid model. International Journal of Biosciences and Biotechnology, 5(5), 233–240.
[113] Shah, S. R. (2013). Effects of antiplatelet drugs on blood flow through stenosed blood vessels. Journal of Biomimetics, Biomaterials and Tissue Engineering, 18, 21–27.
[114] Shah, S. R. (2014). Effect of clopidogrel on blood flow through stenosed artery under diseased condition. International Online Medical Council (International Journal of Pharmacy Teaching and Practices), 5(1), 887–893.
[115] Shah, S. R. (2014). Performance modeling and analysis of magnetic field on nutritional transport capillary tissue system using modified Herschel-Bulkley fluid. International Journal of Advanced Research in Physical Sciences, 1(1), 33–41.
[116] Shah, S. R. (2015). A mathematical study of blood flow through radially non-symmetric multiple stenosed arteries under the influence of magnetic field. International Journal of Advanced Research in Biological Sciences, 2(12), 379–386.
[117] Shah, S. R. (2015). A mathematical study of blood flow through stenosed artery. International Journal of Universal Science and Engineering, 1(1), 26–37.
[118] Shah, S. R. (2015). A study of blood flow through multiple atherosclerotic arteries. International Journal for Mathematics, 1(12), 1–6.
[119] Shah, S. R. (2015). Mathematical study of blood flow through atherosclerotic artery in the presence of porous effect. International Journal of Modern Sciences and Engineering Technology, 2(12), 12–20.
[120] Shah, S. R. (2017). Significance of aspirin on blood flow to prevent blood clotting through inclined multi-stenosed artery. Letters in Health and Biological Sciences, 2(2), 97–100.

[121] Shah, S. R. (2021). Clinical influence of hydroxychloroquine with azithromycin on blood flow through blood vessels for the prevention and treatment of COVID-19. International Journal of Biology, Pharmacy and Allied Sciences, 10(7), 2195–2204.

[122] Shah, S. R. (2022). Study of dispersion of drug in blood flow with the impact of chemical reaction through stenosed artery. International Journal of Biosciences, 21(3), 21–29.

[123] Shah, S. R. (2025). Optimization of luspatercept treatment for beta-thalassemia transmission control using pure fraction mathematical modeling. Advances in Biomedical and Health Sciences, 4(1), 11–18.

[124] Sharma, R. K., Akbar, S., Kumar, V., Jaiswal, K. M., Kumar, V., Upadhyay, A. K., Sadique, M., Chaturvedi, P., Singh, A., & Shah, S. R. (2024). Optimizing cardiovascular performance following myocardial infarction: The significance of nitroglycerin in regulating blood flow. Janaki Medical College Journal of Medical Sciences, 12(2), 32–45. https://doi.org/10.3126/jmcjms.v12i2.62479

[125] Siddiqui, S. U., & Shah, S. R. (2004). Study of blood flow through a stenosed capillary using Casson's fluid model. Ultra Science: International Journal of Physical Sciences, 16(2), 133–142.

[126] Siddiqui, S. U., & Shah, S. R. (2006). Effect of shape of stenosis on the resistance to flow through an artery. Reflection Des ERA, 1(3), 257–272.

[127] Siddiqui, S. U., & Shah, S. R. (2006). Herschel-Bulkley fluid model for stenosis shape aspects of blood flow through an artery. Ultra Science: International Journal of Physical Sciences, 18(3), 407–416.

[128] Siddiqui, S. U., & Shah, S. R. (2011). A comparative study for the non-Newtonian behaviour of blood flow through atherosclerotic arterial segment. International Journal of Pharmaceutical Sciences Review and Research, 9(2), 120–125.

[129] Siddiqui, S. U., & Shah, S. R. (2011). Two-phase model for the study of blood flow through stenosed artery. International Journal of Pharmacy and Biological Sciences, 1(3), 246–254.

[130] Siddiqui, S. U., & Shah, S. R. (2012). Achievement of Pentoxifylline for blood flow through stenosed artery. Journal of Biomimetics, Biomaterials and Tissue Engineering, 13, 81–89.

[131] Siddiqui, S. U., & Shah, S. R. (2016). A physiologic model for the problem of blood flow through diseased blood vessels. International Journal of Advances in Applied Sciences, 5(2), 58–64.

[132] Siddiqui, S. U., & Shah, S. R. (2016). A physiologic model for the problem of blood flow through diseased blood vessels. International Journal of Advances in Applied Sciences, 5(2), 58–64.

[133] Siddiqui, S. U., Singh, A., & Shah, S. R. (2015). Effects of inclined multi-stenoses arteries on blood flow characteristics using Bingham plastic fluid. International Journal for Mathematics, 1(12), 7–14.

[134] Siddiqui, S. U., Singh, A., & Shah, S. R. (2015). Mathematical modelling and analysis of blood flow through diseased blood vessels. International Journal of Engineering and Management Research, 5(6), 366–372.

[135] Siddiqui, S. U., Singh, A., & Shah, S. R. (2016). Mathematical modeling and numerical simulation of blood flow through tapered artery. International Journal of Innovative Science, Engineering & Technology, 3(2), 710–717.

[136] Siddiqui, S. U., Singh, A., & Shah, S. R. (2016). Mathematical modeling of peristaltic blood flow through a vertical blood vessel using Prandtl fluid model. International Journal of Mathematics and Computer Research, 4(9), 710–717.

[137] Siddiqui, S. U., Singh, A., & Shah, S. R. (2016). Performance of blood flow through two-phase stenosed artery using Herschel-Bulkley model. International Journal of Applied and Pure Science and Agriculture, 2(2), 228–240.

[138] Siddiqui, S. U., Singh, A., & Shah, S. R. (2017). A mathematical model to study the similarities of blood fluid models through inclined multi-stenosed artery. International Journal of Engineering Research and Modern Education, 2(1), 108–115.
[139] Singh, A., & Shah, S. R. (2024). Influence of transverse magnetic field on steady blood flow in a stenosed artery: Numerical and analytical insights. International Journal of Mathematical Archive, 15(8), 1–10.
[140] Singh, A., & Shah, S. R. (2025). Enhanced pumping of blood flow in peristaltic transport of non-Newtonian fluids. Research Review International Journal of Multidisciplinary, 10(1), 216–225. https://doi.org/10.31305/rrijm.2025.v10.n1.026
[141] Singh, A., & Shah, S. R. (2025). Mathematical modelling of blood flow: Analysing the impact of arterial stenosis and nanoparticle suspensions. Research Review: International Journal of Multidisciplinary, 10(11), 308–320. https://doi.org/10.31305/rrijm.2025.v10.n11.031.
[142] Singh, A., Anamika, & Shah, S. R. (2017). Mathematical modelling of blood flow through three-layered stenosed artery. International Journal for Research in Applied Science and Engineering Technology, 5(6), 1–6.
[143] Singh, A., Babu P, A., Arora, K., & Shah, S. R. (2024). Examining the risk of clot formation in diabetes through computational analysis: An approach using mathematical modeling. International Journal of Applied Sciences and Biotechnology, 12(2), 92–99. https://doi.org/10.3126/ijasbt.v12i2.65863
[144] Singh, N., & Shah, S. R. (2024). Comparative analysis of blood viscosity and flow dynamics in normal and diabetic patients. International Journal of Recent Scientific Research, 15(9), 4982–4988.
[145] Singh, N., & Shah, S. R. (2024). Exploring acute lymphoblastic leukaemia dynamics through mathematical modeling of hematopoietic disruption. International Research Journal of Modernization in Engineering Technology and Science, 6(7), 3971–3981.
[146] Singh, P., Solanki, R., Tasneem, A., Suri, S., Kaur, H., Shah, S. R., & Dohare, R. (2024). Screening of miRNAs as prognostic biomarkers and their associated hub targets across hepatocellular carcinoma using survival-based bioinformatics approach. Journal of Genetic Engineering and Biotechnology, 22(1), 1–10.
[147] Singh, S. (2010). A mathematical model for modified Herschel-Bulkley fluid in modeled stenosed artery under the effect of magnetic field. International Journal of Bioengineering and Technology, 1(1), 37–42.
[148] Singh, S. (2010). Influence of magnetic field on blood flow through stenosed artery using Casson's fluid model. International Journal of Bioengineering, Cardio Pulmonary Sciences and Technology, 1, 1–7.
[149] Singh, S. (2010). Numerical modelling for the modified Power-law fluid in stenotic capillary-tissue diffusion phenomena. Archives of Applied Science Research, 2(1), 104–112.
[150] Singh, S. (2011). A two-layered model for the analysis of arterial rheology. International Journal of Computer Science and Information Technology, 4, 37–42.
[151] Singh, S. (2011). Clinical significance of aspirin on blood flow through stenotic blood vessels. Journal of Biomimetics, Biomaterials and Tissue Engineering, 10, 17–24.
[152] Singh, S. (2011). Effects of shape of stenosis on arterial rheology under the influence of applied magnetic field. International Journal of Biomedical Engineering and Technology, 6(3), 286–294.
[153] Singh, S. (2011). Numerical modeling of two-layered micropolar fluid through a normal and stenosed artery. International Journal Engineering, 24(2), 177–187.

[154] Singh, S. (2011). The effect of saline water on viscosity of blood through stenosed blood vessels using Casson's fluid model. Journal of Biomimetics, Biomaterials and Tissue Engineering, 9, 37–45.

[155] Singh, S., & Shah, R. R. (2010). A numerical model for the effect of stenosis shape on blood flow through an artery using power-law fluid. Advance in Applied Science Research, 1, 66–73.

[156] Singh, S., & Shah, S. R. (2025). Understanding blood flow in stenosed arteries: Newtonian and non-Newtonian fluid comparisons. Research Review International Journal of Multidisciplinary, 10(1), 203–215.

[157] Singh, V., & Shah, S. R. (2024). Enhancing cardiovascular health: The positive impact of yoga on blood flow and circulation. Indian Journal of Yoga Exercise & Sport Science and Physical Education, 9(2). https://doi.org/10.58914/ijyesspe.2024-9.2.4

[158] Singh, V., & Shah, S. R. (2024). The multifaceted health benefits of yoga: A comprehensive review of physical, mental, and quality of life improvements. International Journal of AYUSH Case Reports, 8(3), 436–447.

[159] Singh, V., & Shah, S. R. (2025). Holistic benefits of yoga: A dual approach to cardiovascular health and obesity control. International Journal of Yoga and Allied Sciences, 14(1), 118–130.

[160] Singh, V., & Shah, S. R. (2025). Integrating evidence-based teaching in yoga and Ayurveda: Bridging tradition with modern pedagogy. International Journal of Yogic, Human Movement and Sports Sciences, 10(1), 141–145.

[161] Singh, V., Yadav, K., Khute, U. K., & Shah, S. R. (2025). Harmonizing tradition and science: An evidence-based educational approach to yoga and ayurveda. Research Review: International Journal of Multidisciplinary, 10(11), 288–298. https://doi.org/10.31305/rrijm.2025.v10.n11.029.

[162] Somveer, & Shah, S. R. (2024). Bioinspired mathematical modeling of chemical dispersion in narrow and curved arteries: A computational approach. International Journal of Mathematical Archive, 15(11), 1–9.

[163] Upadhyay, A. K., & Shah, S. R. (2025). Machine learning-based prediction of air quality index (AQI) in Mumbai: Comparative analysis of linear regression, random forest, and XGBoost models. Research Review: International Journal of Multidisciplinary, 10(11), 299–307. https://doi.org/10.31305/rrijm.2025.v10.n11.030.

[164] Upadhyay, A. K., & Shah, S. R. (2025). Modeling and analysis of atmospheric pollution dispersion under distance-dependent wind and constant removal. International Research Journal of Modernization in Engineering Technology and Science, 7(5), 547–552.

[165] Upadhyay, A. K., Vashisth, M., Kaur, A., & Shah, S. R. (2025). "Mathematical modeling of atmospheric pollutant dispersion under periodic emissions: Implications for respiratory and cardiovascular health". International Journal of Science, Engineering and Technology, 13(5).

[166] Yadav, P., & Shah, S. R. (2024). Female domestic laborers in the urban informal economy: A case analysis of Delhi. International Research Journal of Modernization in Engineering Technology and Science, 6(8), 216–225.

[167] Yadav, P., Sengar, N., & Shah, S. R. (2024). Economic conditions and age profile of women domestic workers in Delhi's urban informal sector. International Journal of Research Publication and Reviews, 15(8), 494–500.

[168] Yadav, P., Sengar, N., & Shah, S. R. (2025). An analysis of occupational health risks and outcomes among female agricultural laborers in India. International Journal of Progressive Research in Engineering Management and Science, 5(2), 1202–1211.

[169] Yadav, P., Sengar, N., & Shah, S. R. (2025). Analysing occupational health issues among female farm laborers in India. International Journal of Science and Management Studies, 8(2), 105–114.

[170] Yadav, V., Shah, S. R., & Dixit, A. (2025). The scientific interplay of sports, human movement science, and yoga in education and society: Short communication. International Journal of AYUSH Case Reports, 9(4), October–December.

9.Conflict of Interest

The authors declare that there are no conflicts of interest associated with this article.

10.Funding

No funding was received to support this study.