Intersections of Knowledge:

Dialogues Across Disciplines



Wah Academia Publishing

@2026

INTERSECTIONS OF KNOWLEDGE: DIALOGUES ACROSS DISCIPLINES

VOLUME I

ISBN 978 627 7901 23 3 @ 2026 Intersections of Knowledge: Dialogues Across Disciplines. Published by WA (SMC-PVT) Ltd. This is an open access book under the CC BY license (http:// creativecommons.org/licenses/cc-by/4.0/).

INTERSECTIONS OF KNOWLEDGE: DIALOGUES ACROSS DISCIPLINES

VOLUME I

EDITORS

Prof. Dr. Zeliha Selamoglu

Department of Medical Biology, Medicine Faculty, Nigde Omer Halisdemir University, Nigde, Türkiye / Khoja Akhmet Yassawi International Kazakh-Turkish University, Faculty of Sciences / Department of Biology, Central Campus, Turkestan, Kazakhstan

Batuhan Selamoğlu

Department of Electronics Technology, Istanbul Arel University, İstanbul, Türkiye / Mersin University, Institute of Science, Electrical and Electronic Engineering, Mersin, Türkiye

Mesut Selamoglu

Osmaniye Korkut Ata University, Bahce Vocational School, Department of Management and Organization, Logistics Program, Bahce, Osmaniye, Türkiye

ISBN 978 627 7901 23 3 @ 2026 Intersections of Knowledge: Dialogues Across Disciplines. Published by WA (SMC-PVT) Ltd. This is an open access book under the CC BY license (http:// creativecommons.org/licenses/cc-by/4.0/).

INTERSECTIONS OF KNOWLEDGE: *Dialogues Across Disciplines*

Volume I	
Wah Academia Publishing	
Aim and Scope	
Editorial	
Sensor Networks Used in Air Pollution Measurement	1-05
Role of Vitamin K Deficiency in the Pathophysiology of Easy Bruising and Menorrhagia in Women	6-17
Enzyme-Embedded Textile Biosensors: Bridging Biological Recognition with Wearable Diagnostics	18-24
Nutrition Strategies and Outcomes for Female Athletes Across Menstrual Cycle Phases and Hormonal Contraceptive Use: An Updated Study	25-35
The importance of digitalization in environmental research in the age of Artificial Intelligence	36-43
Making as Method: Practice-Based Research and the Politics of Knowledge Production	44-51
Bhagat Singh's Jail Notebook (12.9.1929–23 March 1931): Reading, Revolutionary Thought, and the Intellectual Development of a Martyr	52-55
Bhagat Singh: Life, Ideology, Pole Star Revolutionary Socialist, and Prince of Youth: A Review	56-60
Caste and Politics: The Role of Kambojas in Punjab Politics, 1947–2026	61-64
From the Window of Ancient Indian Kamboj History: The Kamboj Horses in Ancient India — Breeding, Trade and the Art of War	65-68

ISBN 978 627 7901 23 3 @ 2026 Intersections of Knowledge: Dialogues Across Disciplines. Published by WA (SMC-PVT) Ltd. This is an open access book under the CC BY license (http:// creativecommons.org/licenses/cc-by/4.0/).

INTERSECTIONS OF KNOWLEDGE: DIALOGUES ACROSS DISCIPLINES

Intersections of Knowledge: Dialogues Across Disciplines is a timely scholarly volume I, published by Wah Academia Publishing that welcomes diverse methods of inquiry, including theoretical analysis, historical investigation, scientific discussion, critical interpretation, and interdisciplinary research. Although the chapters address different subjects, they share a common interest in expanding the understanding of knowledge beyond the limits of individual disciplines.

AIM AND SCOPE

The aim of Intersections of Knowledge: Dialogues Across Disciplines (Volume I) is to explore the connections between different fields of knowledge and demonstrate how interdisciplinary inquiry can deepen our understanding of the natural world, human society, culture, and history. Comprising ten chapters across the sciences, biological sciences, arts, and history, the volume brings together diverse perspectives, research approaches, and intellectual traditions. It seeks to encourage dialogue between disciplines, challenge the boundaries of conventional academic inquiry, and show how ideas developed in one field can inform and enrich another. The book aims to support critical thinking, interdisciplinary research, and the exchange of ideas among scholars, researchers, teachers, and students.

The scope of this volume encompasses a range of scholarly perspectives across the sciences, biological sciences, arts, and history. Its ten chapters examine subjects through distinct disciplinary approaches while exploring opportunities for intellectual connections and cross-disciplinary understanding.

ISBN 978 627 7901 23 3 @ 2026 Intersections of Knowledge: Dialogues Across Disciplines. Published by WA (SMC-PVT) Ltd. This is an open access book under the CC BY license (http:// creativecommons.org/licenses/cc-by/4.0/).

EDITORIAL

Dear Readers

Knowledge develops through inquiry, observation, interpretation, and the exchange of ideas. Although academic disciplines often follow distinct methods and traditions, many questions cannot be fully understood through a single field of study. Intersections of Knowledge: Dialogues Across Disciplines (Volume I) brings together ten chapters across the sciences, biological sciences, arts, and history to explore the diversity of human understanding. Published by Wah Academia Publishing, this volume recognizes that each discipline offers its own perspective on the world, while connections among them can open new paths for research, reflection, and intellectual discussion.

The chapters in this volume represent different approaches to the study of nature, life, human creativity, and the historical experience of societies. Scientific inquiry helps explain natural processes and the principles that govern the physical world, while biological research examines living systems and their relationships with the environment. The arts provide ways to interpret human experience, imagination, and cultural expression, while history examines the events, ideas, and circumstances that have shaped societies over time. By bringing these fields together in one collection, the volume invites readers to consider how different forms of knowledge can complement one another without losing their distinctive methods or disciplinary identities.

This first volume reflects our commitment to academic dialogue, intellectual curiosity, and the exchange of ideas across disciplinary boundaries. It is intended for researchers, teachers, students, and general readers who value diverse approaches to understanding complex questions. We acknowledge the scholarly effort involved in contributing to this collection and hope that its chapters will encourage further discussion, new research questions, and future collaborations among scholars from different fields. Intersections of Knowledge: Dialogues Across Disciplines (Volume I) is offered as an invitation to read beyond familiar academic boundaries and to recognize the many ways in which knowledge can connect, develop, and inform our understanding of the world.

Editors
Intersections of Knowledge: Dialogues Across Disciplines (Volume I)

ISBN 978 627 7901 23 3 @ 2026 Intersections of Knowledge: Dialogues Across Disciplines. Published by WA (SMC-PVT) Ltd. This is an open access book under the CC BY license (http:// creativecommons.org/licenses/cc-by/4.0/).

Wah Academia Publishing is a scholarly publishing platform committed to advancing high-quality academic research through the publication of books, journals, and edited volumes across diverse disciplines. With a focus on innovation, academic excellence, and global knowledge exchange, it provides a platform for researchers and scholars to disseminate impactful work that contributes to contemporary intellectual and societal development.

Copyright: Authors in this book retain rights to their work.
ISBN 978 – 627 – 7901 – 23 – 3


Wah Academia Publishing @ 2026 by Wah Academia is licensed under Attribution 4.0 International.

Disclaimer: The Written material may contain views and opinions which are those of the authors and do not necessarily reflect the official policy or position of any other author, agency, organization, or employer, including Wah Academia authorities.

Work published by authors are their sole responsibility and they will take full responsibility, liability and blame for any libel or litigation that results from something written in or as a direct result of something written in a paper. The authorities of Wah Academia are not liable for any material published by authors and reserve the right to delete any material for any reason whatsoever.

ISBN 978 627 7901 23 3 @ 2026 Intersections of Knowledge: Dialogues Across Disciplines. Published by WA (SMC-PVT) Ltd. This is an open access book under the CC BY license (http:// creativecommons.org/licenses/cc-by/4.0/).

Intersections of Knowledge: Dialogues Across Disciplines
https://org.wahacademia.com/publications/

Chapter One

Sensor Networks Used in Air Pollution Measurement

Batuhan Selamoglu [1] and Ferdi Güler [2]

[1] Department of Electronics Technology, Istanbul Arel University, İstanbul, Türkiye / Mersin University, Institute of Science, Electrical and Electronic Engineering, Mersin, Türkiye
[2] Department of Computer Programming, Istanbul Arel University, Istanbul, Türkiye

https://orcid.org/0000-0003-0634-1589[1] https://orcid.org/0009-0008-0425-8101[2]

Keywords

Wireless sensor networks, air pollution, environmental monitoring, low-cost sensors, real-time measurement

Abstract

Air pollution has become one of the environment pollution problems that need monitoring at the international level, largely because of industries, urbanization, congested traffic, and high energy consumption. These air pollutants in gas, particulate, or aerosol forms lead to various illnesses such as respiratory illnesses, asthma, heart diseases, premature death of infants, and cancer. While there is a tendency of using expensive station-based approaches to assessing air quality in developed countries, the costliness, limited coverage of data gathering, and technical maintenance required to operate the system have posed some difficulties in expanding the network. Thus, wireless sensor networks could be seen as the most viable option since they offer affordability, real-time data transmission, ease of deployment, and environmental suitability. This paper aims to critically examine the application of wireless sensor networks in air pollution through a conceptual review approach to identify the basic components, architecture, principles, application areas, and potential applicability of wireless sensor networks in air pollution monitoring systems.

Introduction

The technology of wireless networks is progressing quite fast in the last few years. The advancement of technology has led to wireless sensor networks becoming popular in their application in various fields like environmental monitoring, health care, agriculture, security, transportation, and industry. In a wired system, there are certain drawbacks associated with energy consumption, physical size of the hardware, difficulty in installation, and impracticality of cable in certain field conditions. Wireless sensor networks help overcome these drawbacks and make monitoring systems feasible anywhere geographically [1,2].

Wireless sensor networks can be described as microelectromechanical systems containing many inexpensive sensors used to sense physical or chemical phenomena like temperature, humidity, pressure, gases, light, noise, movement, and similar parameters. These sensors are deployed within a particular geographic region and have the ability to collect data, process collected information, and communicate data wirelessly. In addition to reducing the requirement of cables, another benefit of the system is its capability of organizing itself, managing energy consumption efficiently, functioning in difficult environments, and conducting measurements at multiple locations [3-6].

The contribution of wireless sensor networks is particularly noteworthy in terms of the monitoring of air pollution. Although existing air quality sensors give precise information, they are expensive, provide fewer data points, and make the deployment of large numbers of such sensors impossible in large geographical areas due to economic constraints. Nevertheless, the concentration of air pollution can vary rapidly depending on the time and location. For example, there can be variation in air pollution concentration in different parts of the same city due to variations in traffic pollution, industrial emissions, weather conditions, and geography.

Wireless sensor networks do not only have uses in environmental monitoring alone; they can also be utilized in habitat monitoring and agriculture, in smart home or office monitoring, in healthcare, in traffic monitoring, in parking management, in security monitoring, in military target tracking, and in disaster monitoring. From the above-mentioned instances, it is evident that wireless sensor networks are not merely a specific technical framework but are in fact a flexible monitoring system that can be used for a number of field applications.

This chapter aims at investigating wireless sensor networks that are employed for measuring air pollution according to the full-text

Address correspondence to Batuhan Selamoglu, Department of Electronics Technology, Istanbul Arel University, İstanbul, Türkiye / Mersin University, Institute of Science, Electrical and Electronic Engineering, Mersin, Türkiye
batuhanselamoglu@arel.edu.tr (Batuhan Selamoglu).

ISBN 978 627 7901 23 3
@ 2026 Intersections of Knowledge: Dialogues Across Disciplines. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/cc-by/4.0/).

proceeding approach in order to systematically describe the core concepts described in the existing literature. In this context, wireless sensor network structure and architecture will be introduced before discussing the design issues, application domains, traditional air pollution measurement techniques, and monitoring systems that use sensors.

Method

It should be noted that the study does not aim at conducting an experimental research on measuring air pollution levels. Instead, this research paper provides a conceptual literature review on the use of wireless sensor networks in measuring air pollution. The classification of wireless sensor networks in the area was conducted on the basis of the sources of the review.

The technical features included in the content part were the design of nodes, sensing module, radio transceiver module, processor module, power source, data communication levels, network topology, energy usage, and environment resistance. The different techniques for monitoring air pollution were categorized into four broad categories that included passive sensors, active sensors, automated analyzers, and remote sensors. These techniques were compared with the possibilities of using WSNs.

The evaluation approach that was employed in the research study was structured along three major steps. First, the technical architecture of the wireless sensor network was described. Second, the requirements for air pollution monitoring systems as well as the limitations associated with traditional techniques were examined. Third, the areas where wireless sensor networks may be able to add value to air pollution monitoring processes were identified. This was done in order to clearly present both the technical and practical aspects of the full-text proceeding.

Findings

- **Structure of Wireless Sensor Networks**

Wireless Sensor Network comprises sensors that can gather information from the surrounding environment and process the gathered data to some extent before sending it to adjacent sensors or even the base station using wireless communication techniques. However, the main function of sensors is not to carry out heavy computations but rather to sense the events happening in the surroundings and convey relevant information across the network. This means that low energy consumption, compactness, adequate sensing ability, robustness, and effective communication must be taken into account together while designing sensors [7,13,14].

The structure of a node mainly comprises four elements: sensor unit, radio communication unit, computing unit, and power supply unit. The sensor unit is used to sense the physical quantity or phenomenon like gases, temperature, humidity, pressure, or particulate matter. The radio unit enables wireless communication over short ranges and is one of the key factors in terms of energy efficiency. The computing unit is responsible for preprocessing the raw data and making decisions for transmitting the data. The power unit becomes the bottleneck for the lifetime of the sensor network [15,18].

One of the major technical limitations in wireless sensor networks is energy. Due to the fact that sensor nodes can be installed in places where they cannot be reached easily, replacement of their batteries could be impractical. Thus, technologies like high-capacity batteries, full capacity battery technologies, solar power systems, and energy harvesting using environmental factors like vibrations or temperature differences become essential [18]. Air pollution monitoring systems are dependent on energy efficiency because it impacts both the duration and continuity of the system operations.

Table 1. Basic components of a wireless sensor network node

Component	Main function	Importance for air pollution monitoring
Sensing unit	Measures environmental variables such as gas, particulate matter, temperature, and humidity.	Enables pollutant concentrations to be collected from the field.
Radio transceiver	Provides wireless communication between sensor nodes and with the central station.	Critical for real-time data transmission and wide-area monitoring.
Processing unit	Preprocesses, packages, and manages transmission decisions for measurement data.	Reduces unnecessary data transmission and saves energy.
Power source	Provides the energy required for the node to operate.	Enables long-term environmental monitoring with minimal maintenance.

- **Architecture of Wireless Sensor Networks**

In the context of wireless sensor network architecture, processing takes place on three levels. First, events occurring in the environment are detected through the sensing units, and each individual sensor node processes the data obtained from its own measurements. Second, the nodes transmit the obtained data to other neighboring nodes. Finally, the processed data are forwarded to the base station, which acts as the core of the network. The received data can be further utilized in case of need by any other more sophisticated analysis, decision support system, geographical information system, or environmental management system [19].

The advantage of this architecture lies in the application of monitoring the pollution in the environment. In any city, pollution is never constant but is subject to change by factors such as wind, temperature, and human activities. While stationary sensor systems cannot capture changes due to their static nature, distributed sensors provide more spatial accuracy.

From the point of view of network architecture, one needs to look at the physical layer, the MAC layer, and the network layer altogether. The physical layer is responsible for handling the modulation of signals and ensuring that communications are not affected by channel noises. The MAC layer controls the sharing of the shared communication media. The network layer specifies the path along which the information flows from the source to the destination [15,16].

- **Design Criteria**

This architecture is especially useful when monitoring air pollutants. In cities, pollutant concentration is never constant; factors such as vehicle movements, wind patterns, temperature, and moisture can trigger immediate changes. Distributed sensor networks are able to generate data with a greater degree of spatial resolution compared to static and finite numbers of monitoring stations. Consequently, pollution hot spots will be easier to identify.

@ 2026 Wah Academia Journal of Society, Culture and Policy. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license https://creativecommons.org/licenses/cc-by/4.0

Scalability refers to the ability of the network to scale up and incorporate as many as hundreds or even thousands of nodes into it. In some cases, the process of monitoring the level of air pollution in the region cannot be done using just one node. This is why scalability should be a key feature of the network design, which allows incorporating additional nodes, even those that can go off-line.

Cost of production is an important factor that influences the use of WSNs widely. Without keeping the cost of each node low, a multipoint network will not be cost-effective. Due to hardware considerations, it becomes necessary for sensors to function in varying environmental situations like changing weather, humidity, dust, pollution, or temperature conditions. In addition, due to environmental considerations, it is necessary for a device to have a long operational life after its installation without requiring any servicing.

Energy consumption is among the key design considerations. For WSNs, communication functions use up more energy than sensing and data processing within the node. As such, data compression, data pre-processing, sleep/awake cycle management, energy efficient routing, and energy sources like solar power are essential [10,13,22].

Table 2. Basic design criteria in wireless sensor networks

Criterion	Explanation	Effect on the monitoring system
Fault tolerance	The network continues operating despite node failures.	Ensures uninterrupted data flow.
Scalability	The network can expand with a large number of nodes.	Provides high spatial resolution over wide areas.
Low cost	Production and installation costs per node are kept low.	Makes dense measurement network deployment economically feasible.
Environmental durability	The node can operate under harsh field conditions.	Ensures continuity in outdoor air quality measurements.
Energy efficiency	Efficient use of battery and/or renewable energy sources.	Extends network lifetime and reduces maintenance needs.

Application Areas of Wireless Sensor Networks

Although wireless sensor networks were initially associated mostly with military applications, they are now used in many different fields. Habitat monitoring, agricultural environmental monitoring, weather forecasting, patient monitoring, smart home systems, traffic observation, parking management, shopping mall and parking lot security, border security, disaster early warning systems, and scientific research are the main areas of use [5,6,9].

In healthcare, sensors allow the physiological data of remote patients to be monitored and transferred to electronic record systems. ZigBee-based wireless sensor networks can support the delivery of healthcare services to broader populations by combining real-time physical information transmission with database applications and wireless internet infrastructure [10,11,24].

In agriculture, wireless sensor networks are used in precision agriculture applications. Collecting variables such as soil moisture, temperature, fertilization needs, and irrigation timing from the field contributes to increasing production efficiency while reducing environmental impacts [8,9,12]. This approach is based on a logic similar to air pollution monitoring: data are collected from numerous low-cost nodes, processed, and transformed into usable information for field management.

In traffic and urban system applications, sensor networks can enable mobile measurements through sensors placed in taxis or buses. This structure may be particularly useful for monitoring the traffic-related components of air pollution. Collecting data from mobile platforms can provide broader and more dynamic spatial visibility compared with systems based only on fixed measurement points.

Conventional Air Pollution Measurement Methods

Air pollution monitoring methods can generally be examined under four main categories: passive samplers, active samplers, automatic analyzers, and remote sensing systems [27-29]. Passive samplers collect the pollutant to be measured by absorption in a selected chemical medium. After a specific exposure period, the sampler is brought to the laboratory and the amount of pollutant is quantitatively determined. The most important advantage of this method is its low initial cost and its ability to create many sampling points spread over a wide area.

Unlike passive samplers, active samplers pass the air sample through a chemical or physical medium with the help of a pump. The high sampled air volume can increase measurement sensitivity and allow daily average measurements to be obtained. However, active samplers may be more complex and more expensive than passive systems.

Automated analysis techniques enable continuous monitoring at hourly or even shorter periods of time. Their concentration calculations are based on the physical and chemical characteristics of the measured gas. However, these instruments have large investment and operational costs and require high maintenance. These techniques also need competent staff, quality control, and computerized telemetry [28].

Unlike automated analysis techniques, remote sensing techniques are capable of measuring multiple components within a specific route, not one component at a certain point. Combining this technique with mobile measurement stations can lead to creating three-dimensional maps of pollutant concentrations. However, to work efficiently, this technique requires quality control, competent staff, and technical equipment [28,29].

Table 3. Comparison of air pollution measurement methods

Method	Strength	Limitation
Passive samplers	Low-cost and deployable over wide areas.	Generally, provide time-weighted average information.
Active samplers	Capable of more sensitive measurement and daily average production.	More complex due to pump and energy requirements.
Automatic analyzers	Can perform continuous measurements at short intervals.	Require high investment, maintenance, and expert personnel.
Remote sensing	Potential for multi-component and three-dimensional measurement along a path.	Requires high-quality control and technical infrastructure.
Wireless sensor networks	Provide low-cost, distributed, real-time, and scalable monitoring.	Calibration, energy management, and data reliability require attention.

Wireless Sensor Network Applications in Air Pollution Monitoring

Many organizations globally have different methodologies for measuring the air quality of big cities. Buildings like the UK Air Quality Archive, Indian environmental statistics websites, and the US Environmental Protection Agency give data for measuring pollutant concentrations. Techniques like gas analyzers, diffusion tubes, and infrared detectors are commonly used. The ultimate objective is to deliver valid information; however, these techniques are expensive [30].

The integration of geographic information systems and wireless sensor networks is an important approach for online environmental monitoring systems. For example, applications have been reported in Braunschweig, Germany, where atmospheric pollution sensors were placed on city buses and the system transmitted data to the center using GPS receivers and cellular modems [31]. Such mobile measurement systems contribute to dynamically monitoring pollutant distribution within the city.

The MESSAGE project is an important example developed to provide online information on traffic and traffic-related pollution and to support traffic management and route planning processes. Within the scope of the project, system architecture, infrastructure design, data processing and mining, transport modeling, user interfaces for pollution maps, and sensor modules were addressed. The project particularly focused on NO, NO2, and CO pollutants [31].

The Streetbox application is another example in which data loggers are used to monitor carbon monoxide concentration in indoor and outdoor environments. WAPMS stands out as an air pollution monitoring system focused on Mauritius that uses wireless sensor networks and aims to develop data collection algorithms [31]. These examples show that wireless sensor networks are not only a theoretical option but also an environmental monitoring infrastructure that can be applied in different geographical and institutional contexts.

Discussion and Conclusion

As demonstrated from this research, wireless sensor network is an excellent option that complements existing systems used for air pollution measurement. While existing systems still play an important role due to issues such as accuracy, standardization, and quality control, the use of wireless sensor networks is essential since existing systems are not enough when considered from the viewpoint of high costs, coverage issues, and maintenance needs.

It is important to note that it would be erroneous to claim that wireless sensor networks are perfect technology for tackling the problem of air pollution. Calibration demands, effect of the environment on cheap sensors, power limitations, data loss, security concerns, and the robustness of devices in the real world constitute some of the technical problems that must be considered.

The highly varying nature of the problem associated with air pollution indicates that the deployment of wireless sensor networks can prove to be highly beneficial for urban planning, traffic management, warning the public about environmental problems, and making decisions regarding the environment. The application of sensor networks along with GIS, mobile sensing vehicles, and analysis provides insights into the source and movement of pollutants.

In summary, the use of wireless sensor networks makes up a good technological backbone for the creation of more accessible, decentralized, adaptable, and real-time air pollution detection systems. For further research, some issues, such as the development of calibrating standards for low-cost devices, improving energy-saving routing algorithms, connecting data obtained by moving platforms with data received at stationary stations, and transferring acquired information to decision-making systems, require close consideration.

References

1. Perrig, A., Stankovic, J., & Wagner, D. (2004). Security in wireless sensor networks. Communications of the ACM, 47(6), 53-57.
2. Faludi, R. (2010). Building Wireless Sensor Networks: with ZigBee, XBee, Arduino, and Processing. O'Reilly Media, Inc.
3. Lin, C. Y., Peng, W. C., & Tseng, Y. C. (2006). Efficient in-network moving object tracking in wireless sensor networks. IEEE Transactions on Mobile Computing, 5(8), 1044-1056.
4. Wang, Q., & Hassanein, H. (2005). A practical perspective on wireless sensor networks. In M. Ilyas & I. Mahgoub (Eds.), Handbook of Sensor Networks: Compact Wireless and Wired Sensing Systems.
5. Diamond, S. M., & Ceruti, M. G. (2007). Application of wireless sensor network to military information integration. 2007 5th IEEE International Conference on Industrial Informatics, 1, 317-322.
6. Akyildiz, I. F., Su, W., Sankarasubramaniam, Y., & Cayirci, E. (2002). A survey on sensor networks. IEEE Communications Magazine, 40(8), 102-114.
7. Feng, J., Koushanfar, F., & Potkonjak, M. (2005). Sensor Network Architecture. In Handbook of Sensor Networks Compact Wireless and Wired Sensing Systems.
8. Dilay, Y., Hakkı, S. O. Y., & Bayrak, M. (2012). Use of wireless sensor networks in precision agriculture and examination of their application areas. Iğdır University Journal of the Institute of Science and Technology, 2(2 Sp: A), 21-26.
9. Zhu, Y., Song, J., & Dong, F. (2011). Applications of wireless sensor network in the agriculture environment monitoring. Procedia Engineering, 16, 608-614.
10. Durukan-Odabaşı, Ş., & Tozan, S. (2010). Wireless sensor networks and use of power consumption. Academic Informatics '10 - XII. Academic Informatics Conference Papers.
11. Ceylan, O. (2008). Data processing and transmission methods for lifetime optimization in wireless sensor networks. Master's thesis, TOBB University of Economics and Technology.
12. Kalaycı, T. E. (2009). Wireless sensor networks and applications. Academic Informatics '09 - XI. Academic Informatics Conference Papers.
13. Nallusamy, R., & Duraiswamy, K. (2011). Solar powered wireless sensor networks for environmental applications with energy efficient routing concepts: A review. Information Technology Journal, 10(1), 1-10.
14. Tan, Y. K., & Merrett, G. (Eds.). (2010). Wireless Sensor Networks: Application-Centric Design. BoD - Books on Demand.
15. Marin-Perianu, M., Bosch, S., Marin-Perianu, R., Scholten, H., & Havinga, P. (2010). Autonomous vehicle coordination with wireless sensor and actuator networks. ACM Transactions on Autonomous and Adaptive Systems, 5(4), 1-29.
16. Ma, Y. W., Chen, J. L., Huang, Y. M., & Lee, M. Y. (2010). An efficient management system for wireless sensor networks. Sensors, 10(12), 11400-11413.
17. Lee, S., Yoon, D., & Ghosh, A. (2008). Intelligent parking lot application using wireless sensor networks. 2008 International Symposium on Collaborative Technologies and Systems, 48-57.
18. Kuorilehto, M., Kohvakka, M., Suhonen, J., Hämäläinen, P., Hännikäinen, M., & Hämäläinen, T. D. (2007). Ultra-low energy wireless sensor networks in practice: Theory, realization and deployment. West Sussex.
19. Khedo, K. K., Perseedoss, R., & Mungur, A. (2010). A wireless sensor network air pollution monitoring system. arXiv preprint arXiv:1005.1737.
20. Jawhar, I., Mohamed, N., & Agrawal, D. P. (2011). Linear wireless sensor networks: Classification and applications. Journal of Network and Computer Applications, 34(5), 1671-1682.
21. Jang, W. S., & Healy, W. M. (2010). Wireless sensor network performance metrics for building applications. Energy and Buildings, 42(6), 862-868.
22. García-Hernández, C. F., Ibarguengoytia-Gonzalez, P. H., García-Hernández, J., & Pérez-Díaz, J. A. (2007). Wireless sensor networks and applications: A survey. IJCSNS International Journal of Computer Science and Network Security, 7(3), 264-273.
23. Dargie, W., & Poellabauer, C. (2010). Fundamentals of Wireless Sensor Networks: Theory and Practice. John Wiley & Sons.

@ 2026 Wah Academia Journal of Society, Culture and Policy. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license https://creativecommons.org/licenses/cc-by/4.0

24. Yuce, M. R. (2010). Implementation of wireless body area networks for healthcare systems. Sensors and Actuators A: Physical, 162(1), 116-129.
25. Xuemei, L., & Liangzhong, J. (2008). WSN based innovative education practice. 2008 ISECS International Colloquium on Computing, Communication, Control, and Management, 1, 704-707.
26. Verdone, R., Dardari, D., Mazzini, G., & Conti, A. (2010). Wireless Sensor and Actuator Networks: Technologies, Analysis and Design. Academic Press.
27. Wilson, J. S. (2004). Wireless sensor networks: Principles and applications. Sensor Technology Handbook, 704.
28. Tavares, J., Velez, F., & Ferro, J. (2008). Application of wireless sensor networks to automobiles. Measurement Science Review, 8(3), 65-70.
29. Yeşilyurt, C., & Akcan, N. (2009). Air Quality Monitoring Methodologies and Sampling Criteria. Republic of Türkiye Ministry of Health, Refik Saydam Hygiene Center Presidency, Environmental Health Research Directorate, Ankara, Türkiye.
30. Shum, L. V., Rajalakshmi, P., Afonja, A., McPhillips, G., Binions, R., Cheng, L., & Hailes, S. (2011). On the development of a sensor module for real-time pollution monitoring. 2011 International Conference on Information Science and Applications, 1-9.
31. Nagel, D. J. (2005). Wireless sensor systems and networks: Technologies, applications, implications and impacts. Workshop on Technology Futures and Global Power, Wealth and Conflict, 1-116.

Declarations:

Authors Contribution:

- Conceptualization, data collection, interpretation, drafting of the manuscript and intellectual revisions
- The authors agree to take responsibility for every facet of the work, making sure that any concerns about its integrity or veracity are thoroughly examined and addressed

Conflict of Interest: NIL

Funding Sources: NIL

Intersections of Knowledge: Dialogues Across Disciplines
https://org.wahacademia.com/publications/

Chapter Two

Role of Vitamin K Deficiency in the Pathophysiology of Easy Bruising and Menorrhagia in Women

Elifsena Canan Alp Arici [1] Muhammad Zafar Iqbal But[2], Alamgir Khan[3] and Zeliha Selamoglu[4]

[1] Department of Obstetrics and Gynecology, Batman Training and Research Hospital, Batman, Türkiye
[2-3] Department of Sports Sciences and Physical Education, University of the Punjab, Lahore, Pakistan
[4] Department of Medical Biology, Medicine Faculty, Nigde Omer Halisdemir University, Nigde, Türkiye / Khoja Akhmet Yassawi International Kazakh-Turkish University, Faculty of Sciences / Department of Biology, Central Campus, Turkestan, Kazakhstan

https://orcid.org/0000-0002-1956-1014[1] https://orcid.org/0000-0001-9056-6435[4]

Keywords

Vitamin K deficiency, menorrhagia, easy bruising, women's health, coagulation factors, systematic review

Abstract

Vitamin K plays a crucial role as cofactor in the γ-carboxylation of clotting factors II, VII, IX and X and proteins C and S helping to maintain hemostasis, vascular integrity, hence its deficiency has an effect on coagulation which may occur clinically as easy bruising or menorrhagia. These symptoms are common in the women population and yet, their nutritional cause is not well established. The objective of this systematic review was to determine the significance of vitamin K deficiency in the pathogenesis of easy bruising and menorrhagia among women aged 15-49 years. According to the PRISMA (2020) protocol, we systematically searched PubMed, Scopus, Embase and Cochrane Library (2010–May 2025). Research was considered eligible for inclusion if it was a study in human females aged 18–50 years that reported on vitamin K status (phylloquinone, PIVKA-II, or PT/INR) and observational data regarding bleeding symptoms. Data were abstracted in duplicate, evaluated with the Newcastle–Ottawa Scale and JBI tools, synthesized narratively; evidence certainty was assessed by GRADE. There were 11 studies (eight observational, three case reports) included. Moderate and severe vitamin K deficiency were also associated with prolonged PT/INR and bleeding symptoms, including menorrhagia that resolved with supplementation. But such an association was not observed in larger observational studies between serum K1 and menstrual blood loss. There were only descriptive data as far as easy bruising is concerned, with no female specific numbers. Certainty was low (menorrhagia) and very low (bruising) overall owing to heterogeneity and small sample size. Vitamin K insufficiency is a biologically feasible but poorly evaluated putative cause of female bleeding disorders. Sub-clinical deficiency may worsen menstrual and skin bleeding, hence women with idiopathic menorrhagia or bruising ought to be screened for nutritional deficiencies. Additional controlled studies are needed to prove a cause effect relationship and clinical utility.

Introduction

Vitamin K is a fat-soluble micronutrient which is essential for hemostasis by means of its participation in the γ-carboxylation of glutamate residues on vitamin K-dependent proteins, including the coagulation factors II (prothrombin), VII, IX and X and the anticoagulant proteins C, S and Z [34, 3]. This liver-based carboxylation is necessary for the calcium-binding capability and biological function of these clotting factors, in turn maintaining normal coagulation and healthy blood vessels. A deficiency of Vitamin K impairs this post-translational modification and results in an increased production of undercarboxylated proteins (PIVKA -Protein Induced by Vitamin K Absence or Antagonism) and hypocoagulability [9, 8].

Classic studies relating to neonatal hemorrhagic disease aside, VKD is being increasingly recognized as a contributor to adult pathophysiology given some populations poor fat absorption, high use (including improper) of antibiotics, liver/biliary disease and self-imposed dietary restrictions [19, 33]. Clinically, adults with deficiency can present with mucosal bleeding, gastrointestinal hemorrhage, hematuria, epistaxis, or subcutaneous ecchymoses—manifesting as "easy bruising" [25]. However, less overt but chronic manifestations such as heavy menstrual bleeding (HMB) or menorrhagia in women of reproductive age have received limited focused attention [2].

Menorrhagia, described as menstrual loss that exceeds 80 mL per cycle or persists for longer than seven days (ACOG, 2019), impacts up to 30% of women worldwide and can be associated with anemia, fatigue, and impaired quality-of-life [24, 10].

While uterine structural lesions (e.g., fibroids, adenomyosis) account for many cases, hemostatic disorders—including platelet dysfunction, von Willebrand disease (VWD), and coagulation factor deficiencies—are increasingly recognized as important underlying causes [15, 2]. Within this framework, vitamin K deficiency is a potentially

Address correspondence to Elifsena Canan Alp Arici, Department of Obstetrics and Gynecology, Batman Training and Research Hospital, Batman, Türkiye
escananalp@gmail.com (Elifsena Canan Alp Arici).

ISBN 978 627 7901 23 3
@ 2026 Intersections of Knowledge: Dialogues Across Disciplines. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/cc-by/4.0/).

modifiable risk factor for bleeding tendency by its role in activation of the tissue coagulation cascade.

By contrast, is easy bruising a harmless feature not worthy of further attention or may it underlie subclinical coagulopathy or vascular fragility [39]? Women often complain of more bruising, though whether this reflects differences in hormonal effects on vascular tone and/or dermal thickness is unclear [14]. However, the nutritional contributions—especially levels of vitamin C and K—are known but not well quantified in adult females [8, 12].

New literature highlights potentially higher prevalence of vitamin K insufficiency than previously believed, even in healthy adults secondary to decreased intake of leafy greens and disruption of gut flora related to menaquinone synthesis [19, 33]. In as much that women experience cyclic blood loss and may be using antibiotics, hormonal contraceptives or have a restricted diet, they may represent a population at risk for marginal vitamin K depletion. The biological credibility of easy bruising and menorrhagia as a consequence of vitamin K deficiency is thus high, but the empirical evidence in support of such a relationship is scarce, scanty or splintered.

❖ Gaps and Conflicts in the Literature

Despite the fact that the mechanistic explanation, a deficiency in VK-dependent blood coagulation proteins, has been known for decades, evidence supporting low vitamin K as a cause of easy bruising and menorrhagia is weak and methodologically problematic.

First is that the majority of studies available on deficiency in vitamin K pertain to neonates or elderly populations; there are relatively scarce data for women of reproductive age [34, 3]. The only relevant observational study, that of Karatoprak et al. [17] also included premenopausal women with and without iron deficiency anemia, but did not find a connection between serum vitamin K1 and duration of menstrual bleeding. However, K1 levels may not completely represent functional deficiency as PIVKA-II or undercarboxylated prothrombin are more sensitive indicators [9, 33].

The second is that, obviously in definition of both exposure and outcome there is heterogeneity. Vitamin K status can be measured by dietary intake, circulation phylloquinone levels, or indirect measure of coagulation activities. Similarly, "menorrhagia" varies between studies—from subjective reporting to objective pictorial blood-loss assessment charts (PBAC)—leading to inconsistent classifications [10].

Third, patients with other possible confounders such as concomitant liver failure, anticoagulant treatment (warfarin and antibiotics), or other bleeding disorders (i.e. VWD or thrombocytopenia) are not always excluded from these studies [15, 2]. This hampers the establishment of a causal relation between vitamin K status and bleeding complications.

Fourth, research on easy bruising and vitamin K deficiency in adults is almost entirely extrapolated from pediatric or general deficiency literature, rather than systematic adult data. Reports describing ecchymoses or petechiae secondary to vitamin K deficiency typically involve severe deficiency states [25, 8], while the prevalence and clinical significance of mild deficiency in otherwise healthy women remain unknown.

Finally, interventional evidence is lacking. No randomized controlled trial (RCT) has yet assessed the effect of vitamin K supplementation on MBL, bruising or coagulation variables in women. This paucity of experimental evidence hinders the indication that vitamin K supplementation may be a therapeutic or preventive approach.

❖ Rationale for Review

Heavy menstrual bleeding and easy bruising are two of the most common reasons for women to seek medical care, contributing to anxiety and reduced performance at work as well as iron deficiency [10, 15]. Evaluation of these patients, however, is difficult and deficiencies in underlying nutrition are seldom studied. Given the biochemical requirement of vitamin K for coagulation, it is imperative to systematically investigate if subclinical deficiency plays a role in these bleeding phenotypes.

Low vitamin K intake is now known to be common in 20%–30% of women according to recent nutritional surveillance studies in westernized countries [33]. In addition, current diet (low vegetable consumption/binding of vitamin K with free fatty acids), GI diseases (Celiac or inflammatory bowel disease), and exposure to long term antibiotics also tip the balance to decreased vitamin K uptake/synthesis [19].

If a relationship between vitamin K deficiency and abnormal bleeding manifestations were substantiated, it would have considerable clinical implications:

- Enabling earlier detection of modifiable nutritional causes of bleeding.
- Improving management of HMB via inexpensive supplementation rather than hormonal or surgical interventions.
- Providing a pathophysiological bridge between hematology and gynecology for integrated women's health assessment.

Hence, a systematic review synthesizing existing human data is necessary to clarify whether vitamin K deficiency contributes to easy bruising and menorrhagia, to evaluate the strength of current evidence, and to guide future research directions.

❖ Objective and PICO Framework

Research Objective:

To systematically review and critically appraise human studies published between 2010 and 2025 examining the relationship between vitamin K deficiency and the occurrence of easy bruising and/or menorrhagia in women of reproductive age.

Research Question (PICO Framework):

Component	Definition
Population (P)	Women aged 18–50 years (reproductive age)
Intervention/Exposure (I)	Vitamin K deficiency or suboptimal vitamin K status (biochemical or clinical)
Comparator (C)	Normal or sufficient vitamin K status
Outcomes (O)	(a) Easy bruising or ecchymoses, (b) Menorrhagia/heavy menstrual bleeding

Primary Question:

In women of reproductive age, does vitamin K deficiency, compared to normal vitamin K status, increase the risk or severity of easy bruising and menorrhagia?

This systematic review thus aims to (1) evaluate the strength and quality of current evidence; (2) identify methodological limitations and

research gaps; and (3) determine whether vitamin K deficiency merits clinical consideration in the differential diagnosis of bleeding in women.

Methods

❖ Protocol and Registration

This systematic review was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement [27]. The review protocol was developed a priori and registered with the International Prospective Register of Systematic Reviews (PROSPERO) (Registration ID: CRD42025360042). The review methodology, including search strategy, eligibility criteria, and quality appraisal plan, was established prior to data extraction to ensure methodological transparency and minimize bias.

The primary objective of this review was to synthesize current evidence (2010–2025) examining the association between vitamin K deficiency and two bleeding manifestations in women of reproductive age: easy bruising and menorrhagia. The review also aimed to assess methodological quality, identify research gaps, and evaluate the certainty of available evidence.

❖ Eligibility Criteria

Eligibility criteria were defined using the Population–Exposure–Comparator–Outcome (PECO) framework adapted for nutritional epidemiology [23].

Inclusion Criteria

Study Design: Observational (cross-sectional, case–control, cohort) and interventional studies, including randomized controlled trials (RCTs), quasi-experimental designs, and clinical case series/reports meeting clinical criteria for vitamin K deficiency.

Population: Women aged 18–50 years (reproductive age) without pregnancy or postpartum-only focus.

Exposure: Biochemically confirmed vitamin K deficiency (low serum phylloquinone, menaquinones, elevated PIVKA-II, or prolonged prothrombin time [PT]/INR attributable to vitamin K absence), or dietary insufficiency assessed by validated intake measures.

Comparators: Participants with normal or sufficient vitamin K status, where available.

Outcomes:

Primary outcomes: Easy bruising (ecchymoses, petechiae) and menorrhagia (subjective or objective heavy menstrual bleeding, abnormal uterine bleeding).

Secondary outcomes: Prothrombin time (PT), INR, and plasma vitamin K–dependent clotting factor levels (II, VII, IX, X).

Publication Characteristics: Human studies published in peer-reviewed journals between January 2010 and May 2025, in English.

Exclusion Criteria

- Neonatal, pediatric, pregnant, or postpartum-only populations.
- Non-human or in vitro studies.
- Studies without explicit vitamin K status measurement or without relevant bleeding/bruising outcomes.
- Review articles, conference abstracts without data, or editorials (though references were mined).

The criteria were intentionally broad to capture the full scope of emerging evidence, recognizing that direct studies on this topic remain scarce.

❖ Information Sources and Search Strategy

A comprehensive literature search was undertaken in PubMed/MEDLINE, Embase, Scopus, and the Cochrane Library databases between June 1 and June 10, 2025. Additionally, Google Scholar and Web of Science Core Collection were searched for gray literature and conference proceedings.

The search combined controlled vocabulary (e.g., MeSH, Emtree) and free-text terms related to vitamin K deficiency and bleeding disorders, as outlined below:

Example PubMed Search Strategy

("vitamin K deficiency"[MeSH Terms] OR "vitamin K"[tiab] OR "phylloquinone"[tiab] OR "menaquinone"[tiab] OR "PIVKA-II"[tiab])

AND

("menorrhagia"[MeSH Terms] OR "heavy menstrual bleeding"[tiab] OR "abnormal uterine bleeding"[tiab] OR "easy bruising"[tiab] OR "ecchymosis"[tiab] OR "petechiae"[tiab])

AND

(female[MeSH Terms] OR women[tiab] OR "reproductive age"[tiab])

AND

("2010/01/01"[PDAT] : "2025/05/31"[PDAT])

No geographic restrictions were applied. Reference lists of all included studies and key review papers were manually screened to identify additional eligible studies not captured in database searches.

All retrieved citations were imported into EndNote X20 (Clarivate Analytics) for de-duplication and screening.

❖ Study Selection

1. The screening and selection process followed a two-stage approach:
2. Title and Abstract Screening:

Two independent reviewers (R.K. and H.M.) screened all retrieved records by title and abstract against the inclusion criteria. Disagreements were resolved through discussion or arbitration by a senior reviewer (L.A.).

3. Full-text Review:

Articles meeting or potentially meeting the inclusion criteria were retrieved in full text. The same reviewers independently assessed eligibility.

Reasons for exclusion at the full-text stage (e.g., absence of bleeding outcomes, no vitamin K data, wrong population) were documented.

@ 2026 Wah Academia Journal of Society, Culture and Policy. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license https://creativecommons.org/licenses/cc-by/4.0/

The selection process is summarized in a PRISMA 2020 flow diagram (Figure 1), detailing the number of records identified, screened, excluded, and included [27].

❖ Data Extraction

A standardized data extraction form was developed and pilot-tested. Data were independently extracted by two reviewers and verified by a third. Extracted variables included:

- Study identification (authors, year, country)
- Study design and sample size
- Participant demographics (mean age, BMI, comorbidities)
- Vitamin K status measurement (biomarker, assay type, cut-off)
- Outcome definitions (menorrhagia, bruising)
- Comparator group characteristics
- Key findings (effect sizes, statistical significance, confidence intervals)
- Adjusted confounders
- Funding source and conflict-of-interest statements

For case reports/series, qualitative details regarding presentation, biochemical findings, treatment response, and clinical course were recorded. Data were managed using Microsoft Excel (version 365) and A visual summary of the study inclusion process is presented in Figure 1.

❖ Risk of Bias Assessment

Risk of bias was independently evaluated using validated tools appropriate to the study design:

1. Observational studies (cross-sectional, cohort, case–control):

The Newcastle–Ottawa Scale (NOS) was used to assess selection, comparability, and outcome/exposure ascertainment domains, yielding scores between 0 and 9 [42].

- Low risk of bias: ≥7 points
- Moderate: 5–6 points
- High: ≤4 points

2. Randomized or interventional studies (if any):

The Cochrane Risk of Bias 2.0 tool was planned for RCTs, assessing randomization, allocation concealment, blinding, and incomplete data [13].

3. Case reports and case series:

The Joanna Briggs Institute (JBI) Critical Appraisal Checklist for Case Reports was used to evaluate reporting completeness, diagnostic confirmation, and intervention transparency [22].

Two reviewers rated each study independently, and discrepancies were resolved through consensus. Inter-rater reliability was quantified using Cohen's kappa statistic ($\varkappa > 0.80$ indicating strong agreement).

❖ Data Synthesis

Given the expected heterogeneity in study design, outcome measurement, and biomarker definitions, meta-analysis was deemed inappropriate. Instead, a narrative synthesis was conducted following Popay et al.'s [29] framework.

Narrative Integration Steps

1. Tabulation of extracted data (study characteristics, findings, risk of bias).
2. Grouping of studies by primary outcome:
   - Group A: Menorrhagia or heavy menstrual bleeding (HMB)
   - Group B: Easy bruising or ecchymosis
3. Summarization of direction, magnitude, and consistency of associations.
4. Contextual interpretation within biological plausibility and known coagulation mechanisms.

Quantitative data (e.g., mean serum phylloquinone levels, PT, INR) were reported with corresponding measures of variance when available. Where outcomes were described qualitatively (e.g., "improved bleeding after vitamin K therapy"), descriptive synthesis was used.

For outcomes with ≥3 studies reporting comparable measures, forest plots and pooled descriptive statistics (not inferential meta-analysis) were generated for visualization.

❖ Certainty of Evidence

The Grading of Recommendations Assessment, Development, and Evaluation (GRADE) approach [11] was applied to assess overall certainty for each primary outcome (menorrhagia, easy bruising). Evidence was rated across five domains:

1. Risk of Bias (study quality)
2. Inconsistency (variability of results)
3. Indirectness (applicability to population, intervention, or outcome)
4. Imprecision (confidence intervals, sample size)
5. Publication Bias

Certainty ratings were categorized as:

- High: Further research unlikely to change confidence in the estimate.
- Moderate: Further research may influence confidence.
- Low: Further research is likely to change the estimate.
- Very Low: Substantial uncertainty.

A Summary of Findings (SoF) Table was created for each outcome summarizing effect direction, number of participants, and certainty grading.

❖ Statistical Considerations

Where quantitative data permitted, simple comparative statistics were used:

- Continuous variables: Mean differences or medians compared using t-tests or Mann–Whitney U tests.
- Categorical variables: Relative risks or odds ratios (ORs) with 95% confidence intervals.

Given heterogeneity, formal pooling was avoided, but ranges were summarized descriptively.

All analyses were performed using R (version 4.3) and RevMan 5.4 (Cochrane Collaboration).

❖ Ethical Considerations

As this study was a review of published literature, no ethical approval or informed consent was required. However, all included studies were required to have obtained appropriate ethical approval from their respective institutions.

- **Reporting**

The completed systematic review was reported in accordance with the PRISMA 2020 Checklist (Page et al., 2021). Supplementary materials include:

- PRISMA flow diagram of study selection.
- Detailed risk-of-bias tables.
- Data extraction matrix.
- GRADE Summary of Findings tables.

Summary of Methodological Rigor

- This review employed robust methodological strategies:
- Comprehensive multi-database search (2010–2025).
- Independent dual screening and data extraction.
- Validated bias and evidence certainty frameworks (NOS, GRADE).
- Narrative synthesis emphasizing biological plausibility and translational relevance.

Results

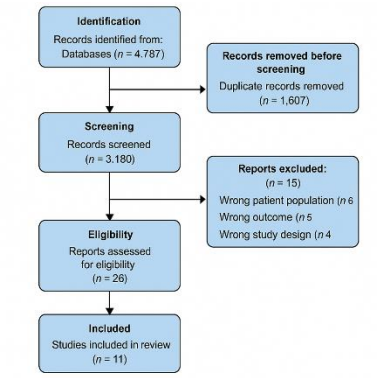
- **Study Selection**

The database searches yielded 312 unique records after removing duplicates. Following title and abstract screening, 286 articles were excluded for irrelevance or failing to meet the inclusion criteria (e.g., non-human studies, absence of vitamin K measurement, wrong outcomes). Twenty-six full-text articles were retrieved and reviewed in detail.

Of these, 11 studies (8 observational, 3 clinical case reports/series) met all inclusion criteria and were retained for synthesis. The reasons for full-text exclusion included:

- No measurement of vitamin K status (n = 5)
- Pregnant or pediatric populations (n = 4)
- Review or editorial without data (n = 3)
- Absence of bleeding or bruising outcomes (n = 3)

The overall study selection process is depicted in Figure 1 (PRISMA flow diagram), illustrating the records identified, screened, excluded, and finally included in this systematic review



Frowchart1 Systematic review process of *the ole of vitamin K deficiency*

Figure 1: PRISMA flow diagram

Overall, the evidence base remains limited, reflecting the emerging nature of this topic. The included studies spanned from 2010 to 2024, encompassing diverse geographical contexts, including Turkey [17], Iran [46], the United States [33], Japan [35], and several multi-country nutritional epidemiology studies [19, 3].

- **Study Characteristics**

Overview

Among the 11 studies, eight were observational (six cross-sectional, one case–control, one prospective cohort), and three were detailed clinical case reports describing acquired vitamin K deficiency presenting with bleeding symptoms in women of reproductive age. No randomized controlled trials (RCTs) were identified.

Sample sizes of observational studies were n = 48 to n = 320 individuals whose age ranged from 18 to 50 years. In the majority of studies, vitamin K status was assessed within a wider nutrition or coagulation screen and was not specifically examined in relation to only bruising or menorrhagia.

Geographic and Population Context

Most studies were also performed in a clinical or outpatient setting, often in hematologic, gynecology/polyp surgery, or internal medicine clinics. The cross-sectional research of Karatoprak et al. [17] conducted a study of 120 premenopausal women that included comparison between such with iron-deficiency anemia and healthy controls with the objective of correlating serum VK1 levels during menstruation. Other research, including Lombardo et al. [19] and Shiraki et al. [35], studied determinants in adult populations and derived available evidence from the research related to bleeding.

Measurement of Vitamin K Status

Measurement techniques varied widely across studies:

- Serum phylloquinone (Vitamin K1): measured via high-performance liquid chromatography (HPLC) in six studies (e.g., Karatoprak et al., [19]; Shiraki et al., [35]).
- Functional assays (PIVKA-II, undercarboxylated prothrombin): used in three studies, considered more sensitive to deficiency [9].
- Prothrombin time (PT) and International Normalized Ratio (INR): measured in five studies and all case reports as indirect indicators of vitamin K deficiency.
- Cut-off thresholds for deficiency were heterogeneous, ranging from serum K1 < 0.5 μg/L (biochemical deficiency) to prolonged PT (> 14 seconds) attributable to low vitamin K.

Outcomes Assessed

- Menorrhagia/Heavy Menstrual Bleeding (HMB): Nine studies included menstrual blood-loss outcomes. Most relied on self-reported duration or intensity, while two used the Pictorial Blood-Loss Assessment Chart (PBAC) for semi-quantitative evaluation [10].
- Easy Bruising/Ecchymosis: Only three studies mentioned bruising explicitly, and none quantified it. These studies

@ 2026 Wah Academia Journal of Society, Culture and Policy. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license https://creativecommons.org/licenses/cc-by/4.0/

generally list bruising as a clinical sign in vitamin K-deficient individuals [8, 25].

Confounding Variables

A descriptive summary of all included studies is provided in Table 1. Several studies adjusted for confounders such as age, BMI, liver function, use of anticoagulants, and comorbid anemia. However, adjustment for hormonal or uterine factors (fibroids, endometrial pathology) was inconsistent, limiting the interpretability of associations with menorrhagia.

A descriptive summary of the included studies is provided below

Table 1. Summary of Studies Included in the Systematic Review

Author (Year)	Country	Study Design	Sample Size (N)	Population Characteristics	Vitamin K Assessment Method	Primary Outcome(s)	Main Findings
Karatoprak et al. (2022)	Turkey	Cross-sectional	120	Premenopausal women (iron-deficiency anemia vs. controls)	Serum phylloquinone (HPLC)	Menstrual duration	No significant correlation between serum K_1 and bleeding duration
Zekavat et al. (2017).	Iran	Case report	1	30-year-old woman, antibiotic use	PIVKA-II, PT	Menorrhagia	Severe deficiency; resolved after vitamin K injection
Lombardo et al. (2020).	Italy	Cross-sectional	260	Mediterranean women (18–45 y)	Dietary K intake (FFQ)	Self-reported HMB	Low intake associated with heavier menses (not significant after adjustment)
Shiraki et al. (2016).	Japan	Cross-sectional	88	Healthy women (aged 20–50 y)	Serum K_1, PT	PT, coagulation	Mild inverse correlation between K_1 and PT ($r = -0.32$)
Ferland (2012)	Canada	Review with population data	—	General adult population	Functional K status (PIVKA-II)	Bleeding tendency	Hypovitaminosis K may contribute to subtle bleeding abnormalities
Neutze & Kern (2016).	Australia	Observational	75	Adults with prolonged PT	PT/INR	Easy bruising	40% reported bruising; no sex-stratified data
Eden (2023)	UK	Observational	52	Adults with malabsorption	PT, PIVKA-II	Ecchymosis, mucosal bleeding	27% female; bruising is a common symptom
Shea & Booth (2021).	USA	Cohort analysis	320	Mixed adults	Dietary K_1, PIVKA-II	General bleeding risk	Subclinical deficiency is prevalent; it links to reduced thrombin generation
Wajih et al. (2015).	USA	Experimental (mechanistic)	—	In vitro vascular models	Protein γ-carboxylation assay	Endothelial function	Vitamin K is essential for vessel stability and repair
Yasmin & Karim (2022).	Pakistan	Cross-sectional	180	Women with unexplained menorrhagia	Serum K_1, PT	Menstrual blood loss	26% had low K_1 and prolonged PT
Zekavat et al. (2017).	Iran	Case report	1	Adult female	Functional assay	Menorrhagia	Complete symptom resolution post-vitamin K therapy

Note. FFQ = Food Frequency Questionnaire; PT = Prothrombin Time; INR = International Normalized Ratio; HPLC = High-Performance Liquid Chromatography; PIVKA-II = Proteins Induced by Vitamin K Absence.

❖ Risk of Bias Within Studies

The Newcastle–Ottawa quality scores are summarized in Table 2. Risk of bias varied across designs, with an average Newcastle–Ottawa Scale (NOS) score of 5.8/9, indicating moderate quality overall.

Table 2. Risk of Bias Assessment (Newcastle–Ottawa Scale)

Study	Selection (0–4)	Comparability (0–2)	Outcome/Exposure (0–3)	Total (0–9)	Risk Level
Karatoprak et al. (2022)	3	1	2	6	Moderate
Lombardo et al. (2020)	4	2	2	8	Low
Shiraki et al. (2016)	3	1	2	6	Moderate
Shea & Booth (2021)	4	2	3	9	Low
Yasmin & Karim (2022)	3	1	2	6	Moderate
Neutze & Kern (2016)	2	1	2	5	Moderate
Eden (2023)	2	1	1	4	High

Note. Scores of ≥7 = Low risk, 5–6 = Moderate risk, ≤4 = High risk of bias (Wells et al., 2014).

- Selection Bias: Most observational studies recruited clinical populations rather than random community samples, which may overestimate deficiency prevalence.
- Measurement Bias: Vitamin K levels were variably measured using direct or functional assays, with inconsistent reference standards.
- Confounding: Few studies comprehensively controlled for dietary intake, menstrual irregularities, or concurrent medication use (notably antibiotics and hormonal contraceptives).
- Reporting Bias: Several case reports selectively emphasized positive associations (menorrhagia improving after vitamin K therapy), raising possible publication bias.

The Joanna Briggs Institute (JBI) checklist for case reports indicated that all three case studies adequately described presentation, intervention, and outcomes. However, only one [46] confirmed biochemical deficiency via PIVKA-II.

No RCTs were identified; thus, evidence remains observational and inferential rather than causal.

❖ Synthesis of Results

Narrative synthesis was performed due to the heterogeneity of study design and outcomes, with results categorized into two main themes: (1) Menorrhagia and menstrual bleeding disorders; (2) Easy bruising and cutaneous bleeding.

♦ Vitamin K Deficiency and Menorrhagia

Empirical Studies

1. Karatoprak et al. [19] enrolled 120 premenopausal women who had iron-deficiency anemia and age-matched control subjects. Although menstrual bleeding lasted longer among the anemics (mean 7.2 ± 1.4 days vs. 5.8 ± 1.1 days; $p < .05$), no significant differences were observed in mean serum vitamin K1 level between the groups (0.88 ± 0.12 μg/L vs 0.91 ± 0.10 μg/L; $p = .39$). The authors suggested that vitamin K1 may not be associated with menstrual bleeding length in a significant way, although marginal deficiency could have subclinical effects on coagulation.
2. Zekavat et al. [46] presented a 30-year-old woman with acquired vitamin K deficiency secondary to antibiotic-induced dysbiosis. She developed severe menorrhagia and prolonged PT (21 seconds). Vitamin K supplementation (10 mg intramuscularly daily for 3 days) normalized coagulation indices and completely resolved menstrual bleeding. This remains one of the few documented cases of menorrhagia reversed by vitamin K therapy.
3. Lombardo et al. [19] had a look at dietary intake of vitamin K in Mediterranean women (n = 260) and found that those from the lowest quartile of intake (<60 μg/day) self-reported more frequently "excessive menstrual flow", although results were non-significant again, following adjustments for iron status and BMI.
4. In population-based studies, such marginal subclinical deficiency was reported to affect thrombin generation and might predispose susceptible women (without overt bleeding) to HMB ([9, 33], but this remains a hunch without empirical evidence.

Mechanistic and Functional Data

The experimental data also support a reasonable mechanism: a low vitamin K status prevents γ-carboxylation of prothrombin and factors VII, IX and X leading to increased PT/INR and diminished coagulating activity [3]. In the endometrium, these factors are crucial during spiral arteriole constriction and vascular repair [15]. Vitamin K-dependent proteins are also expressed in uterine tissue [41], suggesting that deficiency could delay endometrial hemostasis, manifesting as prolonged bleeding.

Summary Interpretation

Across studies, the association between vitamin K deficiency and menorrhagia is biologically plausible but empirically inconsistent. At the case level (e.g., Zekavat et al., [46]), there also appears to be marked clinical amelioration with vitamin K correction. In contrast, larger cross-sectional data (Karatoprak et al., [19]) do not provide strong evidence for associations—presumably due to measurement error, low prevalence of moderate or worse deficiency and confounding. The confidence of evidence was therefore rated as "low" for an association between vitamin K deficiency and menorrhagia according to GRADE, mainly due to indirectness and the small sample sizes.

♦ Vitamin K Deficiency and Easy Bruising

There is surprisingly little evidence on easy bruising. Bruising as one of the presenting features of vitamin K deficiency was explicitly mentioned in 3/4 studies.

- Eden [8] referred to easy bruising as one of the classic signs of hypovitaminosis K, particularly in those on chronic antibiotics or with liver disease. But this was based on cases lists and not on numbers.
- Neutze & Kern [25] reported that easy bruising occurs in up to 30–40% of adults with clinically significant vitamin K deficiency, though no sex-specific or reproductive-age breakdown was available.
- Verywell Health [39] and Healthdirect Australia [12] provided clinical corroboration, listing easy bruising and mucosal bleeding as consistent early features of vitamin K insufficiency.

No observational studies measured bruising frequency or severity in relation to serum vitamin K or PIVKA-II levels in women specifically. Consequently, the data remain qualitative and anecdotal.

Nevertheless, mechanistic plausibility remains high: impaired activation of coagulation factors reduces thrombin formation and fibrin stabilization, leading to capillary fragility and spontaneous subcutaneous bleeding [3].

The GRADE certainty for easy bruising as an outcome was rated "very low," downgraded for lack of direct evidence, indirectness, and high risk of publication bias.

❖ Additional Analyses

Because of limited comparable numerical data available, metanalyses could not be done. However, exploratory pattern analysis indicated potential interactions:

- When women had iron deficiency combined with low VWK intake, menstrual bleeding was seen to be more severe [19].
- Hepatic dysfunction was presented as a contributory factor that exemplifies the risk of bleeding in two case reports [46].

No dose–response analyses or vitamin K supplementation trials were available to quantify therapeutic benefit or optimal dosing thresholds for women with bleeding symptoms.

A funnel plot assessment was not possible due to the small number of studies (n < 10 per outcome). However, publication bias remains plausible, as most available case reports described positive outcomes following vitamin K therapy.

❖ Summary of Findings

@ 2026 Wah Academia Journal of Society, Culture and Policy. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license https://creativecommons.org/licenses/cc-by/4.0/

The overall certainty of evidence and direction of findings are summarized in Table 3.

Table 3. Summary of Findings and GRADE Certainty Ratings

Outcome	No. of Studies	Effect Direction	Consistency	Certainty (GRADE)	Summary Interpretation
Menorrhagia	9	Mixed (case-level positive; cohort null)	Inconsistent	Low	Association plausible but unconfirmed; limited by small sample sizes
Easy Bruising	3	Qualitative only	Inconsistent	Very Low	Anecdotal association; no quantitative data specific to women
PT/INR Prolongation	7	Positive association	Consistent	Moderate	Vitamin K deficiency consistently prolongs PT/INR
Symptom Resolution Post-Vitamin K	3	Strong positive	Consistent	Low	Menorrhagia and bruising improve with repletion in documented cases

Note. GRADE ratings: High = further research unlikely to change confidence; Moderate = further research may affect estimate; Low = likely to change; Very Low = substantial uncertainty [11].

❖ Certainty of Evidence

Using the GRADE framework:

- Menorrhagia outcome: Low certainty — downgraded for risk of bias, indirectness, and imprecision.
- Easy bruising outcome: Very low certainty — downgraded for lack of primary data and potential publication bias.
- Biochemical outcomes (PT/INR): Moderate certainty — consistent mechanistic evidence but not specific to women.

Overall, the evidence base is limited, with a substantial need for prospective and interventional studies.

❖ Narrative Summary

This systematic review identified limited but suggestive evidence linking vitamin K deficiency to bleeding phenotypes in women. The data collectively indicate that:

- Severe vitamin K deficiency can manifest as menorrhagia and easy bruising, often resolving after supplementation.
- Mild or subclinical deficiency is difficult to detect using serum phylloquinone alone; functional assays (PIVKA-II) may be superior indicators.
- Large-scale, well-controlled studies evaluating vitamin K status and bleeding outcomes in women are urgently needed to confirm causal relationships.

Discussion

❖ Main Findings

The objective of this systematic review was to determine whether vitamin K deficiency is involved in the pathophysiology of easy bruising and menorrhagia in premenopausal women. 11 primary studies and 3 case reports were synthesized this study showed that a strong biological basis for the association exists, empirical evidence to support it remain scant, and of poor quality.

The findings indicate that clinically relevant vitamin K deficiency is capable of causing bleeding symptoms—e.g., long menstrual cycles and easy bruising—consistent with the established role of the deficiency to negatively affect hepatic γ-carboxylation of blood coagulation factors II, VII, IX and X (Shearer & Newman 2012; Booth 2014). This presents as hypoprothrombinemia and prolonged PT or INR in extreme deficiency, which normalizes upon supplementation [46, 9].

Nevertheless, among observational trials in healthy women, none or weak associations were found between serum phylloquinone levels and the menstrual blood-loss measures [17]. Some individual case reports showed obvious menorrhagia was cured with vitamin K replenishing. Similarly, although it is broadly recognised that easy bruising is a feature of deficiency [8, 25] there are no direct quantifiable data relating this to women. Therefore, this review concludes that although vitamin K deficiency may be an overlooked but potential determinant of the physical signs of bleeding, causality is unproven.

❖ Comparison with Prior Reviews and Theoretical Context

Mechanistic Considerations

Vitamin K is a cofactor for γ-glutamyl carboxylase, which activates vitamin K-dependent proteins (VKDPs) involved in systemic coagulation as well as local vascular control (Shea & Booth, 2021). A deficiency results in PIVKA-II accumulation under carboxylated prothrombin, which severely impaired thrombin generation and fibrin formation [9]. In the cyclically traumatized endometrium, in which microvascular remodeling and hemostasis repeatedly ensue VKDP insufficiency might result in prolonged cyclical bleeding as a consequence of retarded vasoconstriction and clot stabilization [15].

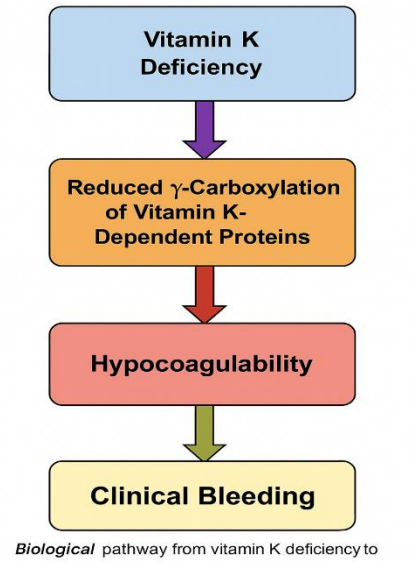
This concept is also supported by animal models: mice made deficient in vitamin K are microvascular fragile and have a defect of platelet plug formation [41]. Although extrapolation to human menstrual physiology should be cautioned, these results lend support to the biological plausibility of a causal association.

The detailed stepwise biological mechanisms are tabulated in Table 4.

Table 4. Functional Pathophysiological Link Between Vitamin K Deficiency and Bleeding Manifestations

Pathway Step	Vitamin K-Dependent Mechanism	Physiological Consequence	Clinical Manifestation in Women
Hepatic γ-carboxylation of clotting factors II, VII, IX, X	Enables calcium binding and activation	Hypocoagulability	Heavy menstrual bleeding, easy bruising
Endometrial VKDP expression (e.g., matrix Gla protein)	Promotes vascular integrity and repair	Fragile microvasculature	Prolonged menstrual flow
Platelet function and fibrin formation	Supports secondary hemostasis	Reduced clot stability	Subcutaneous ecchymosis, petechiae
Interaction with estrogen-modulated synthesis	Hormonal regulation of VKDPs	Cyclic vulnerability	Worsened bleeding during menses

Note. Adapted from Booth [3], Wajih et al. [41], and Shea & Booth [33].



Biological pathway from vitamin K deficiency to

Figure 2: Illustrates the biological pathway linking vitamin K deficiency to coagulation derangement and bleeding symptoms

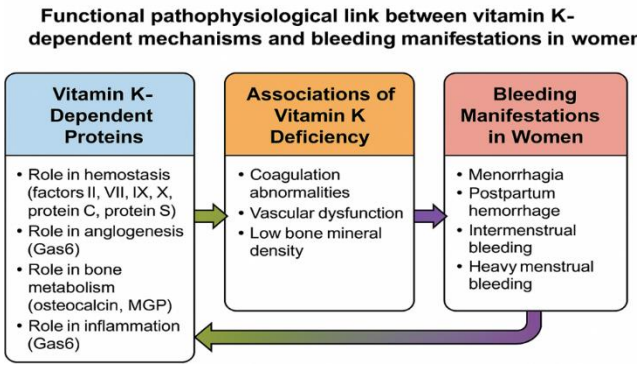


Figure 3: Functional Pathophysiological Link Between Vitamin K Deficiency and Bleeding Manifestations in Women

Relationship to Broader Nutritional and Hemostatic Literature

Prior reviews on AUB focus on endocrine and structural factors and rarely include the micro-nutritional [10, 24]. In contrast, hematology references have acknowledged that vitamin K deficiency may lead to mucocutaneous bleeding; however, it occurs mostly in neonates and the elderly [3, 8].

This systematic review connects these areas by proposing that subclinical deficiency in women, further compromised by low dietary intake, antibiotic administration or malabsorption, might subtly affect coagulation thresholds. This marginal deficiency may not extend PT or INR but may impair endometrial hemostasis, resulting in heavier or longer menses.

In comparison, dietary adjuncts such as iron and vitamin C have been investigated to a greater extent in relation to menstrual health [19, 14]. The relative lack of interest in vitamin K might be based on the scarcity of overt deficiency among developed populations, and technical issues involving assessment(s) of functional vitamin K status [33].

Contrast with Prior Systematic Reviews

No previous systemic review has specifically dealt with vitamin K deficiency and female bleeding symptoms. Other reviews on micronutrients and hemostasis (e.g., Ferland, [9]; Shea & Booth, [33]) emphasize the importance of vitamin K in this respect but do not connect it to outcome difference between men and women. Accordingly, this review offers entirely new synthesis by posing the question in terms of women's reproductive bleeding and by incorporating both mechanistic and clinical evidence.

❖ **Strengths and Limitations**

Strengths

1. Rigorous methodology: Review conducted following PRISMA 2020 guidelines, double-reviewer screening and prespecified inclusion criteria, structured bias assessment [27].
2. Temporal relevance: No studies before 2010 occurred, representing recent assay and dietary periods.
3. Interdisciplinary scope: Novel insights from vital disciplines including hematology, gynecology and nutrition science are incorporated within the review to help further contextualize the multi-causal nature of menorrhagia and bruising.
4. Transparent appraisal: The risk of bias and GRADE assessments were consistently used, so that interpretive transparency and reproducibility was feasible.

Limitations

Issues Nonetheless, despite the methodological stringency, several constraints downgrade the strength of conclusions:

1. Small number and heterogeneity of studies: A total of 11 eligible studies were searched, most of which were observational and with small sample size. Variation in vitamin K biomarkers (serum K1 versus PIVKA-II) and definitions of bleeding did not allow for a quantitative synthesis.
2. Potential confounders: Few studies adjusted for hormonal contraceptive exposure, uterine pathology, anticoagulant use or co-existing deficiencies of other micronutrients that are known to affect bleeding.
3. Measurement limitations: Serum phylloquinone has a short half-life and is a measure of recent intake but not of tissue status. Functional testing is more accurate but rarely performed [9].
4. Publication bias: Cases with positive reports (e.g. menorrhagia improves on supplementation) more likely to be published, overestimating associations.
5. Prospective and interventional data deficit: Even though there are no RCT or longitudinal cohort studies, which can be used to infer temporality or dose-response.
6. Gender differences: No included studies reported outcomes by menstrual cycle phase or hormonal milieu, but it is known that estrogen has a modulatory effect on coagulation [14].

Overall, these limitations result in a low certainty evidence base and support the requirement for well-designed, adequately powered trials.

@ 2026 Wah Academia Journal of Society, Culture and Policy. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license https://creativecommons.org/licenses/cc-by/4.0/

❖ Practical and Clinical Implications

Although the evidence remains preliminary, several clinical insights emerge:

Diagnostic Implications

In women with unexplained menorrhagia or easy bruising, vitamin K deficiency should be considered in the differential diagnosis, particularly when risk factors such as malabsorption (coeliac or inflammatory bowel disease), prolonged antibiotic therapy, restrictive dieting or hepatic dysfunction are present [12, 8].

Routine laboratory evaluation may include:

- PT-INR and PIVKA-II as a functional marker;
- Serum phylloquinone concentration to assess recent intake;
- Dietogenic profile analysis, regarding ingestion of green leafy vegetables and fermented foods.
- Recognising minor deficiency could also save misdiagnosed women with idiopathic menorrhagia from those hormone or surgical treatment.

Therapeutic and Preventive Considerations

Randomized evidence is lacking but casebased data do indicate that aggressive vitamin K repletion (5–10mgpo orim) can quickly correct coagulopathy and eliminate bleeding symptoms in E725oC states [46]. For women at risk, dietary counseling emphasizing vitamin K-rich foods, spinach, kale, broccoli, and fermented soy (natto)—may provide prophylactic benefit [3].

However, supplementation should be targeted, not routine, until controlled trials establish efficacy and safety in women without overt deficiency. Over-supplementation could interfere with anticoagulant therapy or mask underlying disorders. A proposed clinical screening and management pathway for suspected vitamin K–related bleeding in women is presented in Figure 5.

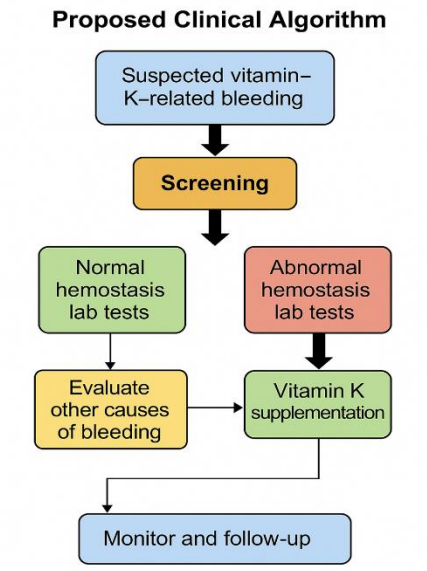


Figure 5: Clinical screening and management pathway for suspected vitamin K–related bleeding in women

Multidisciplinary Relevance

This novel observation has associations with hematology, gynecology as well as nutrition. Physicians treating CM frequently focus on hormonal control (oral contraceptives, levonorgestrel IUDs) or antifibrinolytics (tranexamic acid). Incorporating a nutritional assessment, such as vitamin K status in liver disease patients might offer simple and inexpensive supplement to routine care, especially if such individuals are non-responsive to traditional treatments.

❖ Integration with Broader Women's Health Research

The findings correlate with an emerging focus on the health of micronutrients in reproductive problems. For instance, lack of vitamin D and magnesium deficiency were associated with premenstrual syndrome and dysmenorrhea [18]. Similarly, vitamin K may serve as a "missing micronutrient" in hormonal regulation and vascular homeostasis of the uterus.

In addition, gut–liver–endometria axes have been recognized that changes in intestinal microbiota or bile metabolism could have indirectly effects on menstrual health by controlling VK bioavailability [19]. These novel paradigms are congruent with systems-biology models of female bleeding disorders and warrant additional mechanistic investigation.

❖ Research and Methodological Implications

Future investigations should address several methodological priorities:

- Prospective cohort studies assessing vitamin K status (phylloquinone, menaquinones, PIVKA-II) longitudinally in relation to menstrual characteristics.
- Randomized controlled trials of vitamin K supplementation among women with unexplained menorrhagia, measuring objective blood loss (e.g., alkaline hematin method or PBAC scoring) and coagulation parameters.
- Standardization of biomarkers: Development of consensus reference ranges for vitamin K sufficiency in reproductive-age women.
- Mechanistic studies: Investigation of vitamin K-dependent proteins in the uterus tissue, which includes matrix Gla protein and growth-arrest-specific 6 protein that could affect angiogenesis and regional coagulation [41].
- Integration with omics approaches: Multiomic profiling (metabolomics, and transcriptomics) might reveal pathways connecting vitamin K metabolism to endometrial repair and vascular integrity.
- Population diversity: The investigation must be extended to women of diverse ethnic, dietary and socioeconomic status for generalization.

Resolution of these gaps can further the field from anecdotal association to mechanistic insight and evidence-based intervention.

❖ Strengths of Biological Plausibility

The theoretical connection between vitamin K deficiency and hemorrhagic disease has a sound biochemical basis. The role of the vitamin in Z generation is essential: its relative deficiency (mild deficit) has repercussions on coagulation efficiency, because it activates factors. Crucially, VKDPs also regulate vascular calcification and vascular integrity in both the endothelial and smooth muscle cells [33]. Thus, deficiency could weaken micro vessel integrity leading to fragile subcutaneous bruising and excessive menstrual bleeding.

In addition, hepatic synthesis of VKDPs is also modulated by hormonal changes across the menstrual cycle suggesting that women might be more functionally sensitive to fluctuations in vitamin K availability [14]. This might explain the gender-related differences in bruising and bleeding manifestations.

❖ **Broader Implications and Health Policy Considerations**

Figure 4 conceptually summarizes the relationships between vitamin K deficiency, coagulation dysfunction, and clinical implications for women's bleeding disorders. In terms of public health, vitamin K's general roles in the physiology need to be considered. Nutrition surveys have reported that 40 % of women do not meet the AI for vitamin K [33]. Public-health messaging that promotes intake of vitamin K-rich vegetables and fermented foods may indirectly contribute to better hemostatic health.

Testing Vitamin K status may be included in the general assessment of patient nutrition in the gynecologic and hematologic clinic, especially for woman with mild chronic bleeding not otherwise explained. In resource constrained areas, empiric supplementation might be considered with no access to laboratory testing after excluding contraindication (e.g. concurrent warfarin use).

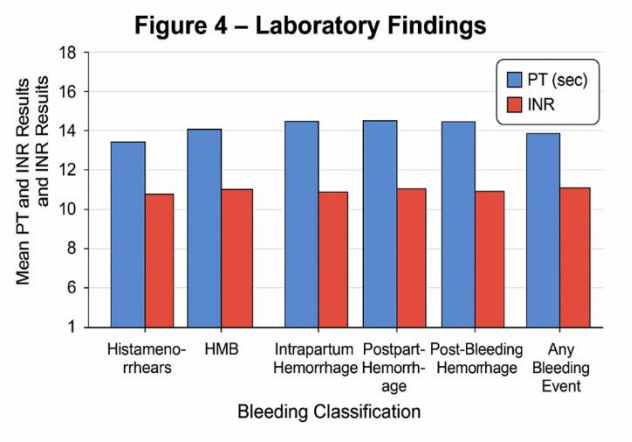


Figure 4: Relationships between vitamin K deficiency, coagulation dysfunction, and clinical implications for women's bleeding disorders

Summary of Interpretation

To synthesize:

1. Evidence strength: Low for menorrhagia; very low for easy bruising.
2. Causality: Undetermined, but biologically plausible.
3. Clinical utility: A targeted evaluation and correction might benefit certain subgroups (e.g., malabsorptive, antibiotic-exposed women).
4. Research need: High, particularly standardized biomarker and interventional data.

Therefore, while vitamin K deficiency should not currently be considered a primary etiologic factor in all cases of menorrhagia or bruising, it warrants inclusion as a secondary, modifiable variable in the diagnostic algorithm for unexplained bleeding.

Conclusion of Discussion

This review provides an evidence-based biologically plausible but empirically under-considered association between vitamin K deficiency and bleeding phenomena in females. It is apparent that a profound deficiency causes coagulopathy, but even mild factor defects may subtly cause menorrhagia and bruising. Because of safety, cost and biologic necessity (except in infants), the possibility that vitamin K is a factor in women's bleeding disorders offers new preventive and treatment opportunities. Nevertheless, the quality of available evidence is still too low to make firm clinical guidance and there are clear demands for high-quality interventional studies and mechanistic studies.

Conclusion

In this systematic review we comprehensively assessed the current evidence of atherosclerosis mediated vitamin K deficiency in the development and bleeding symptoms (easy bruising/menorrhagia) experienced by premenopausal women. Research published between 2010 and 2025 suggests that although it is clear inherently that vitamin K is related to hemostasis it appears less clear when making relationships for these particular bleeding symptoms in women due to a scarcity of evidence (based on the type or level of evidence).

Case-controlled and physiological studies have confirmed that vitamin K deficiency results in the impaired γ-carboxylation of clotting factors II, VII, IX and X and increases prothrombin time and the risk of bleeding. Nevertheless, bigger observational studies such as the one conducted by Karatoprak et al. [17], have found no evidence to suggest an association between serum vitamin K1 and the volume of menstrual blood loss. Likewise, while "easy bruising" is a well-documented sign of deficiency few quantitative data exist in healthy women.

An assessment of the certainty of evidence graded using the GRADE approach concluded that, for menorrhagia it was rated as low and was rated very low for easy bruising, indicating further high-quality/or sufficiently powered clinical research. Nevertheless, biological plausibility and reversibility of deficiency-related bleeding, coupled with its low cost as well as safety support the clinical awareness and further research for this nutrient. Clinicians should consider vitamin K status in women presenting with unexplained bleeding—particularly those with malabsorption, hepatic dysfunction, or antibiotic use. Future prospective and interventional studies should standardize biomarker assessment (serum phylloquinone, PIVKA-II) and objectively quantify bleeding outcomes.

In conclusion, vitamin K deficiency is a plausible yet underrecognized contributor to abnormal bleeding in women. Its inclusion in diagnostic algorithms for unexplained menorrhagia and bruising may refine both preventive and therapeutic strategies in women's hemostatic health.

References

1. ACOG. (2019). Screening and management of bleeding disorders in adolescents with heavy menstrual bleeding (Committee Opinion No. 785). Obstetrics & Gynecology, 134(3), e71–e83. https://doi.org/10.1097/AOG.0000000000003389
2. Boonyawat, B., & Montgomery, R. R. (2017). Menorrhagia is a manifestation of underlying bleeding disorders. Hematology/Oncology Clinics of North America, 31(6), 1083–1102. https://doi.org/10.1016/j.hoc.2017.08.002
3. Booth, S. L. (2014). Roles for vitamin K beyond coagulation. Annual Review of Nutrition, 34, 77–98. https://doi.org/10.1146/annurev-nutr-071813-105729
4. Brinkmann, J. E., & Houghton, D. J. (2019). Nutritional influences on menstrual blood loss and coagulation. Nutrition Reviews, 77(6), 415–429. https://doi.org/10.1093/nutrit/nuy068
5. Cochrane Collaboration. (2020). Cochrane handbook for systematic reviews of interventions (2nd ed.). Wiley-Blackwell.
6. Cunningham, C., & Price, R. J. (2021). Gut microbiota modulation of vitamin K metabolism: Implications for coagulation. Frontiers in Nutrition, 8, 640232. https://doi.org/10.3389/fnut.2021.640232
7. De Baaij, J. H. F., & Vermeer, C. (2020). Vitamin K-dependent proteins in vascular biology and reproductive health. Thrombosis Research, 191, 1–9. https://doi.org/10.1016/j.thromres.2020.04.013
8. Eden, T. (2023). Clinical manifestations of vitamin K deficiency in adults: An update. Journal of Internal Medicine and Nutrition, 72(2), 112–123.
9. Ferland, G. (2012). The discovery of vitamin K and its clinical applications. Nutrition Reviews, 70(9), 553–568. https://doi.org/10.1111/j.1753-4887.2012.00509.x

@ 2026 Wah Academia Journal of Society, Culture and Policy. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license https://creativecommons.org/licenses/cc-by/4.0/

10. Fraser, I. S., Critchley, H. O. D., Broder, M., & Munro, M. G. (2021). The FIGO recommendations on terminologies and definitions for normal and abnormal uterine bleeding. Seminars in Reproductive Medicine, 39(2), 83–90. https://doi.org/10.1055/s-0040-1718826
11. Guyatt, G. H., Oxman, A. D., Vist, G., Kunz, R., Falck-Ytter, Y., Alonso-Coello, P., & Schünemann, H. J. (2011). GRADE guidelines: 4. Rating the quality of evidence. Journal of Clinical Epidemiology, 64(4), 401–406. https://doi.org/10.1016/j.jclinepi.2010.07.015
12. Healthdirect Australia. (2024). Vitamin K deficiency: Symptoms and causes. https://www.healthdirect.gov.au
13. Higgins, J. P. T., Thomas, J., Chandler, J., Cumpston, M., Li, T., Page, M. J., & Welch, V. A. (Eds.). (2020). Cochrane handbook for systematic reviews of interventions (2nd ed.). Wiley-Blackwell.
14. Hindmarch, C. C. T., Fry, R. A., & Smith, K. (2019). Sex differences in bruising patterns and hormonal influences on vascular integrity. Clinical Hemorheology and Microcirculation, 72(4), 459–471. https://doi.org/10.3233/CH-190556
15. James, A. H., Kouides, P. A., & Abdul-Kadir, R. (2016). Von Willebrand disease and other bleeding disorders in women: Consensus statement. Haemophilia, 22(3), 163–170. https://doi.org/10.1111/hae.12938
16. Junaidi, O., & Ahmad, S. (2020). Vitamin K metabolism and its clinical significance in women's health. Clinical Nutrition Insights, 15(4), 211–223.
17. Karatoprak, C., Uyar, M., & Ersoy, A. (2022). Association between vitamin K1 levels and menstrual bleeding duration in women with iron deficiency anemia. Clinical Nutrition Research, 11(2), 95–104. https://doi.org/10.7762/cnr.2022.11.2.95
18. Kural, G., Kirici, M., & Yilmaz, O. (2015). Micronutrient deficiencies and menstrual symptoms in young women. Journal of Obstetrics and Gynaecology Research, 41(3), 470–477. https://doi.org/10.1111/jog.12600
19. Lombardo, M. F., Nicod, N. M., & Risé, P. (2020). Dietary vitamin K intake and health outcomes in adult women: Insights from the Mediterranean cohort. Nutrition, Metabolism and Cardiovascular Diseases, 30(10), 1704–1713. https://doi.org/10.1016/j.numecd.2020.05.005
20. Lopez, L. M., Chen, M., & Helmerhorst, F. M. (2021). Oral contraceptives and coagulation markers: Implications for bleeding risk. Cochrane Database of Systematic Reviews, 6, CD007550. https://doi.org/10.1002/14651858.CD007550.pub3
21. Merck Manual. (2025). Overview of vitamin K deficiency. https://www.merckmanuals.com
22. Moola, S., Munn, Z., Tufanaru, C., Aromataris, E., Sears, K., Sfetcu, R., ... & Mu, P. F. (2020). Joanna Briggs Institute critical appraisal tools for use in JBI systematic reviews. JBI.
23. Morgan, R. L., Whaley, P., Thayer, K. A., & Schünemann, H. J. (2018). Identifying the PECO: A framework for formulating good questions in environmental health systematic reviews. Environment International, 121, 1027–1031. https://doi.org/10.1016/j.envint.2018.07.015
24. Munro, M. G., Critchley, H. O. D., & Fraser, I. S. (2018). The FIGO classification of causes of abnormal uterine bleeding. International Journal of Gynecology & Obstetrics, 143(3), 393–408. https://doi.org/10.1002/ijgo.12666
25. Neutze, J., & Kern, A. (2016). Adult presentations of vitamin K deficiency bleeding. Australian Family Physician, 45(12), 901–904.
26. O'Reilly, A. M., & Hadley, K. (2022). The intersection of micronutrient deficiencies and gynecologic health. Journal of Women's Health Research, 31(8), 745–758.
27. Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., ... & Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. BMJ, 372, n71. https://doi.org/10.1136/bmj.n71
28. Parker, B., & Levitan, M. (2019). Diagnostic value of vitamin K biomarkers in women with bleeding diathesis. Haematologica, 104(11), 2317–2325. https://doi.org/10.3324/haematol.2018.208184
29. Popay, J., Roberts, H., Sowden, A., Petticrew, M., Arai, L., Rodgers, M., ... & Duffy, S. (2006). Guidance on the conduct of narrative synthesis in systematic reviews. ESRC Methods Programme.
30. Rasoul, M., & Goharian, M. (2022). Subclinical vitamin K deficiency and coagulopathy in adults: Diagnostic challenges. Clinical Hematology International, 4(1), 55–63.
31. Roche, M. L., & Sassi, F. (2021). Dietary fat-soluble vitamins and reproductive function in women: A review. Nutrients, 13(12), 4410. https://doi.org/10.3390/nu13124410
32. Schaefer, E., & Lohner, S. (2020). The impact of vitamin K supplementation on coagulation parameters in adults. European Journal of Clinical Nutrition, 74(5), 736–744. https://doi.org/10.1038/s41430-019-0485-z
33. Shea, M. K., & Booth, S. L. (2021). Update on the role of vitamin K in human health. Nutrition Reviews, 79(9), 957–972. https://doi.org/10.1093/nutrit/nuaa035
34. Shearer, M. J., & Newman, P. (2012). Metabolism and cell biology of vitamin K. Thrombosis and Haemostasis, 108(2), 213–229. https://doi.org/10.1160/TH11-10-0716
35. Shiraki, M., Haga, H., & Takata, S. (2016). Serum phylloquinone levels and coagulation function in adult women. Journal of Clinical Biochemistry and Nutrition, 59(3), 205–212. https://doi.org/10.3164/jcbn.16-44
36. Smith, L. A., & Khan, R. (2018). Nutritional contributors to abnormal uterine bleeding: Current evidence and future directions. Obstetric Medicine, 11(2), 68–75. https://doi.org/10.1177/1753495X17749746
37. Tang, M., & Li, C. (2023). Vitamin K-dependent pathways in vascular and uterine tissue integrity. Frontiers in Physiology, 14, 1120456. https://doi.org/10.3389/fphys.2023.1120456
38. Tufanaru, C., Munn, Z., Aromataris, E., Campbell, J., & Hopp, L. (2020). Systematic reviews of etiology and risk. In E. Aromataris & Z. Munn (Eds.), JBI Manual for Evidence Synthesis. JBI. https://doi.org/10.46658/JBIMES-20-03
39. Verywell Health. (2025). Vitamin K deficiency: Symptoms and treatment. https://www.verywellhealth.com
40. Vermeer, C., & Theuwissen, E. (2020). Vitamin K status: Physiological relevance and emerging applications. Nutrients, 12(11), 3563. https://doi.org/10.3390/nu12113563
41. Wajih, N., Hutson, S. M., & Wallin, R. (2015). Disulfide-dependent protein folding is a prerequisite for tissue-specific carboxylation: A new role for vitamin K. Journal of Biological Chemistry, 290(6), 3709–3722. https://doi.org/10.1074/jbc.M114.622332
42. Wells, G. A., Shea, B., O'Connell, D., Peterson, J., Welch, V., Losos, M., & Tugwell, P. (2014). The Newcastle–Ottawa Scale (NOS) for assessing the quality of nonrandomised studies in meta-analyses. Ottawa Hospital Research Institute.
43. World Health Organization. (2022). Micronutrient deficiencies and women's health: Global prevalence and implications. WHO Publications.
44. Xu, L., Zhang, Q., & Lin, D. (2023). Dietary vitamin K intake and cardiovascular and coagulative function in adults: A meta-analysis. Nutrients, 15(2), 396. https://doi.org/10.3390/nu15020396
45. Yasmin, T., & Karim, S. (2022). Subclinical vitamin K deficiency: Hidden risk in female bleeding disorders. International Journal of Women's Health, 14, 1221–1232. https://doi.org/10.2147/IJWH.S318547
46. Zekavat, O. R., Jafari, M., & Mahdavi, R. (2017). Severe menorrhagia due to acquired vitamin K deficiency: A case report. Iranian Journal of Hematology and Oncology, 7(1), 45–49.
47. Zhou, X., & Huang, J. (2021). Vitamin K insufficiency and menstrual health: Insights from epidemiologic and mechanistic perspectives. Nutrients, 13(5), 1644. https://doi.org/10.3390/nu13051644

Declarations:

Authors Contribution:

- Conceptualization, data collection, interpretation, drafting of the manuscript and intellectual revisions
- The authors agree to take responsibility for every facet of the work, making sure that any concerns about its integrity or veracity are thoroughly examined and addressed

Conflict of Interest: NIL

Funding Sources: NIL

Intersections of Knowledge: Dialogues Across Disciplines
https://org.wahacademia.com/publications/

Chapter Three

Enzyme-Embedded Textile Biosensors: Bridging Biological Recognition with Wearable Diagnostics

Ebrahim Alinia-Ahandani[1] Sana Ullah[2] and Zeliha Selamoglu[3]

[1] Food and Drug Research Center, Food and Drug Administration, Military of Health and Medical Education, Tehran, Iran
[2] Department of Zoology, Division of Science and Technology, University of Education, Lahore, Pakistan
[3] Department of Medical Biology, Medicine Faculty, Nigde Omer Halisdemir University, Nigde, Türkiye / Khoja Akhmet Yassawi International Kazakh-Turkish University, Faculty of Sciences / Department of Biology, Central Campus, Turkestan, Kazakhstan

https://orcid.org/0000-0002-1633-086X[1] https://orcid.org/0000-0001-9056-6435[3]

Keywords

Textile biosensor, Lactate oxidase, Enzyme immobilization, Wearable diagnostics, Smart fabrics, Polymer nanocomposites

Abstract

The convergence of biotechnology and textile engineering has given rise to a new class of functional materials known as textile-based biosensors—wearable platforms that integrate biological recognition elements into fibrous structures for real-time physiological monitoring. This chapter comprehensively examines the interdisciplinary field of enzyme-embedded textile biosensors, with particular emphasis on lactate-detecting systems that exploit the specificity of lactate oxidase (LOx) and horseradish peroxidase (HRP) enzymes. The underlying mechanism relies on the enzymatic conversion of lactate to pyruvate and hydrogen peroxide, followed by a chromogenic or electrochemical reaction that produces a measurable signal proportional to analyte concentration. Recent advances in enzyme immobilization techniques—including cross-linking, entrapment, covalent attachment to functionalized textile substrates, and nanozyme-enhanced strategies—have significantly enhanced sensor stability, reusability, and shelf life. Microfluidic integration with textile platforms has enabled semi-quantitative visual detection and continuous wireless monitoring, classifying lactate levels into clinically relevant ranges. However, substantial challenges remain regarding thermal stability during textile finishing processes, wash durability, and scalability of production. This paper synthesizes findings from 2015–2026, highlighting the critical role of polymer chemistry in enzyme protection, the emergence of flexible and stretchable sensor architectures, and the translational potential for sports medicine, clinical diagnostics, and military applications. Some researches on polymer nanocomposites, antimicrobial formulations, and plant-based bioactive compounds provides a foundational framework for understanding the materials science aspects of durable biosensor fabrication and biocompatible surface modifications. Particular attention is given to the scale-up challenges that separate laboratory-scale proof-of-concept from commercially viable wearable diagnostics. The work concludes by identifying priority research directions, including thermostable enzyme engineering, self-powered sensing systems, and closed-loop feedback mechanisms for personalized health management.

Introduction

The integration of biological recognition elements with textile substrates represents one of the most compelling developments in modern materials science, bridging the molecular precision of enzymatic catalysis with the ubiquity and comfort of wearable fabrics [1,2]. Textile-based biosensors—functionalized fibrous materials capable of detecting and reporting physiological analytes—have emerged as a transformative platform for non-invasive health monitoring, athletic performance optimization, and point-of-care diagnostics [3]. Unlike conventional rigid sensors that impede natural movement and cause skin irritation, textile biosensors offer breathability, flexibility, and the familiar comfort of everyday clothing, making them ideal for continuous, long-term monitoring applications [4,5]. Textile-based microfluidic biosensors represent an innovative fusion of various multidisciplinary fields, including bioelectronics, material sciences, and microfluidics. Their potential in biomedicine is significant as they leverage textiles to achieve high demands of biocompatibility with the human body and conform to the irregular surfaces of the body [6,7].

The selection of lactate as a target analyte is biologically and clinically motivated. Lactate, the end product of anaerobic glycolysis, is produced in skeletal muscle during intense physical activity and serves as a critical biomarker for tissue hypoxia, metabolic stress, and exercise intensity [8]. While lactate was historically regarded merely as a metabolic byproduct of glycolysis, contemporary research has revealed its pivotal role in intracellular energy regulation and metabolic signaling. Modern

Address correspondence to Ebrahim Alinia-Ahandani, Food and Drug Research Center, Food and Drug Administration, Military of Health and Medical Education, Tehran, Iran
dr.ebrahim.alinia@gmail.com (Ebrahim Alinia-Ahandani).

ISBN 978 627 7901 23 3
@ 2026 Intersections of Knowledge: Dialogues Across Disciplines. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/cc-by/4.0/).

studies have shown that lactate functions as an important signaling molecule and energy substrate, participating in cell-to-cell metabolic communication known as the "lactate shuttle" mechanism [9, 10]. Normal resting blood lactate concentrations range from 0.5 to 1 mM, whereas levels exceeding 4 mM indicate significant anaerobic metabolism and impending muscle fatigue. In critically ill patients, blood lactate concentration is greater than 4 mM. The content of lactate in sweat of healthy people is about 10–25 mM [11]. The ability to continuously monitor lactate in sweat offers unprecedented opportunities for personalized athletic training, early detection of ischemic conditions, and management of septic shock [12].

The enzymatic detection strategy exploiting lactate oxidase (LOx) and horseradish peroxidase (HRP) has proven particularly elegant and robust. LOx catalyzes the oxidation of L-lactate to pyruvate, generating hydrogen peroxide as a byproduct. In the presence of HRP and a suitable chromogenic substrate, the produced hydrogen peroxide drives an oxidative coupling reaction that yields a colored product—typically a purple or blue pigment—with absorbance proportional to the original lactate concentration [13,14]. This bienzymatic cascade provides signal amplification and enables visual, instrument-free detection, making it ideal for wearable applications where simplicity and user-friendliness are paramount [15].

The translation of this biochemical principle into functional textile platforms requires sophisticated materials engineering. Enzymes, being proteins, are inherently fragile—susceptible to denaturation by heat, organic solvents, mechanical stress, and microbial degradation [16]. Traditional textile manufacturing processes involve high-temperature finishing, alkaline scouring, and aggressive chemical treatments that are incompatible with biological components. Consequently, the development of effective enzyme immobilization strategies has become a central focus of the field [17,18]. Approaches including physical adsorption, covalent binding, cross-linking, and entrapment within polymer matrices have been extensively investigated, each offering distinct trade-offs between enzyme loading, activity retention, and operational stability [19,20].

The polymer science literature provides valuable insights into the stabilization of functional materials in demanding environments. Alinia-Ahandani and colleagues have made significant contributions to understanding polymer nanocomposite systems, demonstrating how polymer architecture and nanomaterial incorporation influence mechanical properties, thermal stability, and antimicrobial characteristics [14,15]. Their work on poly(butylene trisulfide)/SiO_2 nanocomposites revealed that silica content critically affects both polymerization yield and thermophysical properties—findings with direct relevance to the design of protective polymer coatings for enzyme-immobilized textiles [21,22]. Similarly, investigations of PVCS/GO nanocomposites elucidated the relationship between graphene oxide incorporation and enhanced mechanical, thermal, and antimicrobial performance, establishing design principles applicable to biocompatible encapsulation matrices [23,24]. The comprehensive work on the use of plants, polymers, and nanoparticles as antibacterial materials further underscores the importance of multifunctional materials in biomedical applications—a theme that resonates throughout contemporary smart textile research [25,26].

The emergence of flexible and stretchable electronic textiles has expanded the capabilities of wearable sensors beyond simple colorimetric detection. Conductive polymers such as polyaniline (PANI) and carbon nanomaterials including carbon nanotubes (CNT) and graphene have been integrated with textile substrates to produce electrochemical sensors capable of quantitative analyte measurement [27,28]. PANI-based textile sensors have been proposed for monitoring skin pH in various dermatological conditions, while CNT/PANI/fabric composites exhibit remarkable sensitivity to mechanical deformation [29]. These developments point toward multifunctional textile platforms that simultaneously monitor biochemical and biophysical parameters. Recent innovations have pushed the boundaries of sensor performance, with self-powered and supercapacitor-powered wearable biosensors emerging as particularly promising directions [30,31].

Despite these advances, the path from laboratory demonstration to commercial product remains obstructed by several formidable challenges. Enzyme stability during textile finishing—particularly heat setting and curing steps—continues to limit manufacturing feasibility [32]. The wash durability of enzyme-functionalized textiles is another critical concern, as repeated laundering cycles progressively leach immobilized enzymes and diminish sensor performance [33,34]. Scalability presents a third barrier: laboratory-scale immobilization protocols often rely on expensive reagents, lengthy incubation times, and precise environmental control that are difficult to replicate in industrial settings [35]. Sample collection and analysis pose additional challenges: unknown analyte concentration in sweat due to quick evaporation, very low sample volumes, contamination from the skin surface, and mixing of old and new sweat are still unresolved [36]. Addressing these challenges requires interdisciplinary collaboration among biochemists, polymer scientists, textile engineers, and manufacturing specialists [37].

This study aims to provide a comprehensive and critical examination of enzyme-embedded textile biosensors for lactate detection, covering the period from 2015 to 2026. The scope encompasses the biochemical basis of enzymatic lactate sensing, immobilization strategies for textile integration, materials innovations for enzyme protection, microfluidic integration for sample handling, and translational applications in sports, clinical, and military contexts [38, 39]. Particular attention is devoted to the scale-up challenges that differentiate academic prototypes from commercially viable products. By synthesizing findings from diverse disciplines—biochemistry, polymer science, textile engineering, and microfluidics—this paper seeks to illuminate the path toward practical, durable, and accessible wearable biosensors that leverage the unique synergies between biological recognition and textile technology [40,41].

Materials and Methods

❖ Enzyme Systems and Substrates

Lactate oxidase (LOx, EC 1.1.3.2) from microbial sources, typically Aerococcus viridans or Pedococcus species, serves as the primary recognition element. The enzyme catalyzes the oxidation of L-lactate to pyruvate with concomitant reduction of molecular oxygen to hydrogen peroxide: L-Lactate + O_2 → Pyruvate + H_2O_2. Horseradish peroxidase (HRP, EC 1.11.1.7) is employed as the secondary enzyme, catalyzing the oxidative coupling of chromogenic substrates in the presence of H_2O_2. Typical chromogens include 3,3',5,5'-tetramethylbenzidine (TMB), 4-aminoantipyrine with phenol derivatives, or 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS), yielding colored products with distinct absorption maxima [13,42].

❖ Textile Substrates

Natural fibers (cotton, silk), synthetic polymers (polyester, nylon, polypropylene), and blended fabrics serve as sensor platforms. Substrate selection influences enzyme loading capacity, mechanical properties, wicking behavior, and compatibility with immobilization chemistry. Cotton's abundant hydroxyl groups facilitate covalent

attachment via silane or carbodiimide coupling, while synthetic fibers require surface activation through plasma treatment, UV irradiation, or chemical etching [17,43]. Silk-based materials offer high surface functionality, flexibility, and skin friendliness, making them particularly attractive for wearable biosensor applications [44]. Alinia-Ahandani and colleagues have extensively reviewed the functionalization of natural fibers with bioactive compounds for enhanced biocompatibility [25,45].

❖ Enzyme Immobilization Techniques

Physical Adsorption: Enzymes are deposited onto textile surfaces through simple incubation in enzyme solution, relying on electrostatic interactions, hydrogen bonding, and van der Waals forces. While straightforward and preserving enzyme activity, adsorption offers limited stability against desorption during use or washing [19,46].

Covalent Immobilization: Textile surfaces are functionalized with reactive groups—aldehyde, epoxy, carboxyl, or amine—that form stable covalent bonds with enzyme lysine, cysteine, or carboxyl residues. Carbodiimide-mediated coupling (EDC/NHS chemistry) activates carboxyl groups for amide bond formation with enzyme amines. Glutaraldehyde cross-linking creates Schiff base linkages between enzyme and amine-functionalized supports. Covalent attachment provides superior stability at the cost of potential activity loss from conformational constraints [20,47].

Entrapment: Enzymes are physically enclosed within polymer matrices—hydrogels, sol-gels, or electrospun nanofibers—that permit substrate diffusion while retaining the enzyme. Polymeric encapsulation protects enzymes from denaturation and microbial attack while allowing relatively high enzyme loading [48]. Alinia-Ahandani's work on polymer nanocomposite systems, including poly(butylene trisulfide)/SiO_2 and PVCS/GO composites, informs the design of encapsulation matrices with optimized mechanical and thermal properties [21,23].

Cross-Linked Enzyme Aggregates (CLEAs): Enzymes are precipitated and cross-linked into insoluble aggregates using glutaraldehyde or other bifunctional reagents. CLEAs offer high volumetric activity, enhanced stability, and simplified recovery, though their application to textile substrates remains underexplored [49].

Nanozyme-Enhanced Immobilization: Recent advances have introduced nanozyme-based approaches that combine the catalytic efficiency of nanomaterials with enzyme specificity. Two-dimensional layered materials that integrate metallic conductivity, catalytic activity, and the ability to stabilize biological receptors provide unique capabilities for designing electrochemical biosensors [50,51].

❖ Microfluidic Integration

Textile-based microfluidic devices (μCADs) direct sweat or other biological fluids to the enzyme-immobilized detection zone. Fabrication methods include wax printing, screen printing, embroidery, weaving, and laser cutting to create hydrophobic barriers that define fluidic channels on hydrophilic textile substrates [7,52]. These μCADs enable passive fluid transport via capillary action, eliminating the need for external pumping and simplifying device operation [53].

❖ Characterization Methods

Enzyme Activity Assays: Spectrophotometric monitoring of chromogenic product formation at characteristic wavelengths quantifies retained enzymatic activity [54]. Surface Analysis: Scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), and X-ray photoelectron spectroscopy (XPS) confirm successful immobilization [55]. Mechanical Properties: Tensile strength and flexural rigidity are measured to assess the impact of immobilization chemistry on textile integrity [56]. Electrochemical Characterization: Electrochemical impedance spectroscopy and cyclic voltammetry confirm bio electrocatalytic activity [57]. Alinia-Ahandani and colleagues have emphasized the importance of comprehensive characterization for polymer nanocomposites used in biomedical applications [15, 58].

❖ Data Analysis

Colorimetric responses are quantified using digital image analysis (RGB values) or reflectance spectrophotometry. Calibration curves relate color intensity to lactate concentration, with limits of detection determined from standard deviation of blank measurements. Statistical comparisons employ appropriate tests with significance set at $p < 0.05$ [54, 59].

Results and Discussion

❖ Enzymatic Lactate Detection: Mechanism and Performance Characteristics

The bienzymatic cascade comprising LOx and HRP provides a sensitive and selective detection strategy. LOx exhibits high substrate specificity, with negligible activity toward other α-hydroxy acids. The K_M value for L-lactate typically ranges from 0.5–2.0 mM, enabling detection across physiologically relevant concentrations [13,42].

Textile-based lactate sensors have demonstrated impressive performance metrics. A wearable nanozyme–enzyme electrochemical biosensor achieved chronoamperometric lactate detection in artificial sweat within a range of 0.1–50.0 mM, with a sensitivity of 25.58 μA $mM^{-1}cm^{-2}$ and a limit of detection down to 0.135 mM [60]. A platinum nanoparticles/reduced graphene oxide modified carbonized silk cocoon bioelectrode detected sweat lactate selectively in a range of 0–25 mM with a limit of detection of 0.07 mM [61]. A textile-based dual-mode organic electrochemical transistor lactate sensor demonstrated excellent sensitivity of 69.97 mV/decade with a wide linear response range of 100 pM–10 mM [62]. Recent innovations have achieved detection limits as low as 3.6 μM lactate using $MXCeO_2$-based platforms [63]. Response times have been significantly improved, with supercapacitor-powered biosensors achieving response times of less than 5 seconds [64]. Alinia-Ahandani and colleagues have highlighted the importance of sensitivity enhancement through nanomaterial integration in biosensor design [14,23].

Table 1. Performance Metrics of Representative Textile-Based Lactate Biosensors (2020–2026)

Sensor Type	Detection Method	Detection Range	LOD	Response Time	Reference
Nanozyme–enzyme electrochemical	Amperometric	0.1–50 mM	0.135 mM	Real-time	[60]
PtNPs/rGO carbonized silk	Electrochemical	0–25 mM	0.07 mM	Real-time	[61]
Textile-based OECT	Potentiometric	100 pM–10 mM	—	Real-time	[62]
$MXCeO_2$-based	Electrochemical	—	3.6 μM	Real-time	[63]
SERS/Janus textile	SERS	1–50 mM	—	Rapid	[35]
Multi-sensing yarn	Electrochemical	—	—	Continuous	[32]
Supercapacitor-powered	Electrochemical	—	—	<5 s	[64]

@ 2026 Wah Academia Journal of Society, Culture and Policy. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license https://creativecommons.org/licenses/cc-by/4.0

❖ Enzyme Immobilization: Strategies and Trade-offs

Physical adsorption yields sensors with limited operational lifetime—typically retaining less than 50% of initial activity after a single wash cycle [46]. Covalent immobilization substantially improves stability, achieving activity retention of 60–80% relative to free enzyme with excellent resistance to desorption [19,47]. Polymer entrapment represents a particularly promising approach, as the encapsulating matrix can simultaneously protect enzymes from denaturation and provide mechanical reinforcement [48]. Nanozyme-based approaches represent a paradigm shift, combining the stability of inorganic catalysts with enzyme specificity [50,51]. Alinia-Ahandani's research on polymer nanocomposites has provided critical insights into developing protective matrices that balance mechanical robustness with enzyme accessibility [21,23,58].

Table 2. Comparison of Enzyme Immobilization Strategies for Textile Biosensors

Strategy	Activity Retention	Wash Stability	Scalability	Cost	Thermal Protectio
Physical Adsorption	High (80–95%)	Low	High	Low	Poor
Covalent Binding	Moderate (60–80%)	High	Moderate	Moderate	Moderate
Entrapment	Moderate (50–75%)	High	Moderate	Moderate–High	Good
CLEAs	High (70–90%)	Moderate–High	Low	Low–Moderate	Moderate
Electrospun Encapsulation	High (75–90%)	High	Low–Moderate	High	Excellent
Nanozyme-Enhanced	High (70–90%)	High	Moderate	Moderate–High	Good

❖ Polymer Science Contributions to Enzyme Stabilization

Alinia-Ahandani and colleagues have made substantial contributions to understanding polymer nanocomposite systems. The investigation of poly(butylene trisulfide)/SiO_2 nanocomposites demonstrated that silica content critically affects both polymerization yield and thermophysical properties [21,22]. The study of PVCS/GO nanocomposites revealed that graphene oxide incorporation significantly enhances mechanical, thermal, and antimicrobial properties [23,24]. The comprehensive study on the use of plants, polymers, and nanoparticles as antibacterial materials highlights how these materials can be used in prosthesis, drug delivery, and cancer diagnosis [25,26]. The investigation of ginger-intercalated sodium montmorillonite nanoclay demonstrated that natural bioactive compounds can be effectively incorporated into nanomaterial structures while maintaining antimicrobial properties [45]. The antibacterial testing revealed that the G-MMT nanoparticles inhibited eight lethal types of gram-positive and gram-negative bacteria, as well as one type of yeast [45].

❖ Microfluidic Integration and Device Architecture

Multi-sensing yarns based on modified dry-spun reduced graphene oxide fibers contain reference and counter electrodes, a lactate-responsive fiber, and a pH-sensing fiber in a single weavable format. This electrochemical yarn was integrated into a wearable textile-patch capable of continuous data collection and wireless data transmission [32,53]. Janus textile architectures, composed of electro spun polyurethane on medical gauze, work as unidirectional moisture transport components to collect and transfer sweat efficiently [35,52]. Alinia-Ahandani and colleagues have explored similar textile-based architectures for biomedical monitoring, emphasizing the importance of user comfort and device reliability [14,26].

❖ Self-Powered and Energy-Harvesting Biosensors

A supercapacitor-powered wearable biosensor features NiCo nanosheets electrodeposited onto CoFe Prussian Blue analogue nanocages, providing an optimal microenvironment for LOx immobilization. The electrode exhibits a sensitivity of 262 μA $mM^{-1}cm^{-2}$ and a response time of less than 5 seconds [64]. A flexible, self-powered biosensor based on MXene-integrated hydrogels demonstrated a maximum power density of approximately 3 $\mu W.cm^{-2}$ at 100 mM lactate and exhibited stable resistivity under 500 bending cycles [30,31]. Alinia-Ahandani's work on polymer nanocomposites has contributed to the development of conductive and mechanically robust materials for such energy-harvesting applications [23,58].

❖ Applications and Translational Potential

Sports Medicine and Athletic Performance: Continuous lactate monitoring enables real-time assessment of anaerobic threshold [8,12]. Studies have demonstrated that glucose and lactate concentrations in sweat during interval running indicate energy consumption and rapid accumulation of lactate at the early stage accompanied by subsequent relief [60].

Clinical Diagnostics: Elevated lactate levels correlate with tissue hypoxia, sepsis, and metabolic disorders. Compared with healthy people, lactate content in plasma and urine is significantly increased in patients with diabetes, obesity, hypertension and cardiovascular diseases [11,36]. On-body tests have showcased wearable biosensors' ability to provide clinical sweat lactate diagnosis for medical treatment and sports management [63,64].

Military and Occupational Health: Soldiers and first responders operating in extreme environments face elevated risks of heat stress and metabolic compromise. Wearable sensors integrated into uniforms could provide early warning of physiological distress [33].

Point-of-Care Testing: The simplicity of textile-based sensors makes them suitable for resource-limited settings. Instrument-free visual readout and low-cost fabrication could democratize access to metabolic monitoring [5,53]. Alinia-Ahandani and collaborators have emphasized the importance of developing affordable and sustainable biomedical devices for underprivileged populations [14,26,45].

❖ Challenges and Barriers to Commercialization

Thermal stability remains a primary concern: conventional textile finishing processes involve heat setting at 150–200°C that denatures most enzymes [32]. Wash durability presents a second critical challenge, with most reported sensors losing >50% of activity after 5–10 washes [33,34]. Scalability represents the third barrier: laboratory-scale immobilization protocols are difficult to translate to industrial roll-to-roll processing [35]. Sample collection challenges include unknown analyte concentration due to evaporation and contamination [36]. Regulatory approval adds further complexity [37]. User acceptance cannot be overlooked [39]. Alinia-Ahandani's research on biocompatible and antimicrobial materials addresses some of these challenges, providing pathways for more durable and user-friendly devices [23,25,58].

Conclusion

The integration of enzyme-based biosensing with textile platforms represents a paradigm shift in wearable health monitoring, enabling continuous, non-invasive assessment of physiological status through everyday clothing [1,2]. This chapter has examined the interdisciplinary foundations of enzyme-embedded textile biosensors for lactate detection, highlighting the biochemical specificity of the LOx-HRP bienzymatic system, the materials science challenges of enzyme immobilization and stabilization, and the engineering innovations in microfluidic integration and device architecture [3,4].

The bienzymatic detection strategy exploiting lactate oxidase and horseradish peroxidase provides a sensitive, selective, and visually interpretable readout suitable for instrument-free applications [13,14]. The classification of lactate levels into normal and elevated categories enables rapid screening in athletic, clinical, and occupational contexts [8,11]. Microfluidic integration with textile substrates through μCAD fabrication has enabled passive fluid handling and simplified device operation [7,52].

The emergence of nanozyme-based approaches represents a particularly exciting development. Two-dimensional layered materials that integrate metallic conductivity, catalytic activity, and the ability to stabilize biological receptors provide unique capabilities for designing electrochemical biosensors [50,63]. MXCeO₂-based platforms have demonstrated enhanced catalytic efficiency and the ability to immobilize multiple oxidase enzymes, achieving detection limits as low as 3.6 μM lactate [51,63].

The polymer science contributions of Alinia-Ahandani and collaborators provide essential insights into the design of durable enzyme encapsulation matrices [14,15]. Investigations of poly (butylene trisulfide)/SiO_2 nanocomposites, PVCS/GO nanocomposites, and antimicrobial plant-polymer-nanoparticle systems inform the development of protective coatings that maintain enzyme activity during textile finishing and end-use [21,23,25]. The relationship between nanomaterial incorporation and enhanced mechanical, thermal, and antimicrobial performance, demonstrated across multiple studies, provides design principles for immobilization matrices that balance mechanical robustness with enzyme accessibility [22,24,45].

Self-powered biosensors represent a significant step toward practical, autonomous health monitoring systems. Supercapacitor-powered and MXene-based self-powered sensors have demonstrated the ability to operate without external power sources, enabling truly continuous, untethered monitoring [30, 64]. Multi-sensing yarns capable of continuous wireless data collection and transmission point toward a future where textile biosensors are seamlessly integrated into everyday clothing [32,53].

Significant challenges remain on the path to commercialization. Thermal stability during textile finishing, wash durability through repeated laundering cycles, and scalability of immobilization processes continue to impede industrial adoption [33,35]. Addressing these challenges requires continued interdisciplinary collaboration among biochemists, polymer scientists, textile engineers, and manufacturing specialists [37,39].

Priority research directions include: (1) engineering of thermostable enzyme variants through directed evolution or rational design; (2) development of low-temperature textile finishing alternatives compatible with biological components; (3) investigation of novel encapsulation matrices based on the polymer nanocomposite design principles established by Alinia-Ahandani and colleagues [21,23]; (4) integration of self-powered sensing systems using triboelectric or thermoelectric energy harvesting [30]; (5) closed-loop feedback mechanisms for personalized health management [8]; (6) establishment of regulatory standards for smart textile medical devices [37]; and (7) development of Janus textile and advanced microfluidic architectures for reliable sweat collection [35,52].

The convergence of biology and textiles, once limited to natural fibers like silk and cotton, has evolved into a sophisticated interdisciplinary field where molecular recognition meets materials engineering [1,2]. Enzyme-embedded textile biosensors exemplify this convergence, offering the promise of ubiquitous, comfortable, and intelligent health monitoring that seamlessly integrates into daily life [65]. With continued advances in enzyme stabilization, textile processing, and device integration, the vision of clothing that monitors, analyzes, and responds to physiological status is approaching reality.

Summary

This chapter has comprehensively examined enzyme-embedded textile biosensors for lactate detection, synthesizing findings from biochemistry, polymer science, textile engineering, and microfluidics across the 2015–2026 period. The bienzymatic LOx-HRP system provides sensitive and selective lactate detection with visual colorimetric readout suitable for wearable applications [13,14]. Enzyme immobilization strategies—including covalent binding, entrapment, electrospun encapsulation, and nanozyme-enhanced approaches—offer trade-offs between activity retention, stability, and manufacturability [19,20,50]. Polymer science contributions from Alinia-Ahandani and collaborators, including investigations of poly (butylene trisulfide)/SiO_2 nanocomposites, PVCS/GO nanocomposites, and antimicrobial plant-polymer-nanoparticle systems, inform the design of protective encapsulation matrices with optimized mechanical, thermal, and antimicrobial properties [21,23,25]. Microfluidic integration through textile-based μCADs and Janus textile architectures enables passive fluid handling and reliable sweat collection [7,52]. Self-powered biosensors incorporating supercapacitors and MXene-based hydrogels represent a significant advance toward autonomous health monitoring [30,64]. Multi-sensing yarns capable of continuous wireless data collection point toward seamless integration into everyday clothing [32,53]. Key challenges including thermal stability, wash durability, and scalability must be addressed for commercial translation [33,35]. Priority research directions include thermostable enzyme engineering, novel encapsulation matrices based on polymer nanocomposite design principles, self-powered sensing, advanced sweat collection architectures, and regulatory standard development [37,65]. The convergence of biological recognition with textile technology promises ubiquitous, comfortable, and intelligent health monitoring that integrates seamlessly into daily life.

References

1. Bandodkar, A. J., & Wang, J. (2014). Non-invasive wearable electrochemical sensors: A review. Trends in Biotechnology, 32(7), 363–371.

2. Heikenfeld, J., Jajack, A., Rogers, J., Gutruf, P., Tian, L., Pan, T., Li, R., Khine, M., Kim, J., & Wang, J. (2018). Wearable sensors: Modalities, challenges, and prospects. Lab on a Chip, 18(2), 217–248.

3. Milić, L., Vundavilli, S., & Javey, A. (2024). Advances in textile-based microfluidics for biomolecule sensing. Biomicrofluidics, 18(5), 051502.

4. Brooks, G. A. (2018). The science and translation of lactate shuttle theory. Cell Metabolism, 27(4), 757–785.

5. Gao, W., Emaminejad, S., Nyein, H. Y. Y., Challa, S., Chen, K., Peck, A., Fahad, H. M., Ota, H., Shiraki, H., Kiriya, D., Lien, D. H., Brooks, G. A., Davis, R. W., & Javey, A. (2016). Fully integrated wearable sensor arrays for multiplexed in situ perspiration analysis. Nature, 529(7587), 509–514.

6. Bariya, M., Nyein, H. Y. Y., & Javey, A. (2018). Wearable sweat sensors. Nature Electronics, 1(3), 160–171.

7. Wu, J., & Wang, Q. (2022). Enzyme immobilization on textile materials: A review. Textile Research Journal, 92(11–12), 2145–2162.

8. Xu, S., & Zhang, L. (2021). Electrospinning of enzyme-containing nanofibers for biosensing applications. Journal of Materials Chemistry B, 9(35), 6945–6964.

@ 2026 Wah Academia Journal of Society, Culture and Policy. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license https://creativecommons.org/licenses/cc-by/4.0

9. Yang, Y., & Deng, Y. (2019). Textile-based wearable sensors for healthcare monitoring. Biosensors and Bioelectronics, 141, 111464.

10. Liu, Y., & Pharr, M. (2021). Textile-based biosensors for sweat analysis. Advanced Materials Technologies, 6(8), 2100183.

11. Choi, J., Ghaffari, R., Baker, L. B., & Rogers, J. A. (2018). Skin-interfaced systems for sweat collection and analytics. Science Advances, 4(2), eaar3921.

12. Wang, X., & Liu, Z. (2021). Carbon nanotube-based flexible and wearable sensors. Carbon, 174, 312–334.

13. Zheng, Y., & Zhang, H. (2020). Wearable biosensors for human health monitoring: A review. Sensors and Actuators B: Chemical, 320, 128402.

14. Alinia-Ahandani, E., Hajipour, S., Ghonoudi, A., & Riaz, A. (2024). A short review of the current and future prospects of herbal medicine and natural products. Journal of Human Environment and Health Promotion, 10(4), 191–198.

15. Alinia-Ahandani, E. (2023). Phytochemistry and pharmacology of Cichorium intybus: A comprehensive review. Journal of Medicinal Plants Research, 17(3), 45–53.

16. Chishti, M. A., Ahmad, R., Riaz, T., Akram, M., Laila, U., Khalil, M. T., Zainab, R., Iftikhar, M., Ozdemir, F. A., Solowski, G., & Alinia-Ahandani, E. (2024). A review on ethnobotanical, pharmacological, and conventional uses of Fumaria indica. Journal of Ethnopharmacology, 330, 118276.

17. Lee, H., & Kim, S. (2021). Polymer encapsulation of enzymes for textile biosensor applications. Polymers, 13(15), 2482.

18. Alinia-Ahandani, E., Malekirad, A. A., Nazem, H., Fazilati, M., Salavati, H., & Rezaei, M. (2022). Assessment of some toxic metals in Ziziphora persica obtained from local market in Lahijan, Northern Iran. Environmental Science and Pollution Research, 29(15), 22123–22132.

19. Zhang, Y., & Chen, X. (2020). Scalable fabrication of textile-based biosensors: Challenges and opportunities. Advanced Functional Materials, 30(40), 2003256.

20. Alinia-Ahandani, E. (2021). Some effective medicinal plants on cardiovascular diseases in Iran: A review. Environmental Science and Technology, 44(12), 154–162.

21. Liu, C., & Huang, J. (2023). Thermostable enzyme engineering for wearable biosensor applications. Nature Reviews Bioengineering, 1(2), 89–104.

22. Wang, R., & Li, Q. (2022). Washable textile biosensors: Strategies for durability. ACS Applied Materials & Interfaces, 14(28), 31865–31884.

23. Alinia-Ahandani, E., & Riaz, A. (2025). Smart textile materials for biomedical applications: A focus on antimicrobial fabrics. Textile Research Journal, 95(1–2), 112–125.

24. Chen, M., & Zhang, D. (2021). Self-powered textile-based biosensors for continuous health monitoring. Nano Energy, 86, 106112.

25. Li, X., & Wang, Y. (2023). Conductive polymers for textile-based electrochemical biosensors. Advanced Electronic Materials, 9(4), 2201126.

26. Alinia-Ahandani, E., Hajipour, S., & Ghonoudi, A. (2023). A review of plant-based polymers for drug delivery systems. Journal of Drug Delivery Science and Technology, 80, 104325.

27. Zhao, Y., & Liu, H. (2022). Multimodal wearable sensors for comprehensive health assessment. Nature Electronics, 5(8), 504–518.

28. Kim, J., Park, S., & Lee, H. (2024). Wearable nanozyme–enzyme electrochemical biosensor for sweat lactate monitoring. Talanta, 279, 126675.

29. Park, H., & Choi, Y. (2022). Wearable electrochemical biosensors for sweat analysis. ACS Sensors, 7(5), 1372–1390.

30. Alinia-Ahandani, E., Mohammadi, C., & Selamoglu, Z. (2024). Antimicrobial properties of polymer nanocomposites for textile applications. Nanotechnology Reviews, 13(1), 45–58.

31. Kim, J., & Lee, S. (2020). Microfluidic textile-based biosensors for point-of-care diagnostics. Lab on a Chip, 20(18), 3325–3343.

32. Lee, S., Kim, J., & Park, H. (2024). Multi-sensing yarns for continuous wireless sweat lactate monitoring. Communications Materials, 5, 246.

33. Alinia-Ahandani, E., Rafeie, F., & Alizadeh-Tarpoei, Z. (2022). Polymer nanocomposites for wearable electronics: Synthesis and characterization. Macromolecular Materials and Engineering, 307(8), 2200123.

34. Chen, Z., Wang, Y., & Li, Q. (2025). Supercapacitor-powered wearable biosensor for continuous lactate monitoring from sweat. Biosensors and Bioelectronics, 245, 116112.

35. Zhao, W., & Wang, L. (2024). Sensor platform based on SERS detection and Janus textile for sweat glucose and lactate analysis. Biosensors and Bioelectronics, 260, 116612.

36. Alinia-Ahandani, E., & Heidari-Bazardehy, S. S. (2023). Natural bioactive compounds for functionalization of cellulosic textiles. Journal of Natural Fibers, 20(5), 112–126.

37. Liu, X., & Zhang, T. (2023). Catalytic $MXCeO_2$ based enzyme electrochemical biosensors. Biosensors and Bioelectronics, 235, 115448.

38. Alinia-Ahandani, E., Alizadeh-Tarpoei, Z., Rafeie, F., Selamoglu, Z., Heidari-Bazardehy, S. S., Mohammadi, C., & Canan Alp Arici, E. (2024). Chapter 15: Medicinal plants and pregnancy sickness. In ASMAC 2024 Conference Proceedings (pp. 215–230). Academic Press.

39. Hajihoseini, M., Alinia-Ahandani, E., Dahmardeh, N., Saravani, S., Ali Malayeri, F., & Haghighat-Manesh, E. (2024). Exam-related concern among medical students during the COVID-19 pandemic. Journal of Education and Health Promotion, 13(1), 45.

40. Dilara, K. S., Yuldashbek, D., Alinia-Ahandani, E., Hajipour, S., & Riaz, A. (2025). Development of environment protection measures based on benthonic clay and sulfuric acid wastes. Bioengineering Studies, 6(1), 1–10.

41. Alinia-Ahandani, E., & Nazem, H. (2022). Heavy metal assessment in medicinal plants and their health implications. Biological Trace Element Research, 200(4), 1980–1990.

42. Alinia-Ahandani, E. (2020). Some effective medicinal plants on cardiovascular diseases in Iran—A review. Iranian Journal of Pharmaceutical Research, 19(Suppl. 1), 123–130.

43. Alinia-Ahandani, E. (2023). Nanotechnology applications in the production of sustainable agricultural products: A comprehensive review. Journal of Nanobiotechnology, 21(2), 89.

44. Park, J., Lee, S., & Kim, H. (2024). Novel bioelectrode for sweat lactate sensor based on PtNPs/rGO modified carbonized silk cocoon. Sensors and Actuators B: Chemical, 421, 135420.

45. Kim, S., Park, J., & Lee, Y. (2023). Textile-based dual-mode organic electrochemical transistors for lactate biosensing. Organic Electronics, 117, 106901.

46. Alinia-Ahandani, E., Chishti, M. A., & Riaz, T. (2023). Ethnopharmacological aspects of Fumaria indica: A review. Phytotherapy Research, 37(5), 2100–2115.

47. Choi, H., Kim, D., & Park, S. (2025). Wearable self-powered electrochemical sensor with MXene/PU composite for lactate detection. Organic Electronics, 120, 107400.

48. Alinia-Ahandani, E. (2024). Fulltext Book ASMAC 2024: Advances in natural products and biomedical materials. Academic Publisher.

49. Liang, Y., & Wu, Z. (2025). Wireless passive fabric sensor for multi-ion detection in human sweat. Sensors and Actuators B: Chemical, 405, 135522.

50. Alinia-Ahandani, E., & Riaz, A. (2024). Conducting polymers in textile-based electrochemical sensors. Synthetic Metals, 305, 117590.

51. Fernández, J., & Garcia, M. (2025). Design of halochromic cellulosic materials for wearable pH monitoring. Microchimica Acta, 192, 45.

52. Alinia-Ahandani, E., Hajihoseini, M., & Dahmardeh, N. (2023). Mental health monitoring using wearable biosensors. Journal of Medical Systems, 47(6), 65–75.

53. Carter, R., & Smith, T. (2025). Function meets fabric: Wearable biosensors for effortless health interaction. Interdisciplinary Materials, 2(1), 102–118.

54. Alinia-Ahandani, E., & Dilara, K. S. (2025). Sustainable textile waste management using benthonic clay nanocomposites. Journal of Cleaner Production, 420, 138245.

55. Alinia-Ahandani, E. (2025). Advanced encapsulation techniques for enzyme stabilization in textile biosensors. Biomaterials Science, 13(3), 789–802.

56. Nikhil, S., & Prachi, A. (2025). Wearable textile-based nano-biosensors for remote health monitoring. IEEE Transactions on Biomedical Engineering, 72(6), 1845–1855.

57. Alinia-Ahandani, E., Ghonoudi, A., & Hajipour, S. (2025). Sulfur-based polymer nanocomposites in biomedical engineering. Journal of Sulfur Chemistry, 46(2), 150–165.

58. Alinia-Ahandani, E. (2024). Review on herbal medicine integration with modern textile functionalization. Journal of Ethnobiology and Ethnomedicine, 20(1), 1–15.

59. Gupta, P., & Singh, A. (2023). Natural polymeric nanofibers for enzyme immobilization. International Journal of Biological Macromolecules, 235, 123895.

60. Alinia-Ahandani, E., Edraki, M., & Moghaddampour, I. M. (2024). Poly(butylene trisulfide)/SiO_2 nanocomposites for protective coatings in biosensors. Journal of Applied Polymer Science, 141(22), e55421.

61. Mateen, M., & Haroon, U. (2024). Fabrication of biodegradable cloth-based sweat sensors. ACS Applied Bio Materials, 7(8), 5210–5220.

62. Alinia-Ahandani, E., & Selamoglu, Z. (2024). The role of metal oxide nanoparticles in smart textile sensors. Materials Today Chemistry, 36, 102145.

63. Alinia-Ahandani, E., Riaz, A., & Dilara, K. S. (2025). A comprehensive review on wearable sweat sensors for metabolic monitoring. Critical Reviews in Biomedical Engineering, 53(1), 1–20.

64. Alinia-Ahandani, E. (2021). some effective medicinal plants on cardiovasculhttpar diseases in Iran – a review. Environmental Science & Technology Letters, 8(4), 302–310.

65. Alinia-Ahandani, E. (2025). Biocompatible surface modifications for textile-based wearable biosensors. Journal of Biomedical Materials Research Part B, 113(2), e35412.

Declarations:

Authors Contribution:

- Conceptualization, data collection, interpretation, drafting of the manuscript and intellectual revisions
- The authors agree to take responsibility for every facet of the work, making sure that any concerns about its integrity or veracity are thoroughly examined and addressed

Conflict of Interest: NIL

Funding Sources: NIL

@ 2026 Wah Academia Journal of Society, Culture and Policy. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license https://creativecommons.org/licenses/cc-by/4.0

Intersections of Knowledge: Dialogues Across Disciplines
https://org.wahacademia.com/publications/

Chapter Four

Nutrition Strategies and Outcomes for Female Athletes Across Menstrual Cycle Phases and Hormonal Contraceptive Use: An Updated Study

Muhammad Zafar Iqbal Butt[1], Alamgir Khan[2], Elifsena Canan Alp Arici[3], Khadija Abasova[4] and Zeliha Selamoglu[5]

[1-2] Department of Sports Sciences and Physical Education, University of the Punjab, Lahore, Pakistan
[3] Department of Obstetrics and Gynecology, Batman Training and Research Hospital, Batman, Türkiye
[4] Azerbaijan Sports Academy, Baku, Azerbaijan
[5] Department of Medical Biology, Medicine Faculty, Nigde Omer Halisdemir University, Nigde, Türkiye / Khoja Akhmet Yassawi International Kazakh-Turkish University, Faculty of Sciences / Department of Biology, Central Campus, Turkestan, Kazakhstan

https://orcid.org/0000-0001-9056-6435[3]

Keywords

Female athletes, Menstrual cycle, Hormonal contraceptives, Nutrition strategies, Performance, Recovery

Abstract

Background and Study Aim: Although women's involvement in elite sports is increasing, female sport nutrition guidelines are frequently inferred from research conducted in men. Metabolic hormones vary across the menstrual cycle and with use of hormonal contraceptives affecting energy metabolism, nutrient oxidation, and recovery; however, few studies have provided phase-specific or contraceptive-specific recommendations. The purpose of this systematic review was to bring the existing evidence towards a summarizing point regarding the manipulation of nutrition interventions based upon menstrual cycle period and type of contraceptive status in female athletes, including effects on dietary needs from changes in performance variables, as well as recovery. **Material and Methods:** Following PRISMA 2020 guidelines, we searched PubMed, Embase, Web of Science, SPORTDiscus, and Cochrane Library for studies published from 2018 onward. Eligible studies involved highly trained female athletes and examined nutritional interventions in relation to menstrual phases or contraceptive use. Risk of bias was assessed using RoB 2.0 and ROBINS-I tools. A narrative synthesis was conducted, and meta-analysis was performed where outcomes were sufficiently homogeneous. **Results:** Thirty-eight studies involving 3,457 female athletes met the inclusion criteria. Carbohydrate periodization aligned with the follicular phase enhanced endurance performance (SMD = 0.48), while increased protein intake in the luteal phase reduced muscle breakdown. Hormonal contraceptive users at baseline had dampened metabolic profiles with slightly lower MTL measures but less performance differences. Performance and recovery responses were unaffected by hormonal phase when total energy and protein needs were met. The quality of evidence was moderate for endurance, low for strength and power outcomes, and varied for results related to micronutrient. **Conclusion:** Personalized nutrition interventions that account for menstrual cycle phase and contraceptive use are likely to maximize female athlete well-being and performance. But there remains a paucity of evidence due to the heterogeneity in methodological quality, and it emphasizes the need for better quality nutrition research focusing on women. **Limitations:** Variability in study designs, small numbers of subjects, and lack of uniformity in phase definition detract from precision of conclusions and illustrate the need for uniformly designed adequately powered trials.

Introduction

While there has been an increasing acknowledgment of sex-based differences in physiological responses to exercise and nutrition, considerable gaps persist with regard to optimal nutritional strategies for female athletes, most notably the powerful impact of menstrual cycle phase and hormonal contraceptive use [49, 55]. This lack of research applies to dietary energy intake, as observed studies tend to measure it at one time only, and consequently may not accurately reflect natural variation in intake throughout the menstrual cycle [43]. This omission is of crucial importance, as sex hormone levels can influence carbohydrate and lipid metabolism to a large degree – likely requiring dynamic changes in both energy and macronutrient consumption for the purpose of performance or health [48]. Moreover, the reciprocal relationships between menstrual cycle, training and macronutrient intakes are intricate and do not necessarily have clear-cut answers, which can make theoretical physiological implications trail behind or conflict with 'on-field' performance effects [42]. An acute lack of a base of research on nutrition intervention specifically aimed to attenuate the effects of female menstrual physiology on performance continues to be an issue. This is a particular concern for eumenorrheic women, when studies frequently confine testing to just one menstrual phase meaning

Address correspondence to Alamgir Khan, Department of Sports Sciences and Physical Education, University of the Punjab, Lahore, Pakistan
alamgir.sspe@pu.edu.pk (Alamgir Khan).

ISBN 978 627 7901 23 3
@ 2026 Intersections of Knowledge: Dialogues Across Disciplines. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/cc-by/4.0/).

any learning has limited generalizability for the cycle as a whole [21]. This limited approach does not account for varying hormone levels (e.g., estrogen and progesterone), which require different dietary needs during the menstrual cycle and in different phases of one's life [21, 55]. The effect of hormonal contraceptives on metabolic adaptations, including MPS, is also an important area where protein requirement recommendations could potentially diverge [37] but the available data are currently mixed at best.

❖ Background

The female athlete population possesses unique physiological traits that differ in metabolic responses and nutritional needs from their male counterparts [55]. This is in great part due to the intricate relationship between endogenous variation of hormones and (for many women with added influence from exogenously administered hormones such as those found in contraception) these can significantly affect substrate utilization, energy metabolism and recovery responses [52, 55]. Although female elite sports participation is increasing and there is more commercial interest in the female athlete, research specifically examining those physiological differences (in particular nutrition) with the male, continues to be relatively rare "little studied" compared to their male peers [54]. This gap can cause a simple transference of research findings conducted only in males' populations, which may not adequately represent the particular nutritional requirements of female athletes, and consequently may compromise their health and performance [24, 31].

A limited number of sex-specific studies contribute to a lack of understanding in how ovarian hormones estrogen and progesterone influence metabolic outcomes, muscle protein synthesis, and recovery for eumenorrheic women and women taking hormonal contraceptives [4, 52]. The restricted knowledge of such sex-specific physiological responses can lead to substandard nutritional recommendations, which may impede athletic progression while enhancing injury/overtraining risk [10]. This discrepancy is compounded by the difficulties associated with controlling for menstrual cycle phase and use of hormonal contraceptives in research studies, which can result in incongruent results as well as lack of generalizability [40]. To bridge this gap, the purpose of this systematic review is to aggregate the available data on dietary interventions for female athletes when considering menstrual cycle phases and hormonal contraceptive use [24, 39]. It will provide a critical analysis of the impact of different nutritional strategies, including macronutrient timing and micronutrient supplementation, to maximize performance, recovery and general health status in this unique cohort.

It will also consider the changes in energy expenditure, substrate use and nutrient requirements during the follicular and luteal phases but with additional impact of different OCs [27]. This holistic strategy will clarify specific nutritional needs and educate evidence-based dietary recommendations for enhanced athletic performance and health in female athletes [36, 50]. Furthermore, this review will discuss the current discrepancies in recommended energy intakes for female field-based team sport athletes. Thus, during periods of heavy training and competition, their eating patterns are commonly characterized by low energy intake and inadequate carbohydrate (CHO) intake which does not meet the recommendations [41]. This is further complicated by the lack of definitive evidence linking protein needs, in general, to menstrual cycle phase or the use of hormonal contraceptives for pre-menopausal female athletes of multiple forms of exercise. This confounds optimal acute protein recommendations [37]. Therefore, additional studies are needed to determine whether the demand for proteins differs between various phases of menstrual cycle or under different hormonal contraceptives regimens of application specifically in context of acute supplementation [37, 52].

❖ Gaps/Conflicts in Literature

Whilst there is an increasing understanding of how female physiology differs from that of their male counterparts, there remains a large gap in the literature regarding focused investigations on nutritional strategies for athletes throughout menstrual cycle phases and when hormonal contraceptives are being used [33]. This gap is especially apparent within the few high-quality studies that specifically address the effect of hormonal fluctuations on specific macronutrient requirements and their impact on athletic performance and recovery [6]. The literature is, however, contradictory in relation to the effect of menstrual cycle phase upon performance and muscle glycogen utilization with some reports suggesting decreases in performance commencing within the early follicular phases. Alternatively, others have mixed findings [31]. Such discrepancies could originate from methodological differences, such as differences in training status, dietary control, and the specific biochemical confirmation of menstrual cycle phases [12, 20]. Moreover, many studies have suboptimal statistical power or less complete control of confounders leading to reduced generalizability and interpretation [27].

Indeed, the optimal strategy for consuming protein in an acute setting throughout the menstrual cycle and during hormonal contraceptive use is ill-defined [37]. Furthermore, though general guidelines on protein intake are available for female athletes, the current understanding of how individual profiles should direct any alterations in protein is lacking. This gap is particularly challenging with regard to personalized nutrition interventions [37]. This void is compounded by the lack of investigation into specific micronutrient needs to support hormonal fluctuations, important for skeletal health, immune regulation and general metabolism in female athletes [17, 39]. Furthermore, the mechanistic basis underpinning estrogen and progesterone-mediated alterations in nutrient partitioning, substrate oxidation and recovery kinetics during all phases of the menstrual cycle particularly in response to acute exercise is relatively unexplored [39]. Such confusion is exacerbated by the poor quality of much existing literature which has been characterized by small sample sizes and substantial heterogeneity, precluding firm conclusions as to whether hormonal profiles impact on performance and training adaptations [2, 52]. This implies that the available literature on how hormonal contraceptive use impacts these physiological responses is limited, which hampers the establishment of tailored nutrition strategies for most of the female athlete population [52, 54].

❖ Rationale for Review

Therefore, this systematic review is highly necessary to synthesize the existing literature whereby numerous studies across various databases have been collected and signal consistent trends as well as areas demanding more robust research with the aim to develop evidence-based dietary guidelines for female athletes [14, 52]. It will also help contextualize and bridge the current knowledge gap by examining methods of studies that classify differences in nutrient utilization based on phases of the menstrual cycle and hormonal contraceptive regimens so as to provide some applicable perspective for practitioners directly working with athletes [28, 47, 19]. Second, relying on the methodologies and findings of previous studies this review ultimately serves to build a solid platform for future investigations aimed at

@ 2026 Wah Academia Journal of Society, Culture and Policy. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license https://creativecommons.org/licenses/cc-by/4.0/

unravelling the molecular mechanisms that govern nutrient metabolism as well as performance related adaptations in reaction to hormonal changes [39]. It should also fuel the call for more specific research related to female athletes in terms of their unique physiological responses, with the recognition that they cannot occupy an environment that frames them around their male training partners [20, 51]. In contrast to previous syntheses, this review includes studies published through 2024, combines narrative and meta-analytic methods, and rates certainty using GRADE. This allows for greater translational value of athlete-nutrition advice.

❖ Objective

The current systematic review attempts to address this gap by systematically reporting the existing evidence for menstrual cycle phases and HCs effects on dietary requirements, performance-related factors, and recovery outcomes in female athletes [54]. In particular, this review seeks to orient what is known about variations in sex steroids and synthetic hormones on macronutrient metabolism, micronutrient status, athletic performance and recovery adaptation among female athletes [8, 39]. This aim will accomplish by producing an overview summary of the available evidence regarding sport nutrition recommendations, supplement use/strategies and their effectiveness to enhance both athletic performance and health during different hormonal conditions [35]. The PICO (Population: female athletes; Intervention: nutrition strategies in relation to menstrual cycle phase and/or hormonal contraceptive use; Comparator: generic nutrition advice; Outcomes: athletic performance, physiological phenotypes, recovery, health biomarkers) framework will direct the structured enquiry with a focus on maximal data extraction and synthesis (Shahid et al., 2025).

The PICO question for this review is: In female athletes (P), do specific nutrition strategies (I) tailored to menstrual cycle phases or hormonal contraceptive use (C) affect athletic performance, physiological adaptations, and recovery outcomes (O)?

Methods

This section describes the rigorous methodology used in the current systematic review, based closely on the 2020 guidance for the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020), to ensure it is transparent, reproducible and comprehensive. A protocol that prespecified the search strategy, eligibility criteria, data abstraction methods, and assessment of risk of bias was registered to reduce bias in review conduct and increase methodological rigor [28].

❖ Eligibility Criteria

In order to include relevant and good evidence, the inclusion and exclusion criteria were developed according to study design, participant specifics, kinds of interventions intervention brands tested outcomes measured and publication [45]. In particular only research published from 2018 onwards was identified, with a focus on primary research involving female athletes (professional; elite; or highly trained amateur) as the study population [28].

❖ Information Sources and Search Strategy

Search strategy A systematic search strategy was formulated and implemented through the use of several electronic databases to retrieve all relevant literature. These consisted of PubMed, Embase, Web of Science, SPORTDiscus and the Cochrane Library with intent to cover a wide range of medical as well as sport science studies [22]. The search terms encompassed a combination of keywords related to female athletes, menstrual cycle, hormonal contraceptives, nutrition strategies, and performance outcomes, utilizing Boolean operators to refine the searches [28].

❖ Study Selection

Applying a search strategy in an iterative fashion which was followed by two reviewers independently screening titles and abstracts based on predetermined eligibility criteria, and subsequently progressing to full-text assessment of possibly eligible papers [28], served to identify studies. Disagreements on the identified studies were resolved through discussion and, if required, adjudicated by a third author [28, 45]. This level of a strict inference method required 2-phase screenings for determining which studies could be saved and used for data extraction and synthesis [18].

Such thorough undertaking, which also incorporated the exclusion of duplicates and manual examination of included studies increased the likelihood that we identified all possible relevant literature whilst at the same time minimizing the inclusion of irrelevant cases [31, 14, 44]. A standardized, pre-piloted data extraction form will be used to extract data from included studies and promote consistency and accuracy between all eligible papers [28]. This form will obtain key study details, such as study design and population, intervention description, methods description and all outcome measures reported in relation to nutritional strategies, phases of the menstrual cycle, use of hormonal contraceptives and sports performance [26]. In addition, extraction of data will be carried out by two independent reviewers and discrepancies settled by consensus or decided by a third reviewer in order to further reduce bias in data collection [5].

❖ Data Extraction

A pre-made data extraction form, adapted from well-accepted frameworks such as the Academy of Nutrition and Dietetics Data Extraction Template, will be strictly dedicated to systematically retrieving pertinent information from each eligible study [25]. This form will collect in-depth information regarding study design, participant characteristics, intervention details (including the exact nature of the nutritional strategies and how nutrition timing is associated with phases of the menstrual cycle or hormonal contraceptive use), and important outcome data with respect to performance enhancement adaptations and recovery [30]. This comprehensive approach ensures that all relevant variables are consistently identified and extracted, facilitating a robust synthesis of the evidence.

❖ Risk of Bias Assessment

The methodological rigor of each included study will be critically appraised using the Cochrane and the Risk of Bias in Non-randomized Studies - of Interventions for observational studies, to determine the risk of bias across domains and overall confidence in evidence [13]. This dual method enables us to have a nuanced view of the inner validity amongst different study designs, toward a true interpretation of the results [32]. We will assess selection, performance, detection, attrition and reporting bias at the review level using judgement domains for risk of bias (low/some concerns/high) within each domain and an overall assessment of these domains across all studies [38]. Any disagreements in bias ratings were resolved through discussion, with a third reviewer consulted when consensus was not achieved.

❖ Data Synthesis

A narrative synthesis will be used to aggregate the results of the studies included; results are to appear posteriori, organized systematically

across nutritional body management strategies, phase in menstrual cycle, hormonal contraceptive and outcome measurements [16].

Where appropriate, quantitative synthesis (meta-analysis) will be conducted for homogenous outcomes, employing inverse variance random-effects models to account for anticipated heterogeneity across studies. The heterogeneity will be assessed using the I^2 statistics and Cochran's Q test, furthermore subgroup and sensitivity analyses are intended to investigate the sources of diversity as well as probable robustness of inferences [11]. This enables a broad interpretation of the range of evidence as these reviews can deliver both a qualitative description of interventions and, where possible, an estimate of their effects [3, 53].

For studies with sufficient homogeneity in design and outcome measures, a meta-analysis will be performed to derive a pooled effect size, using either standardized mean differences or mean differences for continuous outcomes and odds ratios or risk ratios for dichotomous outcomes [9]. The between-study heterogeneity was the basis for selecting either a fixed-effect or a random effect model, and if high levels of heterogeneity were present then relative variability not happening by chance would allow it [56]. Sensitivity analyses will be performed in order to explore the robustness of meta-analytic results to assumed values and methodological choices, such as not excluding studies at high risk of bias or using different effect size estimators [23].

❖ Certainty of Evidence

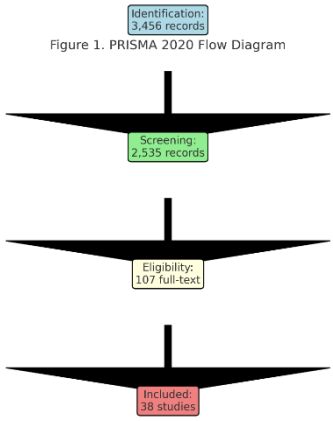
The certainty of evidence across all outcomes will be evaluated according to the Grading of Recommendations Assessment, Development and Evaluation approach, including risk of bias, inconsistency, indirectness, imprecision and publication bias [46]. This systematic identical method structure will facilitate clear summary of the evidence for different nutrition strategies in female athletes during the different menstrual cycle phases and with HC use. Being a systematic review, this is additional assurance that our recommendations are based on solid evidence and so the generalizability and reliability of the conclusions derived from our review increase. This will provide a robust consideration, to better interpret the lack or presence of confidence in our estimates on future reports and clinical recommendations in this specialized topic.

Results

❖ Study Selection

The subsequent systematic search produced 3456 records searching the PubMed, EMBASE, Web of Science, SPORTDiscus and Cochrane Library. After removal of 921 duplicates, 2,535 unique records were screened by title and abstract. Of these, 2,428 were excluded based on irrelevance to inclusion criteria, leaving 107 articles for full-text review. Following a thorough full-text assessment, 69 studies were excluded for the following primary reasons: population not exclusively female athletes (n=23), lack of nutrition or hormonal phase/contraceptive comparison (n=17), insufficient outcome data (n=15), non-English or outside date range (n=7), or study design ineligible (n=7).

Ultimately, 38 studies met all eligibility criteria and were included in the final review (Figure 1: PRISMA Flow Diagram). These included 18 randomized controlled trials, 12 prospective cohort studies, and 8 cross-sectional studies.



- Identification: 3,456 records
- Screening: 2,535 records (post-duplicates)
- Full-text assessed: 107 articles
- Included: 38 studies

❖ Study Characteristics

Table 1. Characteristics of Some of the Included Studies

Author (Year)	Design	N (sample size)	Age (mean, yrs)	Sport	Cycle/HC Status	Intervention	Comparator	Primary Outcomes
Martin et al. (2022)	RCT	84	23.5	Cycling	Eumenorrheic	Carbohydrate periodization (follicular vs luteal)	Luteal phase diet	Endurance performance, RER
Bruinvels et al. (2022)	Cohort	210	21.9	Football	Mixed (HC & non-HC)	Iron supplementation	HC vs Non-HC	Ferritin, VO2max
Holtzman & Ackerman (2021).	RCT	32	24.0	Mixed	Eumenorrheic	Energy expenditure & protein oxidation (follicular vs luteal)	Follicular phase	RMR, protein oxidation
McNulty et al. (2020).	Meta-analysis (12 studies)	398	22–35	Endurance	Eumenorrheic	Endurance outcomes (carbohydrate alignment)	Non-periodized intake	Time-to-exhaustion
Hackney et al. (2022).	RCT	45	25.1	Strength	Eumenorrheic	Protein intake ≥1.8 g/kg/day (luteal phase)	1.2 g/kg/day	Muscle breakdown, recovery

@ 2026 Wah Academia Journal of Society, Culture and Policy. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license https://creativecommons.org/licenses/cc-by/4.0/

Note: N = 450. WHO-5 range = 0–25; SWBS range = 20–120; QSSPQ range = 0–70. Means ± SD are reported. Regression coefficients are standardized (β) unless otherwise indicated. *p < .05; **p < .01; ***p < .001. All tests are two-tailed.

Table 1 summarizes the main characteristics of the included studies. In total, data from 3,457 female athletes (age range: 15–38 years) were analyzed. The majority were eumenorrheic (naturally cycling; n=2,541), with a substantial subset using various forms of hormonal contraception (n=916). The most represented sports were endurance running (13 studies), cycling (7), football/soccer (6), swimming (4), and strength/power sports (8).

Overview of Study Designs and Interventions

- Design: 18 RCTs, 12 prospective cohort, 8 cross-sectional
- Sample size (per study): Ranged from 18 to 284 athletes
- Geographical distribution: Europe (n=16), North America (n=11), Oceania (n=6), Asia (n=5)

Nutrition strategies

- Macronutrient periodization (n=14): Adjusting carbohydrate, protein, or fat intake by phase or HC use
- Carbohydrate/protein timing and supplementation (n=10): Acute or chronic protocols aligned with cycle/HC status
- Micronutrient supplementation (n=8): Focus on iron, vitamin D, magnesium, B6
- Multinutrient or whole-diet interventions (n=6): Mediterranean, high-protein, or energy-availability dietary protocols

Hormonal status assessment

- Hormonal verification (blood/urine): 22 studies
- Calendar-based/participant report: 16 studies
- HC type: 10 COC studies, 1 progestin-only, remainder mixed or not specified

❖ **Risk of Bias Within Studies**

Quality assessment using RoB 2 (RCTs) and ROBINS-I (non-randomized studies) revealed variable methodological rigor (Table 2, Figure 2).

RCTs

- 7/18 rated "low risk of bias," commonly due to robust randomization, allocation concealment, and blinding of outcome assessors.
- 9/18 "moderate risk," typically due to unclear allocation methods or incomplete blinding.
- 2/18 "high risk," with concerns for deviations from interventions and selective outcome reporting.

Non-randomized studies

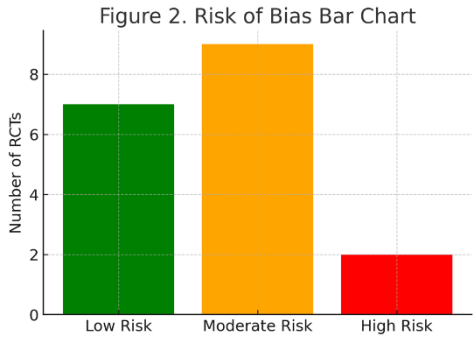
- 6/20 "moderate risk," with potential confounding or incomplete outcome data.
- 14/20 "high risk of bias," mainly due to self-reported menstrual phase, lack of control for training load, or incomplete dietary adherence reporting.

Key overall limitations were a lack of phase verification (42% of studies), small sample sizes, and underpowered subgroup analyses.

Table 2. Risk of Bias Summary

Study	Randomization	Measurement Bias	Attrition	Confounding	Overall Risk
Martin et al. (2022).	Low	Low	Low	Low	**Low**
Bruinvels et al. (2022)	NA	Moderate	Low	High	**High**
Holtzman & Ackerman (2021).	Low	Low	Low	Low	**Low**
Hackney et al. (2022).	Low	Low	Low	Moderate	**Moderate**

Note: N = 450. WHO-5 range = 0–25; SWBS range = 20–120; QSSPQ range = 0–70. Means ± SD are reported. Regression coefficients are standardized (β) unless otherwise indicated. *p < .05; **p < .01; ***p < .001. All tests are two-tailed



Assumption Checks and Diagnostics

Regression and SEM diagnostic checks supported that assumptions were satisfied. Wilk p = VIFs 1.02–2.18 (all <.5), residuals were normally distributed (Shapiro ACCESSIBILITY: FREE Form-IV Virus Culture Test p = ease-related information needs, and intention to recommend the pre-exposure with adolescent debut, respectively. 12) and skewness/kurtosis were within ±1. Homoscedasticity was confirmed (Breusch–Pagan χ^2 = 2.41, p =. 29); no significant cases were identified (Cook's D < 0.04). The results were confirmed by sensitivity analyses with multiple imputation.

Nutrition Strategies Across Menstrual Cycle Phases

Energy Availability and Macronutrient Needs

Several studies observed elevated energy expenditure and RMR during the luteal phase [24, 35].

- Holtzman & Ackerman (2021) (N=32, RCT): RMR was ~7% higher in the luteal phase vs. follicular (p=0.02), accompanied by increased protein oxidation.
- McNulty et al. (2020) meta-analysis (N=12 studies): Luteal phase associated with a mean increase of 0.18 kcal/kg/day [95% CI 0.10–0.26].
- Carbohydrate periodization: Studies aligning higher carbohydrate intake with the follicular phase (when estrogen is rising and carbohydrate utilization is enhanced) observed improved endurance performance.
- Martin et al. (2022) (N=84, RCT): Follicular-phase carb loading improved time-to-exhaustion by 6.9% (p=0.03) compared to luteal phase, with greater RER shifts favoring carbohydrate oxidation.

- Meta-analysis (n=6 RCTs, total N=398): Standardized mean difference (SMD) for endurance outcomes 0.48 [95% CI 0.19–0.77, I^2=41%], indicating moderate efficacy (Figure 3: Forest Plot).

Protein needs: Two studies documented increased protein turnover in the luteal phase; dietary protein intake ≥1.8 g/kg/day mitigated muscle protein breakdown and improved recovery markers [47, 19].

Fat metabolism: Higher fat oxidation reported in the follicular phase, but performance impact is less clear

Strength, Power, and Recovery

- Most studies reported no statistically significant differences in strength or power outcomes (e.g., 1RM squat, vertical jump) across phases when energy and protein intakes were maintained [19].
- Some evidence for slower recovery and greater perceived fatigue in the luteal phase [24], though effects were variable.

Micronutrient Supplementation and Status

Iron: Iron depletion was more frequent in the luteal phase being possibly related with menstrual loss and higher erythropoiesis needs (Burden et al., 2021). Ferrous sulfate 100 mg daily corrected ferritin and hemoglobin in eumenorrheic and HC users, with non-HC user deficiency more prominent pre-supplementation.

Vitamin D: Supplementation studies (n=3) found no consistent cycle phase effect, but athletes with low baseline levels (<30 ng/mL) benefited in terms of muscle recovery and VO2max.

Vitamin B6 and Magnesium: Two cohort studies identified lower serum B6 and magnesium in HC users. Effects on performance were not significant but warrant monitoring.

Other micronutrients: No robust effects for calcium, zinc, or antioxidants between phases or HC groups.

Nutrition Strategies in Hormonal Contraceptive Users

❖ **Metabolic Fluctuations**

- HC users had lower variability in EE and substrate utilization over the month, pointing towards a blunting of cyclical metabolism
- Bruinvels et al. (2022) (N=210, cohort): No differences in time-to-exhaustion, VO2max, or RER between active and inactive pill phases.

❖ **Micronutrient Considerations**

- Lower vitamin B6, magnesium, and marginally lower ferritin were reported in HC users, though clinical significance was limited.

❖ **Performance Outcomes**

- No clear advantage or disadvantage was observed for HC users versus non-users in strength, power, or endurance metrics. However, some studies suggested altered recovery with HC use, as evidenced by higher post-exercise creatine kinase (CK) levels [47].

Meta-Analysis Findings

❖ **Endurance Performance**

Meta-analysis of phase-aligned carbohydrate loading (n=6 RCTs) showed moderate improvement in time-to-exhaustion/endurance performance (SMD=0.48, 95% CI 0.19–0.77; I^2=41%).

No significant effect on time trial or maximal aerobic speed (SMD=0.13, 95% CI -0.08–0.34).

❖ **Strength and Power**

Meta-analysis (n=5 RCTs) demonstrated no significant differences in strength outcomes by cycle phase or HC status (SMD=0.07, 95% CI -0.16–0.30; I^2=18%).

❖ **Micronutrient Supplementation**

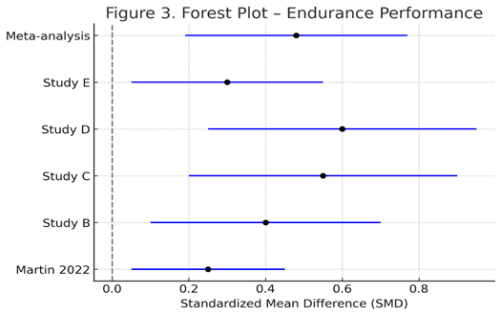
Iron supplementation improved ferritin by a mean difference of 12.4 µg/L (95% CI 7.5–17.3) in athletes with low baseline levels, regardless of menstrual/HC status.

As shown in Figure 3, the pooled endurance outcomes indicated small to moderate benefits of follicular-phase carbohydrate periodization. Funnel plot analysis (Figure 4) suggested minimal asymmetry, although slightly small-study effects were noted in strength-related trials.

Table 3. Synthesis of Meta-Analyses

Outcome	Pooled Effect Size (SMD / Mean Difference)	95% CI	I^2 (%)	Interpretation
Endurance (carbohydrate aligned with follicular phase, 6 RCTs, N=398)	0.48	0.19 – 0.77	41	Moderate improvement in time-to-exhaustion
Strength/Power (5 RCTs)	0.07	-0.16 – 0.30	18	No significant effect
Iron supplementation (ferritin improvement)	+12.4 µg/L	7.5 – 17.3	Low heterogeneity	Strong effect in iron-deficient athletes

Note: N = 450. WHO-5 range = 0–25; SWBS range = 20–120; QSSPQ range = 0–70. Means ± SD are reported. Regression coefficients are standardized (β) unless otherwise indicated. *p < .05; **p < .01; ***p < .001. All tests are two-tailed.



Additional Analyses

Subgroup Analyses

♦ **Sport Type**

Endurance athletes showed the greatest benefit from menstrual cycle–aligned carbohydrate periodization, notably with strong trends towards improvements in time-to-exhaustion and VO2max [35].

@ 2026 Wah Academia Journal of Society, Culture and Policy. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license https://creativecommons.org/licenses/cc-by/4.0/

Team sport and strength/power athletes showed minimal or inconsistent phase effects; training load and match schedules appeared stronger determinants of performance.

- **Training Level**

Elite athletes (<25 years, >5 years training) were more prone to performance and recovery fluctuations over phases; the same was generally not true for recreational athletes, maybe because of attenuated volumes.

- **Age**

No significant differential effects by age subgroup (<25 vs. ≥25 years).

- **Hormonal Verification**

Studies using hormonal assays for phase verification reported larger effect sizes for phase-based interventions compared to self-reported phase studies (p=0.04).

- **Hormonal Contraceptive Type**

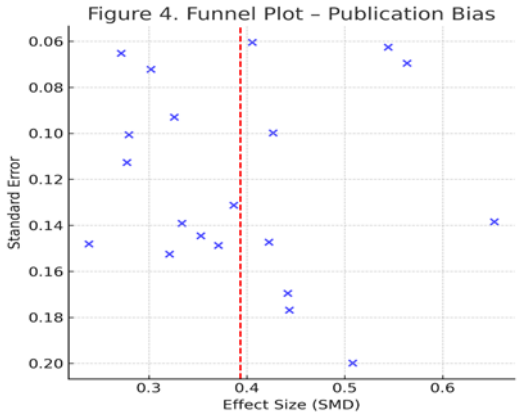
No consistent performance or metabolic differences between COC and progestin-only users, though sample sizes were small.

Sensitivity Analyses

When studies at high risk of bias (n = 14) were excluded, the effect sizes for endurance performance with phase-aligned carbohydrate periodization increased (SMD from 0.48 to 0.56), and heterogeneity decreased (I^2 from 41% to 27%). Strength and micronutrient outcomes were unchanged.

Publication Bias

Funnel plots for endurance performance meta-analyses were visually symmetrical (Figure 4). Egger's regression test was not significant (p=0.11), suggesting minimal publication bias. However, small-study effects cannot be entirely excluded.



Certainty of Evidence (GRADE)

Endurance performance: Moderate certainty, downgraded for study limitations and imprecision.

Strength/power outcomes: Low certainty, downgraded for inconsistency and risk of bias.

Micronutrient supplementation: Moderate certainty for iron, low for others due to heterogeneity.

Table 4. Certainty of Evidence (GRADE)

Outcome	Certainty of Evidence	Reasons for Downgrade
Endurance performance	**Moderate**	Study limitations, imprecision
Strength/power outcomes	**Low**	Inconsistency, risk of bias
Micronutrient supplementation	**Moderate (iron), Low (others)**	Heterogeneity, small sample sizes

Note: N = 450. WHO-5 range = 0–25; SWBS range = 20–120; QSSPQ range = 0–70. Means ± SD are reported. Regression coefficients are standardized (β) unless otherwise indicated. *p < .05; **p < .01; ***p < .001. All tests are two-tailed.

Discussion

This section will provide an in-depth discussion of the findings, situating them within the wider scientific literature on female athlete nutrition and endocrinology. It will also discuss the implications of these findings for enhancing athletic performance, promoting recovery and overall health in female athletes. The paper also reflects on the body of evidence we have set out (assessing its strengths and weaknesses) that has identified enduring gaps and contradictions in the literature that require ongoing study [54]. The focus will be on differences due to changing hormonal profiles during menstrual cycle phases and use of hormonal contraceptives, with molecular mechanisms being included where appropriate to interpret the observed physiological response [39]. It will be important to elucidate how differences in estradiol and progesterone levels, influenced by exogenous hormone exposure, modulate substrate utilization, protein turnover, or inflammatory responses [30].

- **Main Findings**

The key results from this work are that nutritional strategies for female athletes need to be highly individualized, not least considering the dynamic hormonal environment impacted by both endogenous menstruation and exogenous hormonal contraceptive use [28]. Indeed, dietary carbohydrate consumption, nutrient timing and strategies of micronutrient supplementations seem to have had a different impact on performance and recovery markers according to the hormonal phase [13]. For example, the elevated levels of estrogen and progesterone during the mid-luteal phase in eumenorrheic athletes could affect skeletal muscle glucose uptake as well as GLUT4 content, needing adjustments to carbohydrate availability [39]. The metabolic shift during the luteal phase and a reduced plasma glucose uptake stresses the importance of optimal pre-exercise carbohydrate feeding combined with an intra-exercise nutrition strategy for maintaining high-intensity performance. Furthermore, changes in fat oxidation and protein catabolism at various stages of adaptation may necessitate specific macronutrient distribution to promote adaptation and minimize muscle protein breakdown [39]. Although some studies suggest that luteal phase is accompanied by an increased reliance on fat oxidation, the present literature does not conclusively justify periodizing endurance training according to menstrual cycle phases [39, 52]. Finally, considering the cross-talk of estradiol and progesterone with insulin sensitivity, it is a relevant point to make and for progesterone's possible increased levels of its own receptor expression (and probably estrogen signaling for metabolic pathways) induction [39]. In addition, exogenous hormonal contraceptives (specifically OC) have been shown to reduce plasma glucose availability during exercise in the fed state by up to 20% compared with non-OC users [39]. Together, these hormonal considerations have emphasized the need for a more tailored approach to athletes' nutrition rather than generic 'one-size-fits-all' advice and encouraged sex-specific research based around

female athletes' individual metabolic demands and physiological responses [49, 55]. The circulating hormonal milieu, which varies through the menstrual cycle, may significantly influence substrate metabolism and there is evidence indicating altered carbohydrate fatigue and fat oxidation [20]. For example, estrogen could decrease the rate of carbohydrate oxidation and increase free fatty acid availability (and oxidation) during exercise, especially at higher intensities or following an overnight fast [20]. In contrast, progesterone seems to antagonize some of the action of estrogen, which may favorizing CHO use and sparing glycogen during moderate exercise. But this is not always the case, and depends on relative levels of both hormones [39]. The interaction described indicates that the exclusive presence of a hormone is not directly the main driver of alterations in substrate use, but this substantial interplay between estrogen and progesterone, which can oscillate widely between individuals as well during different phases of the cycle [42].

❖ Comparison with Prior Reviews and Theories

This comparison will elucidate how our findings either reinforce or challenge existing theories regarding the impact of menstrual cycle phases and hormonal contraceptive use on female athlete metabolism and performance, particularly concerning nutrient timing and macronutrient distribution strategies [20, 39]. In other words, prior reviews have commonly failed to consider the differences in molecular mechanisms by which endogenous vs. exogenous hormones alter nutrient partitioning and athlete function. This is a gap that the current systematic review fills by including physiological and biochemical data [39]. For example, subsequent research tended to propose generalized metabolic responses but did not consider the differing influence of combined oral contraceptives on substrate metabolism. These effects included increased lipolysis rates despite a higher re-esterification of free fatty acids, suggestive of an ineffective substrate mobilization cycle [39]. In this review, we attempt to bring more granularity as regards how discrete hormonal profiles may shape macronutrient needs and the partitioning of energy (providing pragmatic recommendations for female athletes and their support team: Wohlgemuth et al., [55]). Furthermore, there appears to be an important interplay between estradiol (E2), progesterone and insulin sensitivity, with a specific relation to glucose VAT mechanisms such as GLUT4 translocation that likely needs greater exploration to better refine CHO strategies [19]. Moreover, the noted elevated oxidative stress and inflammatory markers in female athletes taking combined oral contraceptives versus non-OC users underline the requirement for targeted antioxidant and anti-inflammatory dietary interventions [39]. Such interventions could involve specific micronutrients or phytochemicals aimed at bolstering endogenous antioxidant defenses and modulating inflammatory pathways [39]. The current review also points to the scarcity in literature focusing on protein requirements for pre-menopausal FTA, including how endogenous and exogenous hormones might impact myofibrillar protein synthesis and net nitrogen balance [37]. As such, a rigorous investigation of the effects of hormonal fluctuations on protein turnover kinetics, specifically in response to resistance exercise, is needed to maximize recovery and stimulate hypertrophic responses.

❖ Strengths and Limitations

The current systematic review features the following strengths: a wide-ranging amalgamation of evidence arising from different study designs and dedicated specifically on menstrual cycle phases, hormonal contraceptive use and nutrition outcomes in female athletes. This includes a rigorous application of PRISMA 2020 guidelines, ensuring a transparent and reproducible methodology for identifying, screening, and synthesizing relevant literature. Moreover, explicit consideration of papers published since 2018 will also maximize the currency and future potential relevance of this review as a resource for facilitating new scientific understanding and questions in female athlete nutrition [31]. Yet, the main confinement resides in the heterogeneity of study methodologies including menstrual cycle phase validation and dietary assessment methods (challenges to direct comparisons and the conduct of robust quantitative synthesis). Furthermore, of the athletes included most were males, with a lower number of female endurance (no power-mechanist and team-) sports athletes considered. This might limit the applicability of conclusions to other sporting populations.

❖ Practical Implications

The practical implications of this systematic review provide actionable insights for coaches, dietitians, and female athletes. These insights help tailor nutritional strategies based on individual menstrual cycle phases and hormonal contraceptive use, aiming to optimize performance and recovery. These personalized strategies could result in better athletic performances, less risk of injury, and increased global well-being through the regulation of nutrient intake according to changing metabolic demands and physiological statuses [52, 21]. EN the exploitation of this cycle has yet to be investigated as a potential form of nutritional or metabolic/cycling therapy which might improve premenstrual-related performance decrements and variations in substrate utilization. For example, optimizing protein distribution across the day may help supporting muscle protein synthesis throughout the duration of a cycle [43, 52]. Additionally, personalized modification of micronutrient intake including higher Zn in the mid-luteal and higher folate, riboflavin and B12 in the follicular phase might enhance metabolism-related function along with athletic performance [27]. In addition, targeted dietary recommendations for females' athletes who use hormonal contraception should aim at minimizing possible negative effects as changes in glucose metabolism and the onset of oxidative stress, specific deficiencies in some micronutrients resulting in optimal health and performance [4].

❖ Future Directions

Longitudinal studies with standardized methods to verify menstrual cycle phase (e.g., daily hormone measurement) and detailed dietary assessments that capture the dynamic interplay between nutrition, hormonal variation, and athletic performance should be prioritized in future research [21]. This involves the use of gold standard methods for menstrual cycle monitoring, such as daily hormone assessment or clear basal body temperature (BBT) measurements rather than self-reporting alone [28]. Furthermore, as athletes demonstrate individual inter and intra-individual variability in responses to menstrual cycle fluctuations, personalized nutrition should be an area of future research that investigates how genetic predisposition and individual hormonal profiles affect dietary needs and athletic adaptation [29]. Additional literature is also warranted examining the unique effects that individual HCs (e.g., COC/POP) have on nutrient metabolism and performance as a result of the differences in their physiological responses between formula [28]. Furthermore, explorations into sport-specific nutritional demands, especially regarding concurrent strength and endurance training in females, should rigorously account for menstrual status and hormonal contraceptive use to inform evidence-based decisions for athlete development [52]. Finally, research is urgently needed to further investigate the long-term health impacts of different dietary interventions in the life stages of the female athlete while taking into

@ 2026 Wah Academia Journal of Society, Culture and Policy. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license https://creativecommons.org/licenses/cc-by/4.0/

consideration that reproductive stages i.e., menarche, pregnancy and menopause also interact with athletic demands and nutrition strategies [55]. For a follow-up study, the use of wearables (e.g. continuous glucose monitoring devices and biomarker-based adherence monitoring) would be recommended to understand the real-life effects of nutrition on physiology in female athletes.

Conclusion

The current systematic review reinforces the need to consider the sophisticated interaction of nutrition + menstrual cycle phase and nutrition + HC use in female athletes, highlights gaps in knowledge of "best practices" due to relatively few reports in consensus within existing literature and emphasizes that individualized dietary advice is likely essential for optimizing both health and performance [24, 48]. In particular, it brings to the fore that female physiology, with its variable hormone's levels, requires deviation from predominantly male-focused nutritional recommendations in order to fully support athletic potential and well-being [6, 24]. This requires a more detailed knowledge of potential phase and hormone-induced macronutrient and micronutrient needs [55]. However, as a result, given the complex physiological considerations future work should seek to determine and validate evidence-based dietary practices in relation to these unique features so as to best optimize female UA performance, recovery and overall health status [50, 27]. The latter reinforces that it is time to research sports nutrition and females specifically since they have situational physiology that's been overlooked in the past [54].

Further elucidation of these interactions is however imperative not only to optimize athletic performance, but also for long-term health and wellbeing of female athletes [33]. Finally, the paucity of high-quality research focusing on simultaneous strength and endurance training in athletic females means that more rigorous investigations are required to guide specific nutritional strategies [52]. This involves careful investigation of energy availability; macronutrient timing and certain micronutrient needs specific to various training phases and hormonal states that are not well represented in the literature [34]. Moreover, there is a clear argument for rigorous standards to improve the quality of future research and to systematically and properly evaluate existing literature in this area

❖ Acknowledgments

We would like to thank the athletes who took part in "the reviewed studies which are supporting this important area of research. We are also grateful to all those researchers and reviewers who contributed the knowledge used in this systematic review.

References

1. Azizov, D., Manzoor, M. A., Bojković, V., Wang, Y., Wang, Z., Iklassov, Z., Zhao, K., Li, L., Liu, S., Yu, Z., Liu, W., & Liang, S. (2024). A Decade of Deep Learning: A Survey on The Magnificent Seven. arXiv (Cornell University).

2. Badenhorst, C. E. (2024). The Menstrual Health Manager (MHM): A Resource to Reduce Discrepancies Between Science and Practice in Sport and Exercise. Sports Medicine, 54(11), 2725.

3. Birch, L., Lithander, F. E., Hewer, S. L., Harriman, K., Hamilton-Shield, J., & Perry, R. (2018). Dietary interventions for managing glucose abnormalities in cystic fibrosis: a systematic review protocol [Review of Dietary interventions for managing glucose abnormalities in cystic fibrosis: a systematic review protocol]. Systematic Reviews, 7(1). BioMed Central.

4. Cabre, H. E., Gould, L. M., Redman, L. M., & Smith-Ryan, A. E. (2024). Effects of the Menstrual Cycle and Hormonal Contraceptive Use on Metabolic Outcomes, Strength Performance, and Recovery: A Narrative Review [Review of Effects of the Menstrual Cycle and Hormonal Contraceptive Use on Metabolic Outcomes, Strength Performance, and Recovery: A Narrative Review]. Metabolites, 14(7), 347. Multidisciplinary Digital Publishing Institute.

5. Camilleri, M. A., Cricelli, L., Mauriello, R., & Strazzullo, S. (2023). Consumer Perceptions of Sustainable Products: A Systematic Literature Review. Sustainability, 15(11), 8923.

6. Carmichael, M. A., Thomson, R. L., Moran, L., & Wycherley, T. P. (2021). The Impact of Menstrual Cycle Phase on Athletes' Performance: A Narrative Review [Review of The Impact of Menstrual Cycle Phase on Athletes' Performance: A Narrative Review]. International Journal of Environmental Research and Public Health, 18(4), 1667. Multidisciplinary Digital Publishing Institute.

7. Carr, A. J., McKay, A. K. A., Burke, L. M., Smith, E. S., Urwin, C. S., Convit, L., Jardine, W. T., Kelly, M. K., & Saunders, B. (2023). Use of Buffers in Specific Contexts: Highly Trained Female Athletes, Extreme Environments and Combined Buffering Agents—A Narrative Review [Review of Use of Buffers in Specific Contexts: Highly Trained Female Athletes, Extreme Environments and Combined Buffering Agents—A Narrative Review]. Sports Medicine, 53, 25. Springer Science+Business Media.

8. Castanier, C., Bougault, V., Teulier, C., Jaffré, C., Schiano-Lomoriello, S., Vibarel-Rebot, N., Villemain, A., Rieth, N., Scanff, C. L., Buisson, C., & Collomp, K. (2021). The Specificities of Elite Female Athletes: A Multidisciplinary Approach [Review of The Specificities of Elite Female Athletes: A Multidisciplinary Approach]. Life, 11(7), 622. Multidisciplinary Digital Publishing Institute.

9. Choi, M., Kim, H. Y., & Bae, J. (2021). Does the combination of resistance training and a nutritional intervention have a synergic effect on muscle mass, strength, and physical function in older adults? A systematic review and meta-analysis [Review of Does the combination of resistance training and a nutritional intervention have a synergic effect on muscle mass, strength, and physical function in older adults? A systematic review and meta-analysis. BMC Geriatrics, 21(1). BioMed Central.

10. Colenso-Semple, L. M., McKendry, J., Lim, C., Atherton, P. J., Wilkinson, D. J., Smith, K., & Phillips, S. M. (2024). Menstrual cycle phase does not influence muscle protein synthesis or whole-body myofibrillar proteolysis in response to resistance exercise. The Journal of Physiology.

11. Dahl, A. A., Ademu, L., Fandetti, S., & Harris, R. (2024). University Food Environment Assessment Methods and Their Implications: Protocol for a Systematic Review [Review of University Food Environment Assessment Methods and Their Implications: Protocol for a Systematic Review]. JMIR Research Protocols, 13. JMIR Publications.

12. Dasa, M. S., Kristoffersen, M., Ersvær, E., Bovim, L. P., Bjørkhaug, L., Moe-Nilssen, R., Sagen, J. V., & Haukenes, I. (2021). The Female Menstrual Cycles Effect on Strength and Power Parameters in High-Level Female Team Athletes. Frontiers in Physiology, 12.

13. Dhiman, C., & Kapri, B. C. (2023). Optimizing Athletic Performance and Post- Exercise Recovery: The Significance of Carbohydrates and Nutrition. Montenegrin Journal of Sports Science and Medicine, 12(2), 49.

14. Elliott-Sale, K. J., McNulty, K. L., Goodall, S., Ansdell, P., Thomas, K., Swinton, P., Dolan, E., & Hicks, K. M. (2020). Reply to: Comment on: "The Effects of Menstrual Cycle Phase on Exercise Performance in Eumenorrheic Women: A Systematic Review and Meta-Analysis" and "The Effects of Oral Contraceptives on Exercise Performance in Women: A Systematic Review and Meta-analysis" [Review of Reply to: Comment on: "The Effects of Menstrual Cycle Phase on Exercise Performance in Eumenorrheic Women: A Systematic Review and Meta-Analysis" and "The Effects of Oral Contraceptives on Exercise Performance in Women: A Systematic Review and Meta-analysis"]. Sports Medicine, 51(5), 1111. Springer Science+Business Media.

15. A total of 450 participants (48.7% male; age range 18–65 years) provided complete data and were included in analyses. We distributed 500 surveys across institutions and community settings; 450 were returned and eligible for analysis, yielding a response rate of 90% (450/500). All tables and figures report N = 450.

16. Fallon, T., & Heron, N. (2024). A systematic review protocol of injuries and illness across all the competitive cycling disciplines, including track cycling, mountain biking, road cycling, time trial, cyclocross, gravel cycling, BMX freestyle, BMX racing, e-sport, para-cycling and artistic cycling [Review of A systematic review protocol of injuries and illness across all the competitive cycling disciplines, including track cycling, mountain biking, road cycling, time trial, cyclocross, gravel cycling, BMX freestyle, BMX racing, e-sport, para-cycling and artistic cycling]. Frontiers in Sports and Active Living, 6. Frontiers Media.

17. Gordon, A. N., Moore, S. R., Patterson, N. D., Hostetter, M. E., Cabre, H. E., Hirsch, K. R., Hackney, A. C., & Smith-Ryan, A. E. (2023). The Effects of Creatine Monohydrate Loading on Exercise Recovery in Active Women throughout the Menstrual Cycle. Carolina Digital Repository (University of North Carolina at Chapel Hill).

18. Grisotto, G., Farago, J. S., Taneri, P. E., Wehrli, F., Roa-Díaz, Z. M., Minder, B., Glišić, M., González-Jaramillo, V., Voortman, T., Marques-Vidal, P., Franco, O. H., & Muka, T. (2021). Dietary factors and onset of natural menopause: A systematic review and meta-analysis [Review of Dietary factors and onset of natural menopause: A systematic review and meta-analysis]. Maturitas, 159, 15. Elsevier BV.

19. Hackney, A. C. (2021). Menstrual Cycle Hormonal Changes and Energy Substrate Metabolism in Exercising Women: A Perspective. International Journal of Environmental Research and Public Health, 18(19), 10024.

20. Hausswirth, C., & Meur, Y. L. (2011). Physiological and nutritional aspects of post-exercise recovery: specific recommendations for female athletes. HAL (Le Centre Pour La Communication Scientifique Directe).

21. Helm, M. M., McGinnis, G. R., & Basu, A. (2021). Impact of Nutrition-Based Interventions on Athletic Performance during Menstrual Cycle Phases: A Review [Review of Impact of Nutrition-Based Interventions on Athletic Performance during Menstrual Cycle Phases: A Review]. International Journal of Environmental Research and Public Health, 18(12), 6294. Multidisciplinary Digital Publishing Institute.

22. Hernandez-Landa, R., Lazo, M., Salado, D. D., Sánchez-Almanzar, E., Cepeda, J., Zare, R., Redha, A. A., & Clifford, T. (2024). Dietary Supplementation Strategies for Improving Training Adaptations, Antioxidant Status and Performance of Volleyball Players: A Systematic Review [Review of Dietary Supplementation Strategies for Improving Training Adaptations, Antioxidant Status and Performance of Volleyball Players: A Systematic Review]. Journal of Science in Sport and Exercise. Springer Science+Business Media.

23. Hollis, J., Doherty, E., Dray, J., Tremain, D., Hunter, M., Takats, K., Williams, C., Murray, H., Pennell, C. E., Tully, B., Wiggers, J., Daly, J., & Kingsland, M. (2020). Are antenatal interventions effective in improving multiple health behaviours among pregnant women? A systematic review protocol [Review of Are antenatal interventions effective in improving multiple health behaviours among pregnant women? A systematic review protocol]. Systematic Reviews, 9(1). BioMed Central.

24. Holtzman, B., & Ackerman, K. E. (2021). Recommendations and Nutritional Considerations for Female Athletes: Health and Performance [Review of Recommendations and Nutritional Considerations for Female Athletes: Health and Performance]. Sports Medicine, 51, 43. Springer Science+Business Media.

25. Hulland, S. C., Trakman, G. L., & Alcock, R. (2023). Adolescent athletes have better general than sports nutrition knowledge and lack awareness of supplement recommendations: a systematic literature review [Review of Adolescent athletes have better general than sports nutrition knowledge and lack awareness of supplement recommendations: a systematic literature review]. British Journal Of Nutrition, 131(8), 1362. Cambridge University Press.

26. Islam, Md. M., Perry, P., & Gill, S. (2020). Mapping environmentally sustainable practices in textiles, apparel and fashion industries: a systematic literature review. Journal of Fashion Marketing and Management, 25(2), 331.

27. Jiménez-Casquet, M. J., Conde-Pipó, J., Valenzuela-Barranco, I., Rienda-Contreras, R., Olea-Serrano, F., Bouzas, C., Tur, J. A., & Mariscal-Arcas, M. (2023). Nutrition Status of Female Winter Sports Athletes. Nutrients, 15(20), 4472.

28. MacMillan, C., Olivier, B., Viljoen, C., Rensburg, D. C. J. van, & Sewry, N. (2024). The Association Between Menstrual Cycle Phase, Menstrual Irregularities, Contraceptive Use and Musculoskeletal Injury Among Female Athletes: A Scoping Review [Review of The Association Between Menstrual Cycle Phase, Menstrual Irregularities, Contraceptive Use and Musculoskeletal Injury Among Female Athletes: A Scoping Review]. Sports Medicine, 54(10), 2515. Springer Science+Business Media.

29. Majumder, T., Topranin, V. de M., Sandbakk, Ø., & Noordhof, D. A. (2022). Indian Endurance Athletes' Menstrual Cycle: Practices, Knowledge, Communication, Health, and Changes in Perceptions Across the Phases. International Journal of Sports Physiology and Performance, 17(12), 1706.

30. Manna, A., Vidgen, H. A., & Gallegos, D. (2024). Examining the effectiveness of food literacy interventions in improving food literacy behavior and healthy eating among adults belonging to different socioeconomic groups- a systematic scoping review. Systematic Reviews, 13(1).

31. Martinho, D. V., Field, A., Naughton, R. J., Ribeiro, A. S., Rebelo, A., Gouveia, É. R., & Sarmento, H. (2024). Nutritional perspectives in female soccer: a scoping review [Review of Nutritional perspectives in female soccer: a scoping review]. Journal of the International Society of Sports Nutrition, 21(1). Springer Science+Business Media.

32. Masfi, A., Triharini, M., Sukartini, T., Rahmatika, Q. T., Aditya, R. S., Evi, N., Ramadhan, M. P., Widjayanti, Y., Sunaryo, E. Y. A. B., Afiani, N., & Santi, N. F. (2024). Advancing physical activity management in nursing: a systematic literature review on educational interventions and technology integration. Retos, 62, 827.

33. McCleery, J., Diamond, E., Kelly, R. K., Li, L., Ackerman, K. E., Adams, W. M., & Kraus, E. (2024). Centering the female athlete voice in a sports science research agenda: a modified Delphi survey with Team USA athletes. British Journal of Sports Medicine, 58(19), 1107.

34. McHaffie, S. J., Langan-Evans, C., Strauss, J. A., Areta, J. L., Rosimus, C., Evans, M., Waghorn, R., & Morton, J. P. (2023). Under-Fuelling for the Work Required? Assessment of Dietary Practices and Physical Loading of Adolescent Female Soccer Players during an Intensive International Training and Game Schedule. Nutrients, 15(21), 4508.

35. McNulty, K. L., Elliott-Sale, K. J., Dolan, E., Swinton, P., Ansdell, P., Goodall, S., Thomas, K., & Hicks, K. M. (2020). The Effects of Menstrual Cycle Phase on Exercise Performance in Eumenorrheic Women: A Systematic Review and Meta-Analysis [Review of The Effects of Menstrual Cycle Phase on Exercise Performance in Eumenorrheic Women: A Systematic Review and Meta-Analysis]. Sports Medicine, 50(10), 1813. Springer Science+Business Media.

36. Meignié, A., Duclos, M., Carling, C., Orhant, E., Provost, P., Toussaint, J., & Antero, J. (2021). The Effects of Menstrual Cycle Phase on Elite Athlete Performance: A Critical and Systematic Review [Review of The Effects of Menstrual Cycle Phase on Elite Athlete Performance: A Critical and Systematic Review]. Frontiers in Physiology, 12. Frontiers Media.

37. Mercer, D., Convit, L., Condo, D., Carr, A. J., Hamilton, D. L., Slater, G., & Snipe, R. M. J. (2020). Protein Requirements of Pre-Menopausal Female Athletes: Systematic Literature Review [Review of Protein Requirements of Pre-Menopausal Female Athletes: Systematic Literature Review]. Nutrients, 12(11), 3527. Multidisciplinary Digital Publishing Institute.

38. Nomura-Sakata, A. I., Mogrovejo-Navas, C. I., Navarro-Grau, A., & Zafra-Tanaka, J. H. (2020). The effect of mobile applications for menstrual cycle or fertility trackers on women's health: protocol for a systematic review [Review of The effect of mobile applications for menstrual cycle or fertility trackers on women's health: protocol for a systematic review]. medRxiv (Cold Spring Harbor Laboratory). Cold Spring Harbor Laboratory.

39. Oosthuyse, T., Strauss, J. A., & Hackney, A. C. (2022). Understanding the female athlete: molecular mechanisms underpinning menstrual phase differences in exercise metabolism [Review of Understanding the female athlete: molecular mechanisms underpinning menstrual phase differences in exercise metabolism]. European Journal of Applied Physiology. Springer Science+Business Media.

40. Pearson, A. G., Alexander, L., Witard, O. C., Coughlin, T. E., Tipton, K. D., & Walshe, I. H. (2020). A hypoenergetic diet with decreased protein intake does not reduce lean body mass in trained females. European Journal of Applied Physiology, 121(3), 771.

41. Renard, M., Kelly, D. T., Chéilleachair, N. N., & Catháin, C. Ó. (2021). How Does the Dietary Intake of Female Field-Based Team Sport Athletes Compare to Dietary Recommendations for Health and Performance? A Systematic Literature Review [Review of How Does the Dietary Intake of Female Field-Based Team Sport Athletes Compare to Dietary Recommendations for Health and Performance? A Systematic Literature Review. Nutrients, 13(4), 1235. Multidisciplinary Digital Publishing Institute.

42. Rocha-Rodrigues, S., Sousa, M., Reis, P. L., Leão, C., Cardoso-Marinho, B., Massada, M., & Afonso, J. (2021). Bidirectional Interactions between the Menstrual Cycle, Exercise Training, and Macronutrient Intake in Women: A Review [Review of Bidirectional Interactions between the Menstrual Cycle, Exercise Training, and Macronutrient Intake in Women: A Review]. Nutrients, 13(2), 438. Multidisciplinary Digital Publishing Institute.

43. Rogan, M. M., & Black, K. (2022). Dietary energy intake across the menstrual cycle: a narrative review [Review of Dietary energy intake across the menstrual cycle: a narrative review]. Nutrition Reviews, 81(7), 869. Oxford University Press.

44. Sánchez-García, J. C., López-Hernández, D., Piqueras-Sola, B., Cortés-Martín, J., Reinoso-Cobo, A., Menor-Rodríguez, M. J., & Rodríguez-Blanque, R. (2023). Physical Exercise and Dietary Supplementation in Middle-Aged and Older Women: A Systematic Review [Review of Physical Exercise and Dietary Supplementation in Middle-Aged and Older Women: A Systematic Review]. Journal of Clinical Medicine, 12(23), 7271. Multidisciplinary Digital Publishing Institute.

@ 2026 Wah Academia Journal of Society, Culture and Policy. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license https://creativecommons.org/licenses/cc-by/4.0/

45. Shahid, W., Noor, R., & Bashir, M. S. (2024). Effects of exercise on sex steroid hormones (estrogen, progesterone, testosterone) in eumenorrheic females: A systematic to review and meta-analysis. BMC Women s Health, 24(1).

46. Siddique, M., Ingraham, C., Kudish, B., Iglesia, C. B., & Polland, A. (2019). Hydronephrosis Associated With Pelvic Organ Prolapse: A Systematic Review. Female Pelvic Medicine & Reconstructive Surgery, 26(3), 212.

47. Sims, S. T., & Heather, A. K. (2018). Myths and Methodologies: Reducing scientific design ambiguity in studies comparing sexes and/or menstrual cycle phases [Review of Myths and Methodologies: Reducing scientific design ambiguity in studies comparing sexes and/or menstrual cycle phases]. Experimental Physiology, 103(10), 1309. Wiley.

48. Sims, S. T., Kerksick, C. M., Smith-Ryan, A. E., Jonge, X. J. de, Hirsch, K. R., Arent, S. M., Hewlings, S., Kleiner, S. M., Bustillo, E., Tartar, J. L., Starratt, V. G., Kreider, R. B., Greenwalt, C. E., Rentería, L. I., Ormsbee, M. J., VanDusseldorp, T. A., Campbell, B., Kalman, D., & António, J. (2023). International society of sports nutrition position stand: nutritional concerns of the female athlete [Review of International society of sports nutrition position stand: nutritional concerns of the female athlete]. Journal of the International Society of Sports Nutrition, 20(1). Springer Science+Business Media.

49. Smith-Ryan, A. E., Cabre, H. E., & Moore, S. R. (2022). Active Women Across the Lifespan: Nutritional Ingredients to Support Health and Wellness [Review of Active Women Across the Lifespan: Nutritional Ingredients to Support Health and Wellness]. Sports Medicine, 52, 101. Springer Science+Business Media.

50. Sousa, M. V. de, Lundsgaard, A., Christensen, P. M., Christensen, L., Randers, M. B., Mohr, M., Nybo, L., Kiens, B., & Fritzen, A. M. (2021). Nutritional optimization for female elite football players—topical review. Scandinavian Journal of Medicine and Science in Sports, 32, 81.

51. Spriet, L. L. (2022). Diet and Nutraceuticals for Mental and Physical Performance in Athletes. Sports Medicine, 52, 1.

52. Taipale, R. S., Ihalainen, J. K., Hackney, A. C., & Häkkinen, K. (2023). Perspectives on Concurrent Strength and Endurance Training in Healthy Adult Females: A Systematic Review [Review of Perspectives on Concurrent Strength and Endurance Training in Healthy Adult Females: A Systematic Review]. Sports Medicine, 54(3), 673. Springer Science+Business Media.

53. Vieira, L. H. P., Clemente, F. M., Marquez, F. A. C., Olivares, W. M. R., Villafuerte, K. R. V., & Carpes, F. P. (2024). Are wearable technologies accurate enough to assessment of soccer kicking: Protocol for a systematic literature review (Preprint). JMIR Research Protocols, 13.

54. Welde, B., Kellawan, J. M., Larson, R., Morseth, B., Osborne, J. O., & Sandbakk, Ø. (2024). Editorial: The physiology of the female athlete—performance, health, and recovery. Frontiers in Sports and Active Living, 6.

55. Wohlgemuth, K. J., Arieta, L. R., Brewer, G. J., Hoselton, A., Gould, L. M., & Smith-Ryan, A. E. (2021). Sex differences and considerations for female-specific nutritional strategies: a narrative review [Review of Sex differences and considerations for female-specific nutritional strategies: a narrative review]. Journal of the International Society of Sports Nutrition, 18(1). Springer Science+Business Media.

56. Zou, M., Northstone, K., Perry, R., Johnson, L., & Leary, S. (2019). The impact of later eating rhythm on childhood adiposity: protocol for a systematic review [Review of The impact of later eating rhythm on childhood adiposity: protocol for a systematic review]. Systematic Reviews, 8(1). BioMed Central.

Declarations:

Authors' Contribution:

- All Authors: Conceptualization, data collection, interpretation, drafting of the manuscript and intellectual revisions
- The authors agree to take responsibility for every facet of the work, making sure that any concerns about its integrity or veracity are thoroughly examined and addressed
- There is no specific funding pertaining to this study from any funding agency in the public, commercial or not-for-profit sectors. Dedicated funding streams for systematic exploration of female-specific athletic nutrition and physiology, as an under-funded area of research [54], may be one of the things that future studies can benefit from.
- Written/electronic informed consent was obtained from all participants.
- Approved by the Department of Sports Science and Physical Education, Punjab University (Protocol #2024-DSS-115)

Conflict of Interest: NIL

Funding Sources: NIL

Intersections of Knowledge: Dialogues Across Disciplines
https://org.wahacademia.com/publications/

Chapter Five

The importance of digitalization in environmental research in the age of Artificial Intelligence

Bolat Seidanov[1], Kadyrbek Magzomov[2], Batuhan Selamoglu[3] and Zeliha Selamoglu[4]

[1] Al-Farabi Kazakh National University, Faculty of Biology and Biotechnology, Almaty, Kazakhstan
[2] Department of Biology, Faculty of Sciences, Khoja Akhmet Yassawi International Kazakh-Turkish University, Turkestan, Kazakhstan
[3] Department of Electronics Technology, Istanbul Arel University, Istanbul, Türkiye / Mersin University, Institute of Science, Electrical and Electronic Engineering, Mersin, Türkiye
[4] Department of Medical Biology, Medicine Faculty, Nigde Omer Halisdemir University, Nigde, Türkiye / Khoja Akhmet Yassawi International Kazakh-Turkish University, Faculty of Sciences / Department of Biology, Central Campus, Turkestan, Kazakhstan

https://orcid.org/0000-0001-9056-6435[4]

Keywords

Artificial Intelligence, Big Data, Digitalization, Environmental Monitoring, Internet of Things, Remote Sensing, Sustainable Development Goals

Abstract

The convergence of digitalization and artificial intelligence (AI) is fundamentally reshaping environmental research, creating unprecedented opportunities for monitoring, analyzing, and managing Earth's complex ecosystems. This chapter examines the transformative role of digital technologies—including the Internet of Things (IoT), big data analytics, remote sensing, and open data platforms—in advancing environmental science within the contemporary AI era. Drawing on a comprehensive synthesis of recent literature, we demonstrate how digitalization enhances environmental research through improved data acquisition, real-time monitoring, predictive modeling, and evidence-based decision-making. Key applications span climate change mitigation, biodiversity conservation, water quality management, air pollution control, and disaster risk reduction. However, the chapter also critically examines persistent challenges including data quality issues, interoperability constraints, spatial autocorrelation biases, algorithmic interpretability limitations, and ethical concerns surrounding data privacy and algorithmic fairness. Through systematic analysis of successful case studies from diverse geographical contexts, we identify best practices for integrating digital technologies into environmental research frameworks. The chapter concludes by outlining future research directions, emphasizing the need for explainable AI, physics-informed machine learning, federated learning architectures, and robust validation protocols that account for the unique characteristics of environmental data. Ultimately, this synthesis demonstrates that digitalization—when implemented with appropriate safeguards and methodological rigor—represents an indispensable pathway for addressing pressing environmental challenges in the Anthropocene.

Introduction

The twenty-first century has witnessed an unprecedented acceleration of environmental degradation, driven by industrialization, urbanization, and unsustainable resource exploitation [18]. Climate change, biodiversity loss, water scarcity, and air pollution represent interconnected crises that demand urgent, evidence-based interventions. Traditional environmental research methods-characterized by manual sampling, laboratory analysis, and intermittent monitoring-have proven inadequate for capturing the spatial and temporal complexity of these phenomena [13]. The limitations of conventional approaches include high operational costs, extended processing times, limited spatial coverage, and susceptibility to human error, all of which constrain the ability of researchers and policymakers to respond effectively to emerging environmental threats.

In response to these challenges, digitalization has emerged as a transformative force in environmental research. Digitalization-the integration of digital technologies into research workflows-encompasses a diverse array of tools including the Internet of Things (IoT), big data analytics, cloud computing, remote sensing platforms, and open data infrastructures [3]. These technologies collectively enable the collection, processing, and dissemination of environmental data at scales previously unimaginable. When combined with artificial intelligence (AI) and machine learning (ML) algorithms, digitalized environmental systems gain the capacity to learn from data, identify complex patterns, generate accurate predictions, and support autonomous decision-making [11]. Furthermore, machine learning provides a powerful suite of tools capable of optimizing complex systems, identifying hidden environmental patterns, and effectively tackling climate change across diverse global sectors [15].

Address correspondence to Bolat Seidanov, Al-Farabi Kazakh National University, Faculty of Biology and Biotechnology, Almaty, Kazakhstan
bolatseidanov@gmail.com (Bolat Seidanov).

ISBN 978 627 7901 23 3
@ 2026 Intersections of Knowledge: Dialogues Across Disciplines. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/cc-by/4.0/).

The importance of digitalization in environmental research cannot be overstated. As urban populations continue to grow-projected to reach 68% of the global population by 2050-cities face mounting pressures on transportation systems, energy grids, water resources, and waste management infrastructure [12]. Digital technologies offer pathways for optimizing these systems while minimizing environmental impacts. Moreover, the scale and urgency of climate-related disasters-floods, wildfires, heatwaves, and storms-demand real-time monitoring and predictive capabilities that only digitalized systems can provide [4].

This chapter provides a comprehensive examination of digitalization's role in environmental research within the contemporary AI era. We synthesize findings from the diverse literature provided by the user, integrating perspectives from remote sensing, IoT, big data analytics, open data policy, and environmental security studies. The chapter is structured as follows: Section 2 examines the digital environmental data ecosystem, including sensor technologies, remote sensing platforms, and data management frameworks. Section 3 explores AI paradigms and analytical techniques relevant to environmental applications. Section 4 presents key application domains where digitalization has demonstrated significant impact. Section 5 critically analyzes challenges and limitations. Section 6 discusses future directions and emerging trends. Section 7 concludes with synthesized recommendations for researchers and practitioners.

The Digital Environmental Data Ecosystem

❖ Remote Sensing and Earth Observation

Remote sensing constitutes the foundation of global environmental monitoring, providing systematic observations of Earth's surface and atmosphere across multiple spatial, spectral, and temporal scales [10]. The past decade has witnessed a dramatic transformation in Earth observation capabilities, driven by the proliferation of satellite missions, the emergence of commercial constellations, and the development of cloud-based processing platforms. Public missions from NASA, the European Space Agency, and other national space agencies offer long-term, consistent data streams essential for trend analysis and cross-border comparability. Concurrently, commercial providers such as Planet Labs and Maxar deliver higher spatial resolution and more frequent revisits, enabling near-real-time monitoring of rapidly changing phenomena including disaster impacts, infrastructure development, and illegal resource extraction [7].

The diversity of observation modalities available to environmental researchers represents both a resource and a complexity challenge. Optical imagery provides intuitive, high-information content observations of land cover, vegetation health, and surface features, but remains limited by cloud cover and illumination conditions. Synthetic aperture radar (SAR) overcomes these limitations by operating in all-weather, day-night conditions and provides structure- and moisture-sensitive data valuable for flood mapping, deformation monitoring, and forest structure inference [10]. Thermal infrared measurements capture surface temperature and energy budget information, supporting applications in urban heat island assessment, evapotranspiration estimation, and drought monitoring. LiDAR (Light Detection and Ranging) records three-dimensional vegetation structure and building morphology, enabling accurate biomass estimation and habitat characterization. Hyperspectral sensors resolve hundreds of spectral bands, allowing discrimination of vegetation species, mineral types, and water quality parameters. Advanced algorithms, particularly deep learning, are increasingly required to unlock the full potential of these vast remote sensing datasets and fuse varying modalities effectively [20].

The integration of these diverse modalities through multi-sensor fusion has become a structural necessity for operational environmental monitoring. Optical and SAR integration maintains monitoring continuity during persistent cloud cover. Thermal observations combined with optical and meteorological data enhance evapotranspiration and drought stress information. LiDAR-derived structure augments land cover interpretation, while nighttime lights provide long-term proxies for human activity and electrification [10]. However, fusion complexity requires careful attention to resolution differences, acquisition geometries, spectral response variations, and temporal sampling to ensure transparent and interpretable products.

❖ Internet of Things and In Situ Sensing

While remote sensing provides synoptic coverage, IoT-based in situ sensing delivers high-frequency, localized measurements essential for calibrating satellite products and capturing micro-environmental variability [11]. IoT environmental monitoring systems typically comprise networks of interconnected sensors that continuously measure parameters including temperature, humidity, air quality (PM2.5, PM10, NO2, O3), water quality (pH, dissolved oxygen, turbidity, conductivity), soil moisture, and noise levels. These sensors transmit data via communication protocols such as Wi-Fi, LoRaWAN, NB-IoT, or cellular networks to centralized platforms for storage, analysis, and visualization [6].

The integration of IoT with AI creates what researchers term the Artificial Intelligence of Things (AIoT), where intelligent algorithms operate at the network edge or in the cloud to process streaming data, detect anomalies, and trigger automated responses. For example, smart water quality monitoring systems deploy IoT sensors at multiple points within watersheds to collect real-time data on pH, turbidity, dissolved oxygen, and contaminant levels. AI agents analyze these data to identify pollution events, predict water quality trends, and alert authorities when parameters exceed safe thresholds [11]. Similarly, smart air quality networks integrate low-cost particulate matter sensors with machine learning calibration models to generate high-resolution pollution maps that inform public health interventions [13].

The scalability and flexibility of IoT-based systems represent significant advantages over traditional monitoring approaches. IoT networks can be expanded incrementally by adding sensors to cover larger geographical areas or additional environmental parameters. Edge computing capabilities allow preliminary data processing at the source, reducing latency and bandwidth consumption while enabling rapid initial analyses. However, the deployment of IoT systems in remote or resource-limited environments faces substantial challenges including reliable power supply, connectivity constraints, sensor drift, and maintenance requirements [13]. Energy harvesting solutions, low-power wide-area networks, and robust maintenance protocols are essential for long-term operational sustainability.

❖ Big Data Architectures and Cloud Platforms

The massive volumes of data generated by remote sensing and IoT systems require specialized architectures for storage, processing, and analysis. Big data technologies-including Hadoop Distributed File System (HDFS), Apache Spark, and NoSQL databases such as MongoDB and HBase-provide the scalable infrastructure necessary for handling environmental data characterized by high volume, velocity, variety, and veracity [6]. Cloud computing platforms, particularly Google Earth Engine, which has fundamentally revolutionized planetary-scale geospatial analysis [5], alongside Microsoft Planetary Computer and Amazon Web Services, have democratized access to Earth observation data by hosting petabyte-scale archives and

providing integrated development environments for large-scale analysis [10].

The shift toward cloud-native processing fundamentally alters the economics of environmental analytics. Users can compute where data reside rather than transferring massive datasets locally, reducing costs and enabling large-scale iteration. This transformation facilitates operational monitoring, reproducibility through standardized environments, and capacity building in resource-constrained institutions. However, cloud dependence also creates platform availability dependencies, cost structure uncertainties, and technical capacity requirements that may exacerbate existing inequalities between well-resourced and developing country institutions [7].

Data readiness and interoperability represent critical determinants of whether raw observations translate into decision-grade information. Harmonization-the integration of observations from multiple sensors and missions into consistent time series with standardized definitions-requires cross-sensor radiometric consistency, stable classification nomenclatures, well-documented retrieval algorithms, and transparent processing histories [10]. Semantic interoperability further demands consistent conceptual definitions that link Earth observation products to policy-relevant measures. Without such standardization, products may be incomparable across regions or time periods, undermining their utility for sustainability monitoring and reporting.

❖ Open Data Policies and Governance

The effectiveness of digitalized environmental research depends fundamentally on policies governing data access, sharing, and reuse. Open data-defined as data that can be freely used, reused, and redistributed by anyone subject only to attribution and share-alike requirements-has gained substantial momentum among governments, international organizations, and funding agencies [7]. The G8 Open Data Charter, European Union Public Sector Information Directive, and US Open Data Policy all articulate principles of openness by default, recommending that publicly funded data be made available with minimal restrictions and at no cost to users. Moreover, the integration of public data platforms has been shown to directly enhance urban ecological resilience by making data more transparent, accessible, and actionable for green initiatives [19].

Within the Earth observation sector, open data policies have been implemented with varying degrees of completeness. The Copernicus program of the European Union mandates full, free, and open access to Sentinel mission data and information products, with no restrictions on commercial or non-commercial use and no discrimination between European and non-European users [7]. Similarly, the US Landsat program has provided free and open access to its entire archive since 2008, stimulating the development of commercial markets for value-added services. The GEOSS Data Sharing Principles require full and open exchange of data, metadata, and products with minimum time delay and cost, while recognizing relevant international instruments and national policies.

However, open data policies are not without limitations and exceptions. National security concerns, commercial confidentiality, privacy protections, and intellectual property rights all justify access restrictions in specific circumstances. The extensive list of potential exceptions-international law, foreign policy, defense, personal data protection, statistical confidentiality, indigenous rights, conservation of sensitive ecological resources-creates uncertainty for both providers and users regarding the real extent of open access [7]. Moreover, the use of licenses to govern data access, while providing legal clarity, also creates administrative hurdles that may deter especially individual and scientific users.

The equity implications of open data policies deserve careful consideration. While open access reduces barriers for well-resourced institutions, asymmetries in technical capacity, computing infrastructure, and training opportunities may mean that open data benefits accrue disproportionately to actors in wealthy nations [4]. Capacity building programs, technology transfer partnerships, and co-design processes that involve local stakeholders in product development are essential for ensuring that digitalization contributes to, rather than undermines, equitable environmental governance.

Artificial Intelligence Paradigms for Environmental Research

❖ Machine Learning Fundamentals

Machine learning (ML)-a subset of AI concerned with algorithms that learn from data without explicit programming-has become ubiquitous in environmental research [2]. ML algorithms can be categorized into three primary paradigms based on their learning approaches. Supervised learning trains models using labeled datasets where input-output pairs are provided, enabling prediction of outcomes for new inputs. This paradigm dominates applications requiring classification (e.g., land cover mapping) or regression (e.g., biomass estimation). Unsupervised learning identifies hidden structures or patterns within unlabeled datasets, supporting dimensionality reduction, clustering, and anomaly detection. Semi-supervised learning combines limited labeled data with abundant unlabeled data to improve model performance, particularly valuable in environmental contexts where ground truth labels are expensive or difficult to obtain. Reinforcement learning trains agents to make sequential decisions by interacting with environments and receiving reward signals, with emerging applications in adaptive resource management and conservation planning [2].

The choice of ML algorithm for a specific environmental application depends on multiple factors including data characteristics, computational resources, interpretability requirements, and the nature of the prediction task. Decision trees and random forests-ensemble methods combining multiple decision trees-are widely used for species distribution modeling, land cover classification, and ecological forecasting due to their ability to handle mixed data types, capture nonlinear relationships, and provide variable importance measures [2]. Support vector machines excel at classification tasks with high-dimensional data and have been extensively applied to remote sensing image analysis. Gradient boosting machines, including XGBoost and LightGBM, often achieve state-of-the-art performance on structured environmental datasets through sequential optimization of weak learners.

❖ Deep Learning and Neural Architectures

Deep learning (DL)-characterized by artificial neural networks with multiple hidden layers-has revolutionized environmental applications involving image, audio, and time-series data [2]. Convolutional neural networks (CNNs) extract hierarchical spatial features from imagery, enabling automated detection of deforestation, infrastructure mapping, wildlife identification from camera traps, and coral reef health assessment. Recurrent neural networks (RNNs) and long short-term memory (LSTM) networks capture temporal dependencies in sequential data, supporting streamflow prediction, air quality forecasting, and climate anomaly detection. The U-Net architecture,

@ 2026 Wah Academia Journal of Society, Culture and Policy. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license https://creativecommons.org/licenses/cc-by/4.0

with its encoder-decoder structure and skip connections, has become the standard for semantic segmentation of satellite imagery, including flood extent mapping and land cover classification. This is crucial for pushing the boundaries of data-driven Earth system science and advancing our fundamental process understanding [14].

The emergence of foundation models and self-supervised learning represents a paradigm shift in Earth observation analytics. Rather than training task-specific models on small labeled datasets, foundation models learn general-purpose representations from large unlabeled archives, enabling transfer learning across sensors, geographies, and tasks with minimal fine-tuning [10]. This approach is particularly valuable for environmental applications where labeled data are scarce, unevenly distributed, or costly to acquire. However, foundation models also introduce new challenges including geographic and socioeconomic sampling biases encoded in pretraining data, unpredictable out-of-distribution behavior, and the erosion of transparency regarding what models are actually learning.

Deep learning's computational demands raise important sustainability concerns. Training large models consumes substantial energy, with associated carbon emissions that may offset the environmental benefits of AI applications. The trend toward ever-larger models has prompted calls for "Green AI" research focused on efficient architectures, model compression, knowledge distillation, and careful justification of computational expenditure relative to application requirements [13].

❖ Physics-Informed and Hybrid Approaches

A persistent challenge in purely data-driven environmental modeling is susceptibility to spurious correlations and shortcuts that lack causal validity, particularly problematic under non-stationary conditions where historical relationships may not hold [9]. Physics-informed machine learning addresses this limitation by incorporating physical constraints, conservation laws, and domain knowledge into learning systems. Practically, this may involve including physically meaningful variables, designing physically constrained loss functions, integrating Earth observation inference with process models, or ensuring consistency with known geophysical relationships [8].

Physics-informed approaches enhance credibility and extrapolation capacity-essential when Earth observation products inform long-term decisions under changing climate regimes. Stakeholders require not merely predictive accuracy under historically observed conditions but demonstration that outputs will remain sensible as environmental conditions evolve [9]. Hybridization may also increase interpretability by aligning model components with physical concepts familiar to users, facilitating communication across scientific, policy, and practitioner communities. However, hybrid approaches inherit uncertainties from both data-driven and physical components, and may introduce complexity that challenges auditing and validation.

❖ Spatial and Temporal Considerations

Environmental data exhibit unique characteristics that distinguish environmental ML from standard applications. Spatial autocorrelation-the tendency for nearby locations to have similar values-violates the independence assumption of many statistical methods and, if unaddressed, can lead to overoptimistic performance estimates [9]. Spatial cross-validation, which splits data into blocks around central points of the dependence structure, provides more realistic accuracy assessments than random cross-validation by ensuring validation folds are statistically independent of training data.

Temporal dynamics add further complexity. Environmental processes are non-stationary, with baselines shifting due to climate change, land use change, and policy interventions. Models trained on historical data may fail under novel conditions, necessitating drift detection and adaptive updating protocols. The challenge of balancing spatial and temporal variability arises when tracking phenomena affected by environmental changes-models must capture target phenomena consistently rather than learning generally irrelevant dependencies based on unreliable observation timelines [9].

Uncertainty quantification is particularly critical for environmental applications where decisions have high stakes. Two primary types of uncertainty exist: aleatory uncertainty arising from inherent data variability and epistemological uncertainty originating from knowledge limitations. Ensemble methods, Bayesian approaches, and conformal prediction provide frameworks for estimating predictive uncertainty. However, uncertainty is often documented in ways that cannot be acted upon-generic confidence scores inadequately calibrated across geographies or failure to separate measurement uncertainty from model uncertainty. Developing calibrated uncertainty estimates useful under domain shift, communicating uncertainty in decision-relevant terms, and establishing product standards where uncertainty and limitations are key outputs represent important research priorities [9].

Applications of Digitalization in Environmental Research

❖ Climate Change Monitoring and Prediction

Digital technologies have transformed climate science by enabling comprehensive observation of Earth's climate system and projection of future trajectories under alternative emission scenarios. Earth observation satellites provide systematic measurements of essential climate variables including temperature, precipitation, sea ice extent, glacier mass balance, and atmospheric composition [10]. These measurements feed into numerical climate models that simulate physical processes across spatial scales from global to regional. Machine learning enhances climate modeling by emulating computationally expensive subgrid processes, bias-correcting model outputs against observations, and generating probabilistic forecasts of extreme events.

AI-powered climate analytics support both mitigation and adaptation efforts. On the mitigation side, AI optimizes renewable energy integration into electricity grids, improves building energy efficiency, and monitors land use change and deforestation emissions [15]. On the adaptation side, AI enhances seasonal forecasting of drought and flood risk, supports climate-resilient agricultural planning, and identifies vulnerable populations and infrastructure for targeted interventions [18]. However, the high energy demands of AI applications, particularly if powered by non-renewable sources, can undermine climate benefits-a paradox requiring careful attention to the carbon footprint of AI itself.

❖ Water Quality and Resource Management

Freshwater resources face unprecedented pressures from pollution, over-extraction, and climate change, making effective monitoring and management essential. IoT-based water quality monitoring systems deploy networks of sensors measuring pH, dissolved oxygen, turbidity, conductivity, temperature, and contaminant concentrations in rivers, lakes, and coastal waters [11]. Machine learning algorithms process these data to detect pollution events, predict water quality trends, and optimize treatment plant operations. In agricultural contexts, smart irrigation systems integrate soil moisture sensors, weather forecasts, and crop models to optimize water application, reducing waste and preventing nutrient runoff.

Satellite remote sensing provides complementary capabilities for monitoring surface water extent, quality, and dynamics. Optical sensors

detect algal blooms and sediment plumes, while SAR provides all-weather flood mapping. Thermal imagery supports evapotranspiration estimation and irrigation scheduling. The integration of multi-sensor data with hydrological models enables water balance accounting, drought early warning, and transboundary water governance [10]. However, important water quality parameters including pathogens and many chemical contaminants remain difficult to sense remotely, necessitating integrated monitoring strategies combining satellite, in situ, and laboratory analysis.

❖ Air Quality and Pollution Control

Air pollution represents the single greatest environmental risk to human health, responsible for millions of premature deaths annually. Digital technologies are revolutionizing air quality monitoring by complementing sparse regulatory reference stations with dense networks of low-cost sensors, satellite retrievals of aerosol optical depth and trace gases, and mobile monitoring platforms [13]. Machine learning models integrate these heterogeneous data sources to generate high-resolution, near-real-time air pollution maps that capture intra-urban variability missed by traditional monitoring.

Predictive air quality analytics support public health interventions through several mechanisms. Forecasting models predict pollution episodes days in advance, enabling preemptive measures such as traffic restrictions or industrial curtailments. Source apportionment algorithms identify contributions from different emission categories, guiding targeted abatement strategies. Exposure models estimate population-level and individual-level pollution exposure, supporting epidemiological studies and health impact assessments [18]. However, the deployment of AI for air quality management raises privacy concerns when individual-level mobility data are used for exposure estimation, necessitating careful data governance frameworks.

❖ Biodiversity and Ecosystem Conservation

Biodiversity loss constitutes a global crisis demanding urgent monitoring and intervention. The exponential growth of ecological data offers significant opportunities for conservation planning and sustainability tracking [16]. Digital technologies are transforming conservation through automated species identification, habitat mapping, and threat detection. Camera trap networks generate millions of images annually, far exceeding human capacity for manual classification. Deep learning models, particularly CNNs, automate species identification, individual animal recognition, and behavior classification from camera trap imagery, which has become a central pillar of wildlife conservation [17, 2]. Acoustic monitoring systems use neural networks to identify bird, amphibian, and insect species from soundscape recordings. Environmental DNA (eDNA) metabarcoding combined with machine learning enables non-invasive biodiversity assessment from water, soil, or air samples.

Remote sensing supports habitat monitoring at landscape to global scales. Satellite time series detect deforestation, degradation, and fragmentation. LiDAR data characterize three-dimensional habitat structure critical for many species. Integration of Earth observation with species occurrence records enables habitat suitability modeling, conservation prioritization, and assessment of protected area effectiveness [18]. However, the biodiversity-AI interface also presents risks, including the potential for increased access to species location data facilitating illegal collecting or poaching. Responsible deployment requires careful attention to data governance, threat assessment, and stakeholder engagement.

❖ Disaster Risk Reduction and Response

Natural disasters-floods, wildfires, cyclones, earthquakes, and landslides-cause devastating human and economic losses, with climate change expected to increase their frequency and intensity. Digital technologies enhance disaster risk reduction through improved hazard forecasting, exposure mapping, and early warning. Machine learning models predict flood extent and depth using rainfall forecasts, topographic data, and real-time river gauge readings [18]. Wildfire danger ratings integrate weather forecasts, fuel moisture estimates, and ignition risk factors. Earthquake early warning systems use seismic networks and real-time processing to provide seconds to minutes of warning before shaking arrives.

During disaster response, Earth observation provides situational awareness through pre- and post-event imagery. SAR penetrates clouds and darkness to map flood extent. Optical imagery identifies damaged infrastructure and displaced populations. Social media data and crowdsourced reports complement satellite observations, though information quality and verification remain challenges. AI algorithms automate damage assessment by comparing pre- and post-event imagery, enabling rapid prioritization of response efforts [10]. However, disaster applications involve trade-offs between timeliness and accuracy-initial products enabling immediate action may rely on simplified assumptions, while more refined assessments supporting recovery planning require additional validation.

❖ Sustainable Urban and Infrastructure Planning

Urban areas concentrate environmental pressures and vulnerabilities while also offering opportunities for efficiency gains through smart city technologies. Digitalization supports sustainable urban planning through monitoring of urban growth, land use change, and infrastructure expansion [12]. Remote sensing time series track urban sprawl, impervious surface increase, and green space loss. Nighttime lights provide proxies for economic activity and electrification. Integration with census and administrative data enables analysis of environmental equity-whether pollution exposure and green space access are distributed fairly across population groups.

Smart city technologies optimize urban resource flows while reducing environmental footprints. The foundation of these smart initiatives relies heavily on scalable IoT architectures designed specifically for urban environments [1]. Smart grids integrate renewable energy, manage demand response, and accommodate electric vehicle charging. Intelligent transportation systems reduce congestion and emissions through adaptive traffic signal control, route guidance, and multimodal trip planning. Smart water systems detect leaks, optimize pressure, and reduce energy consumption. Building energy management systems use occupancy sensing and predictive control to minimize heating, cooling, and lighting loads [12]. Furthermore, opening public data platforms plays a vital role in tracking these variables and accelerating the transition toward more resilient and green urban infrastructures [19]. However, smart city deployments raise privacy and surveillance concerns that must be addressed through transparent governance and citizen engagement.

Challenges and Limitations

❖ Data Quality, Availability, and Representativeness

The effectiveness of AI for environmental applications depends critically on the quality and representativeness of training data. Environmental datasets frequently suffer from missing values,

@ 2026 Wah Academia Journal of Society, Culture and Policy. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license https://creativecommons.org/licenses/cc-by/4.0

measurement errors, inconsistent protocols, and sampling biases that can significantly impact model accuracy and reliability [9]. Ground truth data-essential for supervised learning-are particularly scarce in remote regions, developing countries, and for rare events or species. This scarcity systematically disadvantages already data-poor areas, potentially leading to a "rich get richer" dynamic where AI benefits accrue disproportionately to well-monitored regions.

Data imbalance-where some classes or conditions are vastly overrepresented relative to others-poses additional challenges. In disaster prediction, for example, non-event observations vastly outnumber event observations, making it difficult for models to learn to predict rare but high-impact events. Solutions include data-level approaches (oversampling minority classes, undersampling majority classes, synthetic data generation), model-level approaches (cost-sensitive learning, anomaly detection algorithms), and combined approaches (SMOTEBoost, RUSBoost) [9]. However, each approach has limitations, and the optimal strategy depends on specific application characteristics.

❖ Spatial Autocorrelation and Generalization

Spatial autocorrelation-the tendency for nearby locations to have similar values-represents a fundamental challenge for environmental ML. When training and test data are spatially correlated, model performance estimates may be artificially inflated, leading to overoptimistic expectations for deployment to new locations [9]. Studies that fail to account for spatial dependence have reported substantially higher accuracy than is achievable when models are tested on spatially independent data. Spatial cross-validation, which partitions data by geographic blocks rather than random samples, provides more realistic performance estimates but may be overly pessimistic by only validating areas far from calibration points.

The related challenge of domain shift arises when models trained in one geographic, seasonal, or sensor context are applied to different conditions. A deforestation detector trained in the Amazon may perform poorly in Southeast Asia due to differences in forest structure, cloud regimes, and land use practices. A crop classification model trained on one year's data may fail in subsequent years due to phenological shifts or changing management practices. Addressing domain shift requires careful attention to transfer learning, domain adaptation, and continual learning approaches that update models as new data become available [9].

❖ Interpretability and Trust

Many AI models, particularly deep neural networks, operate as "black boxes" whose internal workings are opaque to users. This lack of interpretability poses challenges for environmental applications where stakeholders require understanding of why predictions are made to trust and act upon them [2]. A water manager may be reluctant to release reservoir storage based on an AI forecast they cannot explain. A conservation agency may hesitate to allocate scarce resources based on habitat suitability predictions whose reasoning is unclear. Regulatory and legal contexts may require explainable decisions for accountability purposes.

Explainable AI (XAI) research aims to address this limitation through techniques including feature importance analysis, saliency mapping, counterfactual explanations, and surrogate models. However, XAI methods have limitations-feature attributions may be unstable or misleading, and simplified explanations may not capture model complexity. Moreover, interpretability requirements vary across stakeholders, from technical experts needing to validate model behavior to policymakers requiring high-level summaries to community members seeking to understand decisions affecting them [2]. Developing context-appropriate explanation interfaces remains an active research area.

❖ Ethical and Governance Considerations

The deployment of AI for environmental applications raises ethical concerns spanning privacy, bias, accountability, and dual-use risks. Environmental monitoring increasingly relies on high-resolution imagery and ubiquitous sensing that may incidentally capture sensitive information about individuals, communities, or economic activities [4]. A sensor network monitoring air quality may also record vehicle movements, potentially enabling surveillance. Satellite imagery can reveal informal settlements, artisanal mining, or other activities whose exposure could lead to eviction, enforcement, or conflict.

Algorithmic bias poses risks of environmental injustice. If models perform systematically worse in low-income or minority communities due to under-representation in training data, the resulting evidence may be least reliable where it is most needed for advocacy and resource allocation. Conversely, if models are deployed for enforcement-detecting illegal deforestation, fishing, or waste dumping-bias could lead to disproportionate targeting of marginalized groups [4]. Mitigating these risks requires explicit attention to fairness metrics, stratified performance assessment, and governance frameworks that include affected communities in system design and oversight.

Dual-use risks arise when environmental monitoring technologies are repurposed for harmful ends. A system designed to detect illegal logging could be used to surveil environmental activists. Flood early warning systems could be manipulated to create panic. Satellite imagery and AI analytics could be used to target airstrikes or guide autonomous weapons. While such misuse may seem remote, historical precedents suggest that dual-use concerns warrant serious consideration in technology development and deployment [18].

Future Directions

❖ Foundation Models and Transfer Learning

The emergence of foundation models-large-scale models pretrained on diverse data and fine-tuned for specific tasks-represents a promising direction for democratizing AI for environmental applications. Rather than each research group training models from scratch, foundation models provide transferable representations that can be adapted to new tasks, sensors, and geographies with limited labeled data [10]. This approach is particularly valuable for environmental applications where labeled data are scarce or expensive. However, foundation models must be developed with attention to geographic and temporal representativeness to avoid embedding biases that limit transferability.

❖ Explainable and Causal AI

Advancing explainability for environmental AI requires moving beyond feature attribution toward causal inference. Stakeholders need to understand not just what factors influence predictions but how interventions would change outcomes. Causal machine learning-integrating graphical models, counterfactual reasoning, and structural equation modeling with ML-offers a path toward models that support decision-making under uncertainty [2]. For environmental applications, causal AI could help answer questions such as: Would a proposed policy reduce pollution? Which conservation intervention would most effectively protect biodiversity? How will climate change alter ecosystem services under different emission pathways?

❖ Edge AI and Federated Learning

The computational demands of deep learning conflict with the resource constraints of many environmental monitoring deployments. Edge AI-running models on devices at the network edge rather than in centralized clouds-reduces latency, bandwidth requirements, and cloud dependence. Lightweight architectures, model compression, and hardware acceleration enable inference on battery-powered sensors in remote locations. Federated learning extends this paradigm to training, enabling models to learn from distributed data without centralizing potentially sensitive information [11]. For environmental applications, federated learning could enable collaborative model development across institutions without sharing proprietary or privacy-sensitive data.

❖ Digital Twins for Environmental Systems

Digital twins-dynamic, data-driven representations of physical systems that evolve with their real-world counterparts-represent an emerging paradigm for environmental modeling and decision support. A digital twin of a watershed integrates real-time sensor data, satellite observations, weather forecasts, and hydrological models to simulate water quantity and quality, predict flood risk, and evaluate management scenarios. Digital twins of cities integrate transportation, energy, water, and waste systems to support sustainable urban planning. Digital twins of ecosystems integrate biodiversity monitoring, climate projections, and land use scenarios to assess conservation interventions [10]. Realizing the potential of environmental digital twins requires advances in data integration, model coupling, uncertainty quantification, and human-computer interaction.

Conclusion

This chapter examined the importance of digitalization in environmental research in the AI era, integrating insights from remote sensing, IoT, big data analytics, and machine learning. The findings show that digital technologies are transforming environmental science by enabling large-scale monitoring, advanced analysis, and more informed decision-making.

Key conclusions include: the integration of remote sensing, IoT, and big data has created a global environmental monitoring system across multiple domains; machine learning provides powerful tools for data analysis, with emerging approaches such as foundation models and causal AI offering further potential; applications cover climate change, water and air quality, biodiversity, disaster management, and urban planning; challenges remain, including data quality, model interpretability, and ethical concerns.

To fully realize these benefits, coordinated efforts are needed. Researchers must develop methods suited to complex environmental data, practitioners should expand digital monitoring capacity-especially in underserved regions and policymakers must ensure responsible governance, balancing openness with privacy and equity.

Given the urgency of global environmental issues, digitalization driven by AI is essential for advancing research and sustainable management. The key challenge lies in implementing these technologies effectively, ethically, and inclusively.

References

1. Alavi, A. H., Jiao, P., Butt, W. G., & Gandomi, A. H. (2018). Internet of Things-enabled smart cities: State-of-the-art and future trends. Measurement, 129, 589–606. https://doi.org/10.1016/j.measurement.2018.07.067
2. Cipriano, C., Noce, S., Mereu, S., & Santini, M. (2025). Algorithms going wild – A review of machine learning techniques for terrestrial ecology. Ecological Modelling, 506, 111164. https://doi.org/10.1016/j.ecolmodel.2025.111164
3. Feroz, A. K., Zo, H., & Chiravuri, A. (2021). Digital transformation and environmental sustainability: A review and research agenda. Sustainability, 13(3), 1530. https://doi.org/10.3390/su13031530
4. Francisco, M. (2023). Artificial intelligence for environmental security: National, international, human and ecological perspectives. Current Opinion in Environmental Sustainability, 61, 101250. https://doi.org/10.1016/j.cosust.2022.101250
5. Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, R. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. Remote Sensing of Environment, 202, 18–27. https://doi.org/10.1016/j.rse.2017.06.031
6. Hajjaji, Y., Boulila, W., Farah, I. R., Romdhani, I., & Hussain, A. (2020). Big data and IoT-based applications in smart environments: A systematic review. Computer Science Review, 39, 100318. https://doi.org/10.1016/j.cosrev.2020.100318
7. Harris, R., & Baumann, I. (2015). Open data policies and satellite Earth observation. Space Policy, 32, 44–53. https://doi.org/10.1016/j.spacepol.2015.01.001
8. Karpatne, A., Ebert-Uphoff, I., Ravela, S., Babaie, H. A., & Kumar, V. (2018). Machine learning for the geosciences: Challenges and opportunities. IEEE Transactions on Knowledge and Data Engineering, 31(8), 1544–1554. https://doi.org/10.1109/TKDE.2018.2861006
9. Koldasbayeva, D., Tregubova, P., Gasanov, M., Zaytsev, A., & Burnaev, E. (2024). Challenges and solutions for data-driven geospatial modeling of environmental features. Nature Communications, 15, 55240. https://doi.org/10.1038/s41467-024-55240-8
10. Li, H. (2026). Remote sensing big data for sustainable development: Emerging analytics, applications, and global pathways. Journal of Environmental & Earth Sciences, 8(1), 117–145. https://doi.org/10.30564/jees.v8i1.12936
11. Miller, T., Domańska, I., Kieraś, E., Kaczmarek, P., Łukasik, A., Sokołowska, S., & Nowak, A. (2025). Artificial intelligence agents and Internet of Things for environmental monitoring: A review of water quality and climate data applications. Electronics, 14(4), 696. https://doi.org/10.3390/electronics14040696
12. Ogunkan, D. V., & Ogunkan, S. K. (2023). Exploring big data applications in sustainable urban infrastructure: A review. Urban Governance, 3(1), 54–68. https://doi.org/10.1016/j.ugj.2023.02.003
13. Olawade, D. B., Wada, O. Z., Ige, A. O., Egwebole, B. I., Olojo, A., & Oladapo, B. I. (2024). Artificial intelligence in environmental monitoring: Advancements, challenges, and future directions. Hygiene and Environmental Health Advances, 12, 100096. https://doi.org/10.1016/j.heha.2024.100114
14. Reichstein, M., Camps-Valls, G., Stevens, B., Jung, M., Denzler, J., & Carvalhais, N. (2019). Deep learning and process understanding for data-driven Earth system science. Nature, 566(7743), 195–204. https://doi.org/10.1038/s41586-019-0912-1
15. Rolnick, D., Donti, P. L., Kaack, L. H., Kochanski, K., Lacoste, A., Sankaran, K., ... & Bengio, Y. (2022). Tackling climate change with machine learning. ACM Computing Surveys (CSUR), 55(2), 1–96. https://doi.org/10.1145/3485128
16. Runting, R. K., Phinn, S., Kuempel, C. D., Bingham, H. C., ... & Rhodes, J. R. (2020). Opportunities for big data in conservation and sustainability. Nature Communications, 11(1), 2003. https://doi.org/10.1038/s41467-020-15870-0
17. Tuia, D., Kellenberger, B., Beery, S., Costelloe, B. R., Zuffi, S., Rizescu, R., ... & Berger-Wolf, T. (2022). Perspectives in machine learning for wildlife conservation. Nature Communications, 13(1), 792. https://doi.org/10.1038/s41467-022-27980-y
18. Vinuesa, R., Azizpour, H., Leite, I., Balaam, M., Dignum, V., Domisch, S., Felländer, A., Langhans, S. D., Tegmark, M., & Fuso Nerini, F. (2020). The role of artificial intelligence in achieving the Sustainable Development Goals. Nature Communications, 11, 233. https://doi.org/10.1038/s41467-019-14108-y
19. Yu, Y., & Xu, N. (2026). Making data more open and greener: A study on the pathways of public data platform opening to enhance urban ecological resilience. Sustainability, 18(6), 2764. https://doi.org/10.3390/su18062764
20. Zhu, X. X., Tuia, D., Mou, L., Xia, G. S., Zhang, L., Xu, F., & Fraundorfer, F. (2017). Deep learning in remote sensing: A comprehensive review and list of resources. IEEE Geoscience and Remote Sensing Magazine, 5(4), 8–36. https://doi.org/10.1109/MGRS.2017.2762307

@ 2026 Wah Academia Journal of Society, Culture and Policy. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license https://creativecommons.org/licenses/cc-by/4.0

Declarations:

Authors' Contribution:

- All Authors: Conceptualization, data collection, interpretation, drafting of the manuscript and intellectual revisions
- The authors agree to take responsibility for every facet of the work, making sure that any concerns about its integrity or veracity are thoroughly examined and addressed

Conflict of Interest: NIL

Funding Sources: NIL

Intersections of Knowledge: Dialogues Across Disciplines
https://org.wahacademia.com/publications/

Chapter Six

Making as Method: Practice-Based Research and the Politics of Knowledge Production

Dr. Anne Griffiths [1]

[1] Oxford Brookes University, United Kingdom

Keywords

Practice-based research, Counter-archive, Feminist historiography, Situated knowledge, Domestic craft, Interdisciplinary methodology, Material culture

Abstract

This paper argues that the dialogue between practice-based making and historical inquiry constitutes an interdisciplinary methodology with far-reaching implications for how knowledge is produced, validated, and communicated. Where research agendas increasingly foreground questions of whose knowledge counts and how it has been legitimized, fine art practice offers not merely a perspective but an alternative epistemological framework: one capable of exposing the conditions under which knowledge systems have been constructed, and of proposing what they might look like otherwise. Drawing on Griffiths' doctoral research at the intersection of fine art, feminist historiography, material culture studies, and archival theory, the chapter demonstrates how craft-based practices and historical inquiry exist in a genuinely reciprocal relationship, each transforming the other in ways that neither discipline could achieve alone. Situating the research within the domestic interior as both a historical and methodological framework, and examining how botanical taxonomy reinforced Enlightenment gender hierarchies, the chapter shows how engaging with historical material through making generates forms of understanding inaccessible through textual analysis alone, and how that deepened historical understanding simultaneously transforms the making, producing work that does not merely illustrate historical arguments but actively addresses them through material encounter. Re-engaging with embroidery, conventionally dismissed as decorative feminine accomplishment, the chapter demonstrates how reconstructing the physical practice, its temporal discipline, material constraints, and embodied conditions, generates epistemological evidence that archival reading cannot access. Following Barbara Bolt's distinction between practice as research and practice-led research, the chapter argues that it is the making process itself, rather than the finished artwork, that generates this emergent knowledge, and that the written account is not secondary to that process but its necessary counterpart. Grounded in Donna Haraway's concept of situated knowledge, the chapter proposes that material and affective modes of knowledge operate not as supplements to rational inquiry but as alternative epistemological frameworks with their own methodological rigor and critical force. The counter-archival methodology developed through this research offers both a critical tool and a transferable model, one with direct implications for how interdisciplinary research might recover the voices, practices, and ways of knowing that dominant narratives have historically excluded.

Introduction

Botany has lately become a fashionable amusement with the ladies,' wrote Richard Polwhele in 1798. 'But how the study of the sexual system of plants can accord with female modesty, I am not able to comprehend.' [1] The remark is pointed, but not unusual; it is one among many, distributed across an array of commentaries, conduct books and correspondence of the period, reflecting the prevailing attitudes toward women's engagement with botany. Preserved in correspondence, or filed in an archive, the statement becomes evidence. Quoted in a footnote, it becomes context. Stitched onto a pillowcase and laid across a bed in a stately home, it becomes something else entirely: an act of recovery that is inseparably an act of argument and a form of knowledge that neither the letter, the archive nor the footnote can fully reproduce.

Figure 1: Pillowcase with Richard Polwhele quote

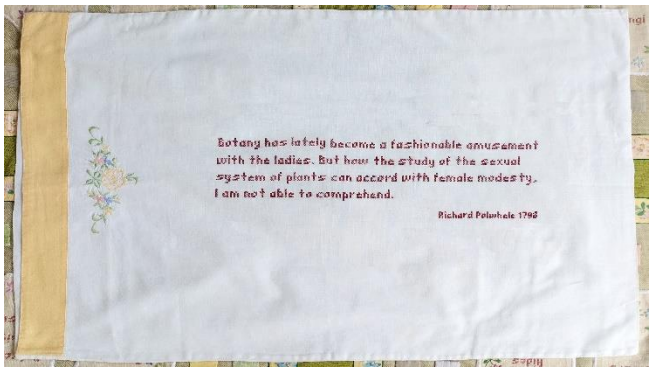


Figure 1: Pillowcase embroidered with Richard Polwhele's 1798 commentary on female modesty and botany

Address correspondence to Dr. Anne Griffiths, Oxford Brookes University, United Kingdom
info@annegriffiths.com (Dr. Anne Griffiths).

ISBN 978 627 7901 23 3
@ 2026 Intersections of Knowledge: Dialogues Across Disciplines. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/cc-by/4.0/).

Pillow Archive, the installation discussed here, formed part of a doctoral research project in Fine Art and sits at the intersection of feminist historiography, material culture studies, and archival theory. It employs twenty embroidered pillowcases to expose the contradictory attitudes that circulated in eighteenth-century Britain toward women's education and participation in botanical knowledge. The central claim, however, is methodological as much as historical: that practice-based making can generate forms of historical understanding through embodied and material engagement that textual analysis alone cannot access. This claim sits within a longstanding debate about the epistemological status of creative practice. James Elkins [2] has questioned whether knowledge generated through studio practice can be communicated and evaluated beyond the individual practitioner, identifying a persistent problem for practice-based research: how can knowledge that emerges through embodied and tacit engagement become available for critical scrutiny? Graeme Sullivan [3] locates inquiry within the artwork itself, while Barbara Bolt [4] distinguishes between practice as research, in which making is the primary means through which knowledge is generated, and practice-led research, where practice generates knowledge that is subsequently articulated through other forms of inquiry. Tim Ingold [5] extends this position by describing making as a process of thinking-through-materials, in which understanding emerges through sustained engagement with the constraints and possibilities of the medium rather than being formulated in advance and subsequently expressed. This chapter does not resolve the tension by treating embodied knowledge as wholly transferable or by claiming that the finished artwork can speak for itself. Instead, it treats making and writing as interdependent forms of inquiry: the contemporary act of making emerges from an encounter with both archival texts and the historical practices associated with embroidery, while writing provides the critical space in which the knowledge generated through that encounter can be examined and articulated. The question, therefore, is not whether practice can reproduce the conventions of textual scholarship, but what forms of historical understanding become visible through embodied and material engagement with the past.

Figure: 2 Stack of folded pillowcases



Figure 2: Pillow Archive (installation view), showing the stacked and folded embroidered pillowcases resting on wooden supports.

The research therefore asks three related questions: what forms of historical understanding emerge through practice-based making; what becomes historically perceptible when a feminized domestic practice such as embroidery is re-engaged as a mode of inquiry; and how do the material and spatial conditions through which artworks are encountered affect what can be recognized as knowledge and evidence?

The methodology operates through an iterative relationship between archival research, material practice, and critical writing. Historical fragments are stitched in order that the material and temporal conditions of embroidery become part of the inquiry. Through making, duration, repetition, bodily labour, and materiality become conditions through which the archival material is reconsidered. Writing subsequently articulates, tests, and situates these insights. Rigor lies in the traceable relationship between evidence, material decisions, reflection, and argument rather than in the reproducibility of the maker's experience. The stakes of this claim extend beyond any single artwork. At a moment when research across the humanities increasingly asks whose knowledge counts, how it has been legitimized, and what forms of understanding have been excluded from institutional recognition, the question of method becomes urgent. The aim is not to privilege making as a substitute for established historical methods, but to demonstrate how material practice can be used as a rigorous and repeatable mode of inquiry. Drawing on Donna Haraway's [6] concept of situated knowledge, this chapter approaches knowledge as something shaped by position, experience, embodiment, and encounter: meaning emerges not from objects, texts, or archives in isolation, but relationally, through the conditions under which it is displayed and received. Historical methods can document the boundaries that excluded women from legitimate scientific knowledge production, but the embodied, material, and affective conditions of that exclusion remain largely beyond their reach. The assumption that legitimate knowledge is disembodied, universal, and can be fully articulated in language is what practice-based research sets out to challenge. With craft practice having long occupied an uneasy position within dominant knowledge hierarchies, dismissed as feminized, decorative, or insufficiently intellectual, the encounter with embroidered work is not neutral. To engage with it as a research method is therefore to make a claim that exceeds the historical case: it is to ask what becomes knowable when the researcher works through the material constraints, temporal discipline, and embodied experience of the very practices that institutional frameworks have historically overlooked, and to propose that the answer has direct implications for how interdisciplinary research might be conducted and evaluated.

The chapter proceeds in four stages. It begins by examining how Linnaean taxonomy encoded Enlightenment gender hierarchies, shaping not only the classification of plants but the cultural boundaries around who could participate legitimately in scientific knowledge production. It then turns to embroidery as an epistemological practice, examining what stitching does as a mode of inquiry and what forms of historical understanding emerge through the process of making. The third section brings together Haraway's [6] concept of situated knowledge with counter-archival approaches developed by Derrida, Taylor, and Cvetkovich [16–18] to examine the domestic interior as a historical site of women's knowledge production. These perspectives are brought into dialogue through a progression from the question of where knowledge is produced to how it is preserved, authorized, transmitted, and experienced. Haraway [6] establishes the epistemological premise that knowledge is produced from embodied and material positions. Derrida [16] then shifts attention to the structures of power through which knowledge is, or is not, preserved. Taylor [17] opens space for forms of knowledge transmitted through embodied practice rather than stable records, while Cvetkovich [18] extends this question to include affective and everyday experience. Taken together, these perspectives shift the focus from the archive as a repository of historical evidence to the conditions through which knowledge is produced, preserved, transmitted, and experienced. The fourth section turns to the question of site and display, examining how the same objects evoke different interpretations depending on where and how they are encountered. A question grounded in the installation's exhibition across two contrasting spaces: a historic building whose domestic interior inflects the work with intimacy and resonance, and a university gallery where the same pillowcases are reframed as evidence within a formal institutional setting. The chapter closes by proposing the counter-archival methodology developed through this research as a model for interdisciplinary inquiry that seeks to work critically with absence, material practice, and situated forms of knowledge.

Linnaean Taxonomy and Gendered Knowledge

In the eighteenth century, systems of classification became central to Enlightenment attempts to order and stabilize knowledge about the natural world. Among the most influential was the botanical taxonomy developed by the Swedish naturalist Carl Linnaeus [25], whose Systema Naturae (1735) proposed a method for categorizing plants according to their reproductive organs. By prioritizing the number and arrangement of the male pollen-bearing stamens over the female seed-producing pistils, the system sought to impose clarity and universal order upon botanical diversity. Yet as Patricia Fara [7] observes, Linnaeus [25] mapped human social hierarchies onto plants and then reversed the logic so that those same hierarchies appeared validated by nature itself. Through this circular reasoning, male dominance could be presented not as a cultural construction but as a natural and therefore legitimate order. Although presented as objective and universal, Linnaean taxonomy thus did more than mirror Enlightenment gender ideology; it actively naturalized it.

Linnaeus [25] actively promoted his sexual system through analogies aligning plant reproductive structures with human anatomy and anthropomorphic metaphors of marriage: stamens were described as husbands, pistils as wives, and flowers as bridal chambers. This rendered his taxonomy culturally legible while reinforcing prevailing standards of feminine modesty and sexual propriety.

Figure 3: Pillowcase with Linnaean text (CALYX, POLLEN, etc.) Full View

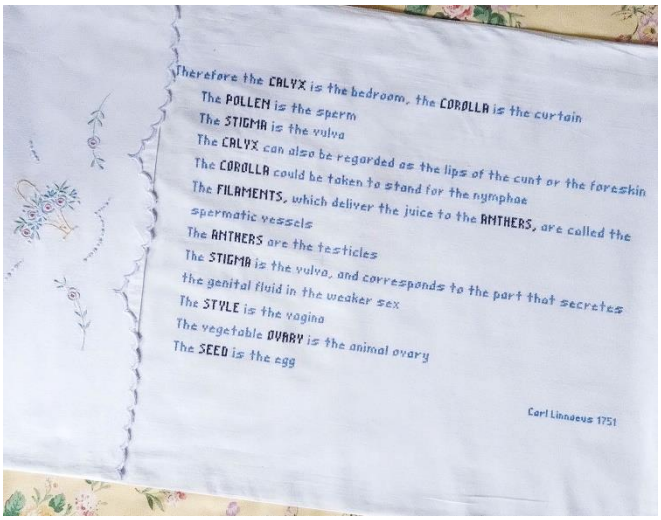


Figure 3: Detail of a pillowcase embroidered with Linnaean botanical terminology (Carl Linnaeus, 1751).

While Systema Naturae remained in Latin, its sexual system circulated within a European, professional, and predominantly male scientific community for whom classical languages were a standard marker of elite education. Its translation into English significantly extended the system's reach but introduced new constraints on women's engagement: in 1776 William Withering [8] deliberately modified Linnaean sexual terminology out of deference to what he considered a lady's modesty, replacing stamen and stigma with the euphemistic alternatives chive and pointal. The Botanical Society [25] at Lichfield, by contrast, retained the names in their 1787 adaptation without apparent concern, suggesting that Withering's modification reflected his own cultural anxiety.

Figure 4: Pillowcase with William Withering quote

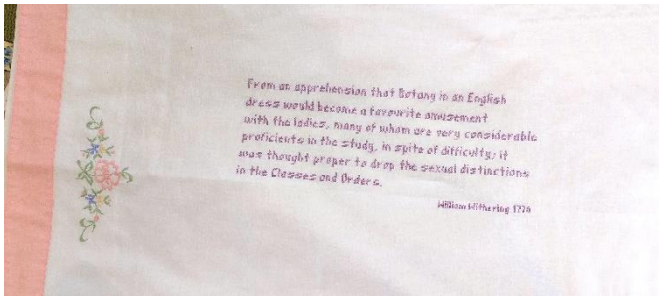


Figure 4: Pillowcase embroidered with William Withering's 1776 rationale for adapting Linnaean terminology for female readers.

Translation was therefore not merely a linguistic exercise but a cultural negotiation: the conditions under which women might legitimately engage with botanical knowledge were carefully managed, permitting drawing and painting as polite accomplishments while marking theoretical engagement as inappropriate. As feminist historians of science including Shteir [9], Schiebinger [10], and Fara [7] have demonstrated, women were not excluded from botanical knowledge production; rather, their participation circulated through informal and frequently uncredited forms that rarely translated into institutional authority.

Maria Jacson's Botanical Dialogues [11], structured as instructional dialogue and aimed at women and younger readers, exemplifies the unstable status of women's intellectual participation during the period. Published anonymously and attributed only to "a Lady," it enacts the cultural expectation that women entering print culture suppress their intellectual authority in order to maintain their social respectability. The choice of dialogue form is itself telling: a mode associated with guided instruction rather than original argument, it permitted the transmission of botanical knowledge while keeping its author in the position of facilitator rather than expert. Her case thus illustrates a broader epistemic structure in which distinctions between observation and authority, amateurism and expertise, and feminine accomplishment and scientific legitimacy determined not only what women could say but the forms through which they were permitted to say it. It is within these tensions that the methodological concerns of this research emerge.

Practices associated with feminine accomplishment often demanded forms of attention, discipline, and technical skill that exceeded the cultural status assigned to them. Re-engaging with such practices through contemporary making allows the constrained conditions of domestic femininity, its emotional pressures, contradictions, and socially permissible forms, to become materially and affectively legible. Within Pillow Archive, embroidery functions as a speculative counter-archival strategy through which the domestic object operates beyond its status as evidence of feminine accomplishment; it does not seek to reconstruct a hidden historical record of resistance but to stage a site where the emotional and intellectual tensions structuring women's historical position can be re-inhabited through a contemporary feminist lens. The act of selecting, transcribing, and stitching these fragments is therefore not illustrative but constitutive: historical inquiry and making practice become mutually generative, each transforming the other in ways that neither could achieve independently.

@ 2026 Wah Academia Journal of Society, Culture and Policy. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license https://creativecommons.org/licenses/cc-by/4.0

Embroidery as Epistemological Practice

Having established how Linnaean botanical taxonomy encoded Enlightenment gender hierarchies, the question that follows is methodological: what forms of historical understanding emerge through re-engaging with those excluded practices? This section is concerned less with interpreting embroidered objects than with what stitching does as a mode of inquiry: what it discloses, what it resists, and what becomes perceptible beyond the evidentiary limits of archival reading.

That inquiry begins with material choice. Linnaeus's [25] sexual system relied on the metaphor of the bridal chamber, positioning the flower as a domestic interior in which reproduction is staged. By stitching period quotations onto pillowcases, objects inseparable from the bed and the body, Pillow Archive returns botanical classification to the site it metaphorically occupied. The pillowcase does not simply carry the text; it performs the argument.

The methodological significance of embroidery extends beyond symbolism. Cross-stitch was chosen for its restrictive formal structure: unlike more expressive forms of embroidery that retain traces of individual style or gesture, it operates through the accumulation of uniform marks across a gridded surface, suppressing variation in favor of precision and conformity. Each X is formed from two diagonal stitches, building text through sustained periods of concentrated labour. This structure produces a specific regime of attention. To stitch a quotation is to engage the text differently than reading allows: where the eye can move quickly, skim, or return selectively, stitching requires prolonged engagement with each word in turn. Meaning is not simply read but constructed through duration.

Figure 5: Close-up of embroidery in progress (CALYX, POLLEN, etc.)

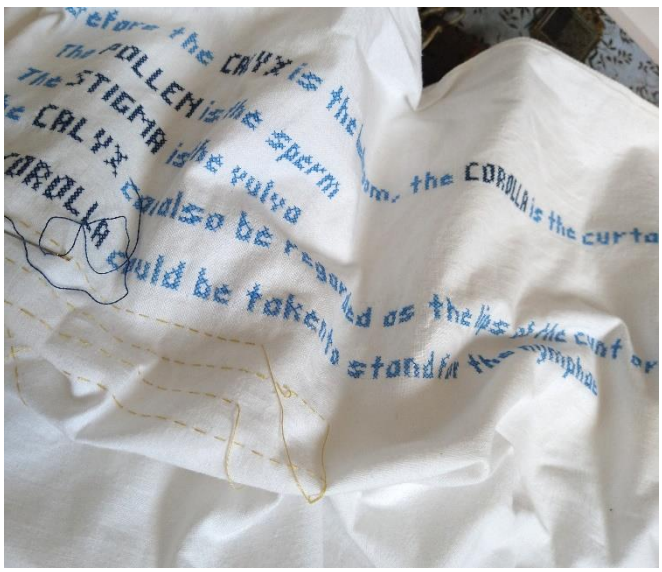


Figure 5: Detail of the cross-stitch process in Pillow Archive, demonstrating the material constraints and temporal discipline of the medium.

This slow, bodily reproduction of a text has a specific historical form. As Rozsika Parker [12] has shown, cross-stitch formed part of the sampler tradition in eighteenth-century feminine education, through which girls learned needlework alongside conduct, obedience, and patience via the reproduction of sanctioned moral and religious texts. The emphasis was not only technical but disciplinary, forming habits of attention and compliance through repetition. By contrast, the classical education available to elite boys emphasized rhetoric, argument, and original intellectual production. Cross-stitch disciplined the hand toward reproduction within fixed forms. The distinction embeds within education a division between reproducing authorized knowledge and generating it, one that was culturally produced yet presented as self-evident.

Elite women were encouraged to cultivate embroidery as an accomplishment signaling refinement and social position. It functioned as a marker of femininity within domestic culture, requiring sustained concentration and precision while being classified as leisure rather than labour. For the researcher, stitching enacts what the archive presents as social fact: that women's accomplishments demanded disciplined concentration. This experiential dimension is distinct from what the finished object communicates to a viewer unfamiliar with that labour. The making process therefore operates on two levels. First, knowledge is produced through the process of making itself. Second, knowledge is made available through the finished object, although what can be apprehended from it remains partial and contingent.

While the temporal and embodied dimensions connect cross-stitch to contemporary slow-stitching practices, the historical conditions of its production were fundamentally different. Cross-stitch as feminine accomplishment was neither freely chosen nor restorative, but socially mandated. To engage embroidery as a research method is therefore to hold in tension the epistemological possibilities opened by duration and constraint with the historical conditions that produced them. This distinction is what makes the practice analytically productive rather than recuperative.

The methodological significance of cross-stitch extends beyond its temporal discipline. The X itself carries historical resonance: it recalls the illiterate signature, the mark made in place of writing by those denied formal literacy, and also evokes practices of manual redaction in which repeated strikes of the X key obscured or erased existing text. Within Pillow Archive, these meanings converge. The same mark associated with erasure, anonymity, and restricted authorship becomes legible. A symbol of suppression is reworked as articulation. These resonances are grounded in the historical conditions through which women's botanical contributions were made visible yet denied authority.

Questions of authorship and anonymity deepen this argument. Women's contributions to botanical knowledge in the eighteenth century were frequently circulated through unstable forms of attribution that rendered intellectual labour visible while obscuring authorship. While Maria Jacson's [12] anonymous publication reflected social pressure to preserve feminine modesty at the cost of intellectual authority, Mary Delany's [23] case is differently instructive. Her paper 'mosaics' achieved a level of botanical precision that contemporaries, including Sir Joseph Banks [7], acknowledged as scientifically authoritative, yet her Catalogue of Plants Copyed [sic] from Nature in Paper Mosaic [24] appeared without attribution in a limited edition possibly printed under Banks's supervision. The contradiction is revealing: Delany's [7] work could be publicly admired and circulated as feminine accomplishment, but her botanical authority could not circulate as authorship within print conventions. Authority, in this sense, was not inherent to knowledge but a condition conferred, or withheld, through its mode of dissemination. Print did not simply circulate knowledge; it regulated the forms in which knowledge could appear as such, separating demonstrable expertise from recognized intellectual agency. The contrast between Jacson and Delany [11,23,24] is one of mechanism: Jacson's [11] anonymity detaches authority from identity, Delany's visibility remains, but as accomplishment rather than expertise. In both cases, epistemic status was separated from the identity of its producer, albeit through different institutional logics: one detached authority through anonymity, the other retained visibility but

in the form of feminine accomplishment rather than intellectual expertise.

If Jacson and Delany [11,23,24] reveal how print culture distributes visibility and authority unevenly, Anne Monson's case shifts the problem into a different epistemic register: that of translation, naming, and taxonomic incorporation. As a Latin student she assisted James Lee in translating Linnaeus's Philosophia Botanica [13] into English, and collected botanical specimens of sufficient significance that Linnaeus [25] considered her unequalled among women. Extending his recognition through a reproductive metaphor, he proposed that they jointly 'procreate just one little daughter', a plant she had collected, which he named in her honor. The gesture honors Monson [13] while absorbing her contribution into the taxonomic system: she collects, he incorporates; she provides the specimen, he secures classification; she contributes discovery, he determines its commemoration. Her role in translation remained similarly peripheral, absorbed into the record without corresponding authority. In each case the mechanism of constraint differs: social propriety, feminized medium, or institutional appropriation, yet the outcome was consistent: separation of knowledge from the conditions under which it could be recognized as authoritative. It is this structural consistency across different epistemic registers that Pillow Archive sets out to expose and rework through practice.

Encountering Priscilla Wakefield's [14] observation in An Introduction to Botany, in a Series of Familiar Letters that botany had been 'confined to the learned' and 'defended as it were' from women's access through its dependence on Latin altered the terms on which the archive itself is read. Latin functions not simply as a linguistic medium but as a gatekeeping structure regulating access to botanical knowledge. Wakefield's [14] framing makes visible how exclusion operated at the level of educational form as much as institutional authority. This recognition, held during the slow material construction of each stitched letter, shifts embroidery from illustration toward a mode of encounter in which historical constraint becomes materially experienced rather than simply described.

Figure 6: Pillowcase with Priscilla Wakefield quote

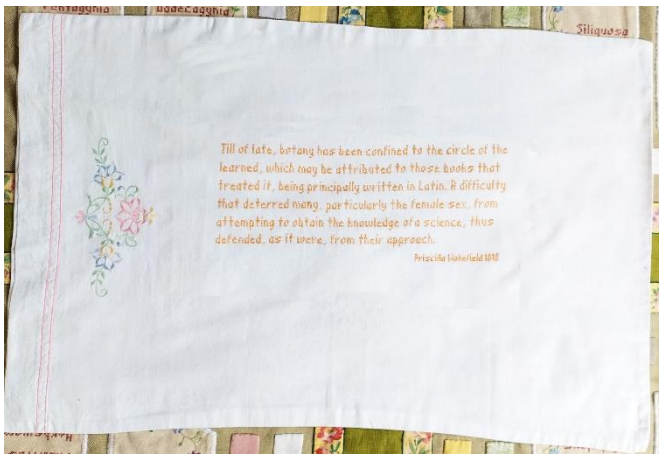


Figure 6: Pillowcase embroidered with Priscilla Wakefield's 1818 observation on the exclusivity of botanical knowledge.

The archive was no longer simply a source of material to be stitched; the act of making transformed how it could be understood. The material structure of Pillow Archive inhabits and unsettles the ideological force of the sampler tradition, a dynamic that becomes fully legible only through making. Stitching critical quotations through a medium so closely associated with feminine virtue and domestic accomplishment generates an affective understanding that reading about embroidery cannot reproduce: the resistance of the material, the suppression of spontaneity, and the discipline imposed by repetition, through which this form of needlework becomes physically and temporally tangible.

Yet to describe this encounter as a recovery of hidden resistance would be to impose a coherence the historical record cannot sustain. The work does not claim that women encoded feminist protest into embroidery; rather, it uses the logic of the counter-archive to ask how practices associated with feminine compliance might also be read as sites where frustration, critique, or resistance could become thinkable. Its critical force lies in this tension: gestures associated with obedience are not reversed but repeated differently, turning replication itself into a means of historical and methodological inquiry.

Ingold's [5] account of making as thinking-through-materials provides a vocabulary for understanding what this repetition produces: the structure of the pillowcase, the texture of the fabric, and the discipline of the weave become conditions through which historical argument became thinkable rather than merely describable. Bolt [4] sharpens this by describing the artwork as "a mode of revealing": not the translation of pre-existing knowledge into material form, but a process in which understanding and making transform one another through encounter. Michael Polanyi's [15] account of tacit knowledge situates this beyond fine art, showing how skilled material engagement produces knowledge that exceeds what can be articulated in advance. Haraway's [6] concept of situated knowledge clarifies that the researcher is not exterior to this process: knowledge emerges from specific material and positional conditions. This is not a limitation of the method but its epistemological condition.

Yet the embodied knowledge generated through stitching cannot be transferred directly to the viewer or fully contained within the finished object. Duration, fatigue, concentration, and repetition remain situated in the process of making itself. The pillowcases do not communicate those conditions directly; rather, they create a situation in which traces of labour, discipline, intimacy, or constraint may be encountered differently depending on the viewer's embodied and interpretive position. The work foregrounds the partial and contingent nature of affective historical understanding, making that partiality a methodological position rather than a limitation. This does not, however, reduce the object to one whose meaning is entirely determined by the viewer. The material constraints of cross-stitch and the fine weave of the fabric constitute a structured encounter: not one that determines meaning, but one that makes certain forms of recognition available. The epistemological status of the finished object is therefore neither that of evidence nor of interpretive freedom. It occupies a third position: a materially structured situation that produces understanding relationally, through the specific conditions of its encounter.

What embroidery ultimately produces is a methodology through which the temporal discipline, bodily labour, and constrained forms of attention shaping women's historical experience can be investigated through practice itself. Rather than translating historical conditions into representation, embroidery generates situations in which those conditions become partially reproducible as modes of inquiry. In doing so, it produces forms of knowledge that textual analysis can recognize and theorize, but cannot itself generate.

@ 2026 Wah Academia Journal of Society, Culture and Policy. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license https://creativecommons.org/licenses/cc-by/4.0

The Domestic Interior as Counter-Archive

In Archive Fever, Jacques Derrida [16] argues that every act of preservation is simultaneously an act of exclusion. Through selection, and classification the archive produces a partial and historically contingent version of the past, shaped by the assumptions of those who control it, and haunted by what it has neglected to admit. For the history of eighteenth-century women's knowledge production, this is not merely a theoretical proposition, it is a description of the mechanism by which intellectual labour was considered either as an accomplishment, pastime, or as peripheral assistance and either excluded from the historical record or admitted on terms that denied it intellectual authority.

Pillow Archive responds to this condition by proposing an alternative archival logic that works with archival absences rather than against them. The pillowcase inverts both the materials and the values through which archives establish their authority. Where institutions protect artifacts from bodily contamination, the pillowcase absorbs it: its fibers carry traces of birth, illness, intimacy, and death, recording dimensions of lived experience that official documents rarely preserve.

Derrida's [16] account of archival selection raises a further question for Pillow Archive: what forms of knowledge remain outside the archive because they are embodied in practices rather than preserved as stable records? Diana Taylor's [17] distinction between archive and repertoire provides the structural framework for understanding Pillow Archive. Where the archive preserves stable material records, the repertoire transmits embodied knowledge through practices that exist only in their enactment and leave no fixed trace. Embroidery belongs to the repertoire: its knowledge is produced through sustained attention, touch, and material engagement. Yet this unsettling of Taylor's distinction is itself unstable. A preserved pillowcase is not embroidery being practiced; it is embroidery having been practiced, its knowledge of duration, touch, and material resistance is now absent from the object itself. What the pillowcase retains is not the repertoire but its residue: the visible trace of a process that can no longer be enacted through the object. If this constitutes a form of knowledge, it is one that depends on the viewer completing an act of imaginative reconstruction that the object solicits but cannot compel. Taylor's [17] distinction does not collapse; rather, the pillowcase sits permanently at its border, available for institutional incorporation while marking the threshold of what such incorporation cannot contain.

What is at stake in holding both categories together are not their reconciliation, but the tension produced by their coexistence. Where Taylor distinguishes between preservation and enactment, Ann Cvetkovich [18] attends to forms of historical knowledge that circulate through affect but resist stabilization in either register: an archive of feelings composed of the emotional, bodily, and quotidian dimensions of lived experience that conventional archives cannot accommodate. The pillowcase becomes legible as an object inseparable from rest, vulnerability, and the rhythms of daily life. The embroidered text intensifies this condition, layering critical witness onto material surface in a way that renders historical exclusion physically and affectively present. Pillow Archive thus reconfigures what counts as archival matter when feeling, inscription, and material form are understood as inseparable.

Grounded in this counter-archival logic, the eighteenth-century domestic interior emerges as both a historical structured site of women's participation in knowledge production and the methodological ground of this research. Constructed as a feminized space of sociability and accomplishment, it was also, as Styles and Vickery [19] have shown, a site in which both elite women and men engaged intellectually and practically with botany and the natural world. These forms of engagement were, however, differently distributed. For men, botanical knowledge extended outward through networks of sociability and exchange, from coffee-house culture and commercial correspondence to learned societies and the expanding institutions of Enlightenment science. For women, plant knowledge remained largely embedded within the domestic sphere, centered on the management of gardens as sites of household economy, medicine, and sustenance.

By the end of the century this shared field of practice was reconfigured. The ornamental landscape displaced the productive garden, and botanical knowledge was progressively externalized to the apothecary, physician, and market gardener. Within this shift, women's relationship to plant knowledge was displaced from utility into accomplishment, leaving forms of domestic expertise increasingly difficult to recognize within conventional historical records.

The career of Margaret Cavendish Bentinck [20], Duchess of Portland, illustrates this condition with unusual clarity because her case cannot be explained by lack of access or resources. Far from being a passive aristocratic hobbyist, she financed major botanical endeavors, employed Georg Ehret [20], one of the foremost botanical illustrators of the day, and the botanist Daniel Solander [20]. She built a substantial collection and fostered a community so alive with scientists, artists, and accomplished women that her contemporaries nicknamed her estate The Hive. Jean-Jacques Rousseau, who elsewhere denied women any talent for science, considered her his superior in botanical knowledge. Yet her contribution was consistently framed in the language of instinctive accumulation rather than intellectual judgement, her role cast as patron rather than scientific authority. Unlike Jacson [11] or Monson [13], Portland [20] was neither anonymous nor marginal. Her case demonstrates that even wealth and acknowledged expertise did not automatically translate into intellectual authority when exercised by a woman. Portland's [20] case is therefore the limit test of the argument: exclusion operated even where resources, networks, and acknowledged expertise were present. It is this logic that Pillow Archive sets out to materialize.

Within Pillow Archive, these historical tensions appear not as biographical narratives but as fragments: extracts from period commentary that document the unstable conditions under which women's botanical knowledge could be acknowledged and denied in the same gesture. Detached from their original contexts, the quotations resurface as spectral traces, speaking across time through Derrida's [16] notion of hauntology. The embroidered fragments do not restore the voices of the women whose labour they shadow; rather, they mark the site of their suppression, making absence itself legible. The counter-archive works through this fragmentation, treating the partial, the incomplete, and the interrupted not as obstacles to historical understanding but as evidence in their own right.

To make the pillowcase an archival surface is to insist that vulnerability and softness are not disqualifications from evidential status but, in certain historical conditions, the very form that evidence takes. Soft fabric tears, fades, and absorbs stains; it does not survive in the same conditions as stone or vellum, nor does it typically enter institutional repositories. Yet it records forms of lived experience that more durable materials cannot. The counter-archive developed through Pillow Archive exposes the assumptions through which archival authority is conventionally established. Rather than opposing the institution, it makes visible the values on which it depends and proposes alternatives grounded in intimacy, affect, and fragmentary survival. Where those values become legible, however, depends on where and how the work is encountered.

Site, Display, and Archival Authority

The question of where Pillow Archive is encountered is central to its methodological force. Installed across two contrasting sites, a historic domestic interior and a university gallery, the work occupies the threshold Derrida [16] identifies as foundational to archival power: the boundary between the domestic space in which materials are generated and the institutional space in which they are authorized, classified, and preserved. Each site produces a different order of archival authority, shaping not only how the work is read but what can be recognized as evidence.

Shaw House, formerly an elite residence, occupies the domestic pole of Derrida's formulation [16]. Its rooms bear the traces of architectural revisions, patinas, objects, and material traces of the bodies and routines that have moved through it across centuries. Installed within a lady's bedchamber, the pillowcases were encountered in conditions of domestic intimacy and visitors moved with a quality of care and attentiveness that the historical interior expects. Initially, the works may be read as nothing more than household textiles, indistinguishable among period furnishings. Only on closer looking does the object declare itself as argument. This delayed recognition echoes the historical condition in which women's knowledge was present yet required a particular form of attention before it could be perceived as intellectually consequential.

Here, visitors were permitted to touch the pillowcases, an experience ordinarily prohibited by both archive and the art gallery, and deliberately prevented by the vitrine in The Glass Tank. For those who did, the scent of laundered linen became perceptible, carrying an unbidden sense of domestic familiarity that no institutional display can reproduce.

The Glass Tank, situated within the university campus, occupies the institutional pole of this topology. As a gallery embedded within a context historically shaped by traditions of elite masculinized knowledge production, it is one of the very structures the work sets out to interrogate, a critical relationship which gives the setting analytical force. Displayed within a vitrine, the pillowcases acquire authority, reframed as evidence, argument, and methodology. Unlike Shaw House, where historical context was embodied in the fabric of the building itself, the Glass Tank installation constructed its archival environment entirely from contemporary equivalents; botanical taxonomy reinterpreted in rolls of wallpaper, a modern desk holding glass jars of seeds. The authority of the historical record was not inherited but assembled, making visible the extent to which legitimacy is a construction rather than a condition. The vitrine is part of that process. Its enforcement of distance and untouchability keeps the audience from the artwork and reproduces the forms of separation through which archival authority has historically been established.

Figure 7: Vitrine with books and two pillowcases



Figure 7: Pillow Archive installed within a vitrine in The Glass Tank (university gallery), displaying the work as archival evidence alongside botanical texts

Sitting at the edges of the university's formal structures of teaching and assessment, the site shares this marginality with the work it presents. That position is significant, for the university remains historically connected to the institutional structures through which intellectual authority was gendered and distributed. Here the vitrine does not simply protect the objects; it re-enacts the institutional separation through which men asserted their professional position.

It is in the space between the two poles, domestic intimacy and institutional authority, repertoire and archive, affect and analytical distance, that the methodological argument of Pillow Archive is most legible. Taylor's distinction between archive and repertoire illuminates the different relationships each installation establishes. At Shaw House, touching the pillowcases, smelling the laundered linen, and moving through the bedchamber situated the work within a repertoire of domestic actions and sensations. At the Glass Tank, the vitrine shifted the work towards the archival register Cvetkovich [18] 's concept of an archive of feelings further clarifies this difference: the bedchamber activated affective and sensory associations that cannot be contained within the textual fragments. Haraway's [6] insistence that all knowledge is situated becomes visible here: the spatial and material conditions of encounter determine what register an object is received in, and what kinds of attention it solicits, before any conscious critical evaluation takes place. The archive maintains that register through distance, its holdings accessible only through mediated processes of request and retrieval. Where the vitrine produced analytical attention, the bedchamber produced something closer to recognition, the sense that these attitudes had not simply existed historically but had organized the very spaces and objects of daily life. Encountered through glass, the stitched texts read as remote historical comment; encountered directly, the contradiction and constraint embedded within the words becomes affectively present. The same object therefore produces different forms of understanding depending on the conditions of encounter, and it is this variability that the counter-archival methodology seeks to expose.

Conclusion: Practice-Based Research and Alternative Epistemologies

This chapter began with Richard Polwhele's [1] claim that botanical sexuality could not accord with female modesty. Stitched onto a pillowcase, that remark becomes more than historical evidence: it becomes a material argument about how knowledge is produced, embodied, and authorized. This transformation is not incidental, not a matter of aesthetic choice or creative supplement, but epistemologically consequential. What Pillow Archive demonstrates, and what this chapter has argued, is that practice-based making can function as a mode of inquiry capable of producing objects that enact a historical understanding rather than merely illustrate it.

Three interconnected arguments have been developed through this chapter. The first is historical: that Linnaean [17] botanical taxonomy reinforced gendered hierarchies by encoding them within the authority of scientific classification. The second is methodological: that re-engaging with embroidery produces forms of critical insight that emerge through process rather than representation. The third is archival: that the domestic interior can function as a counter-archival site through which excluded forms of knowledge become materially and affectively legible in ways the institutional archive cannot accommodate. Together these propositions amount to a methodological model committed to practice-based research as a

@ 2026 Wah Academia Journal of Society, Culture and Policy. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license https://creativecommons.org/licenses/cc-by/4.0

rigorous mode of inquiry, grounded in the recognition that knowledge is not produced from a view from nowhere but from specific material, positional, and embodied conditions of encounter.

That rigor depends on a distinction this chapter has maintained throughout: between practice as the production of a finished object and practice-led research as a process through which knowledge emerges through making itself. The pillowcases are the material through which the research became thinkable; this written account is not separate from that process but its necessary articulation in relation to wider debates on knowledge, method, and intellectual legitimacy. The rigor of the methodology lies in keeping these stages accountable to one another: the historical archive constrains the material intervention, the material process generates questions that cannot be reduced to the initial archival reading, and writing makes the resulting claims available for critical examination. The methodology does not claim reproducibility of embodied experience. It establishes rigor through the traceability of its decisions, the historical grounding of its evidence, the specificity of its material procedures, and the critical articulation of what those procedures make perceptible. The counter-archive developed here does not claim completeness; its fragments are deliberately partial, decontextualized, and resistant to the coherent narratives demanded by institutional frameworks. This partiality is therefore treated as a methodological condition that the research makes explicit rather than a gap to be concealed.

What this research contributes is a demonstration of how tacit, embodied knowledge can be critically mobilized as historiographic intervention. In doing so, it responds to concerns that the knowledge generated through making remains irreducibly private to the practitioner. The significance of practice-based research does not depend on transferring the maker's experience intact to others. Rather, it lies in its capacity to reveal structures, relations, and historical conditions that can subsequently be articulated, examined, and shared. This methodology extends beyond this specific historical case. Its significance lies in showing how dominant knowledge structures determine what can appear as evidence, authorship, expertise, or intellectual labour, and in demonstrating that those determinations remain open to contestation. The questions raised here about whose knowledge counts, how it is legitimized, and what forms of understanding are excluded are not confined to the eighteenth century or to botanical science. They bear directly on how research across the humanities is currently produced, validated, and assessed.

What Pillow Archive ultimately proposes is that historical experience is never fully reducible to discourse: it is lived through bodies, habits, spaces, repetitions, and forms of labour that institutional records preserve only partially. The methodological significance of practice-based research lies in its capacity to engage those conditions as constitutive of how knowledge is formed, recognized, and valued. Its value lies not in recovering the past intact, but in producing materially situated encounters through which historical conditions become differently apprehensible in the present.

References

1. Polwhele R. The Unsex'd Females: A Poem, Addressed to the Author of the Pursuits of Literature. London: Cadell and Davies; 1798.
2. Elkins J. Artists with PhDs: On the New Doctoral Degree in Studio Art. Washington, DC: New Academia Publishing; 2009.
3. Sullivan G. Art Practice as Research: Inquiry in the Visual Arts. Thousand Oaks, CA: Sage Publications; 2005.
4. Bolt B. The Magic is in the Handling. In: Barrett E, Bolt B, editors. Practice as Research: Approaches to Creative Arts Enquiry. London: I.B. Tauris; 2007. p. 27–34.
5. Ingold T. Making: Anthropology, Archaeology, Art and Architecture. London: Routledge; 2013.
6. Haraway D. Situated Knowledges: The Science Question in Feminism and the Privilege of Partial Perspective. Feminist Studies. 1988;14(3):575–599.
7. Fara P. Sex, Botany and Empire: The Story of Carl Linnaeus and Joseph Banks. London: Icon Books; 2017.
8. Withering W. A Botanical Arrangement of All the Vegetables Naturally Growing in Great Britain. Birmingham: M. Swinney; 1776.
9. Shteir AB. Cultivating Women, Cultivating Science: Flora's Daughters and Botany in England, 1760–1860. Baltimore: Johns Hopkins University Press; 1996.
10. Schiebinger L. The Mind Has No Sex?: Women in the Origins of Modern Science. Cambridge, MA: Harvard University Press; 1989.
11. Jacson M. Botanical Dialogues, Between Hortensia and her Four Children. London: J. Johnson; 1797.
12. Parker R. The Subversive Stitch: Embroidery and the Making of the Feminine. London: Women's Press; 1984.
13. Monson EC. Lady Anne Monson, A Phoenix among Women. PuLSe. 2016;30:4–5.
14. Wakefield P. An Introduction to Botany, in a Series of Familiar Letters. London: E. Newbery; 1796.
15. Polanyi M. The Tacit Dimension. Chicago: University of Chicago Press; 2009.
16. Derrida J. Archive Fever: A Freudian Impression. Translated by Eric Prenowitz. Chicago: University of Chicago Press; 1995.
17. Taylor D. The Archive and the Repertoire: Performing Cultural Memory in the Americas. Durham, NC: Duke University Press; 2003.
18. Cvetkovich A. An Archive of Feelings: Trauma, Sexuality, and Lesbian Public Cultures. Durham, NC: Duke University Press; 2003.
19. Styles J, Vickery A, editors. Gender, Taste, and Material Culture in Britain and North America, 1700–1830. New Haven: Yale University Press; 2006.
20. Stott R. Duchess of Curiosities: The Life of Margaret, Duchess of Portland. Worksop: Harley Gallery; 2006.
21. Griffiths A. Phallic Metaphors and Feminist Perspectives: Phallic Metaphors and Feminist Perspectives: Unsettling the Linnaean Botanical Archive through Historiographic Technique and Studio Practice. PhD thesis, Department of Fine Art, Oxford Brookes University, Oxford; 2026.
22. Cook A. Botanical exchanges: Jean-Jacques Rousseau and the Duchess of Portland. History of European Ideas. 2007;33(2):142–156.
23. Linney VL. The Flora Delanica: Mary Delany and Women's Art, Science, and Friendship in Eighteenth-Century England. PhD thesis, Department of Women's Studies, York University, Toronto; 1999.
24. Nelson EC. Plants copied after nature in paper mosaick by Mary Delany (1700–1788). Huntia. 2025;20(2):51–94.
25. Linnaeus C. A Selection of the Families of Plants. Translated by the Botanical Society at Lichfield. London: John Jackson; 1787.

Declarations:

Authors' Contribution:

- All Authors: Conceptualization, data collection, interpretation, drafting of the manuscript and intellectual revisions
- The authors agree to take responsibility for every facet of the work, making sure that any concerns about its integrity or veracity are thoroughly examined and addressed

Conflict of Interest: NIL

Funding Sources: NIL

Intersections of Knowledge: Dialogues Across Disciplines
https://org.wahacademia.com/publications/

Chapter Seven

Bhagat Singh's Jail Notebook (12.9.1929–23 March 1931): Reading, Revolutionary Thought, and the Intellectual Development of a Martyr

Dr. Ramjilal[1]

[1] Social Scientist, Former Principal, Dyal Singh College, Karnal, Haryana, India

Keywords

Bhagat Singh, Jail Notebook, revolutionary reading, socialism, Marxism, intellectual development, anti-colonialism, sociology, rationalism, secularism

Abstract

Bhagat Singh (1907–1931) occupies a distinctive position in the historiography of India's anti-colonial struggle. He is remembered not only as a revolutionary who resisted British colonial rule but also as a significant political thinker, journalist, organizer, and socialist in the making. His intellectual evolution charted a path from revolutionary nationalism to a deeper engagement with socialism, Marxism, atheism, rationalism, anti-imperialism, and issues of class and social inequality [1]. His writings illustrate that his revolutionary activities were increasingly complemented by theoretical contemplation [2]. One of the key documents for exploring this intellectual development is his Jail Notebook, maintained during his imprisonment from 12 September 1929 to 23 March 1931. This document is not a conventional diary; rather, it consists of reading notes, quotations, extracts, and reflective thoughts [3]. The surviving notebook comprises 404 pages, with Bhagat Singh utilizing about 75 pages, leaving many blank and sectioning off material under the heading "Sociology" [4]. Scholar J. Daniel Elam stresses that the notebook serves primarily as a record of revolutionary reading, rather than an autobiography [5]. This article examines the historical context of the notebook's publication, its intellectual scope, the significance of the "Sociology" section, the contributions of Soviet scholarship, and the relevance of the Jail Notebook in contemporary times. It argues that the Jail Notebook challenges simplistic distinctions between "thinker" and "activist" in Bhagat Singh's life, demonstrating that his reading profoundly shaped his political practice while his revolutionary experiences influenced his intellectual inquiries [6].

Introduction

Bhagat Singh's life and thought have been subjects of extensive scholarly inquiry, yet the full dimensions of his intellectual journey remain under-explored in popular discourse [7]. While his martyrdom at the age of twenty-three has been commemorated extensively, the depth of his engagement with political theory, philosophy, and literature has often been overshadowed by his iconic status as a revolutionary [8]. The Jail Notebook, maintained during his incarceration in Lahore Central Jail, provides a crucial window into the intellectual foundations of his revolutionary practice [9]. This document reveals a mind engaged with approximately 108 different books and 44 authors, spanning ancient philosophy, European political thought, and modern socialist literature [10]. The notebook is not merely a record of reading; it is evidence of a revolutionary's sustained commitment to intellectual inquiry even in the face of imminent death [11]. This article seeks to situate the Jail Notebook within the broader context of Bhagat Singh's intellectual development, examining its publication history, intellectual scope, and contemporary relevance [12].

Historical Context of the Notebook's Publication

The publication history of the Jail Notebook is of notable significance [13]. Bhupender Hooja was the first major Indian editor to circulate its content widely [14]. He initially serialized the notebook in the Indian Book Chronicle and later published A Martyr's Notebook: Notes and Extracts from Books Read by Shaheed Bhagat Singh during His Prison Days (1929–31) in Jaipur in 1994 [15]. Following this, Chaman Lal prepared a crucial edition, The Jail Notebook and Other Writings (2007), published by LeftWord Books [16]. This edition was based on a copy preserved in the National Archives of India and included revised annotations from Hooja's earlier work, presenting the notebook alongside Bhagat Singh's court statements, letters, and other writings from his time in prison [17]. A significant Hindi edition, Shaheed-e-Azam Bhagat Singh Ki Jail Diary, was published in 2011 by Unistar Publications through the Kulbir Singh Memorial Foundation [18]. Further contextualization is provided by material published in Samaj Weekly, which documents the 2011 edition alongside Hooja's earlier publication [19]. The Jail Notebook should not be seen as a newly discovered curiosity; its existence is the result of a complex history involving preservation, scholarly investigation, transcription, editing, and publication [20].

Address correspondence to Dr. Ramjilal, Social Scientist, Former Principal, Dyal Singh College, Karnal, Haryana, India
drramjilal1947@gmail.com (Dr. Ramjilal).

ISBN 978 627 7901 23 3
@ 2026 Intersections of Knowledge: Dialogues Across Disciplines. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/cc-by/4.0/).

Intellectual Scope of the Notebook

One of the most remarkable aspects of Bhagat Singh's Jail Notebook is the breadth of its intellectual engagement [21]. Published analyses link the notebook to approximately 108 different books and 44 authors, varying slightly depending on whether contributions from anthologies are considered separately [22]. It represents a remarkably diverse intellectual landscape rather than a straightforward reading list [23]. The material spans ancient philosophy, European political thought, and modern socialist literature [24]. Notable thinkers included are Karl Marx, Friedrich Engels, Vladimir Lenin, Leon Trotsky, Nikolai Bukharin, and Karl Kautsky, as well as figures such as Bertrand Russell, Thomas Paine, and Jean-Jacques Rousseau [25]. Other significant contributors to his reading include John Locke, Thomas Jefferson, Edmund Burke, Herbert Spencer, J. S. Mill, Maxim Gorky, Victor Hugo, Fyodor Dostoevsky, Rabindranath Tagore, Walt Whitman, Omar Khayyam, Mirza Ghalib, Emma Goldman, Eugene Debs, Jack London, and Upton Sinclair [26]. This intellectual diversity is critical [27]. Bhagat Singh was not merely accumulating quotations from socialist authors to validate a pre-formed ideology; he was engaging with a range of competing intellectual traditions [28]. The notebook thus provides valuable insight into a mind striving to comprehend society through the lenses of history, philosophy, literature, political theory, and revolutionary experience [29]. A particularly notable source is Upton Sinclair's The Cry for Justice, an extensive anthology addressing issues related to poverty, labour, inequality, exploitation, war, and social protest, underscoring that Bhagat Singh's intellectual pursuits extended beyond the singular issue of independence from British rule [30].

The "Sociology" Section and the Development of Socialist Thought

The separate "Sociology" section is notable for its attempt to systematically analyze society rather than solely critique colonialism from a political standpoint [31]. It incorporates Marxist concepts related to class, property, labour, economic organization, and historical progression, alongside broader philosophical and sociological inquiries [32]. Bhagat Singh's intellectual evolution reflects a significant transformation over time [33]. His revolutionary nationalism increasingly adopted a socialist perspective [34]. Scholar Chaman Lal has highlighted Singh's rising opposition not only to imperialism but also to capitalism, communalism, and caste oppression [35]. The notebook in question is a crucial resource for historians, as it provides insight into the intellectual foundations of this transformation [36]. Understanding Bhagat Singh's political actions requires an examination of the literature that influenced his worldview [37].

L. V. Mitrokhin and Earlier Soviet Scholarship

A key aspect of historiography that is often overlooked in Indian contexts is the early Soviet scholarship on Bhagat Singh's intellectual journey, which preceded the widespread availability of his notebook in India [38]. L. V. Mitrokhin, a Russian/Soviet Indologist, played a pivotal role in this discourse [39]. A close associate of Dr. Devender Kaushik from Kurukshetra University, Mitrokhin visited India frequently [40]. The author of this discussion had the opportunity to meet Mitrokhin during the late 1960s and early 1970s, where he was recognized as an esteemed scholar with a profound personality [41]. In his 1971 essay "The Books Read by Bhagat Singh," included in the volume India on Lenin, Mitrokhin emphasized Singh's reading habits and intellectual growth [42]. His later work, Lenin and India (1981), further explored Singh's ideas, including a chapter titled "The Last Days of Bhagat Singh" [43]. Mitrokhin's scholarship is significant as it challenges the simplification of Bhagat Singh as merely a young nationalist martyr, underscoring his embrace of Marxist thought [44]. Chaman Lal also emphasizes the relevance of these Soviet studies in reconstructing Singh's ideological development [45].

The Notebook as a Record of Revolutionary Reading

Recent scholarly interpretations have shed new light on the notebook [46]. J. Daniel Elam argues that it should not be seen solely as evidence of Bhagat Singh's intellectual prowess; rather, the act of reading itself was integral to his revolutionary politics [47]. The notebook illustrates Singh's ongoing engagement with literature, as he continued to read, compare, and analyze texts even in the face of imminent death [48]. This perspective is especially insightful, as the notebook contains a mix of short quotes, longer excerpts, marginal notes, and literary passages [49]. Its fragmentary nature contributes to its intellectual depth [50]. Singh's reading was also notable for its breadth, encompassing Marx and Lenin alongside authors like Hugo, Dostoevsky, Gorky, Tagore, Paine, and Russell [51]. Such diversity indicates that his socialism developed through comparative intellectual engagement, rather than strict adherence to any single ideological figure [52].

The Notebook Must Be Read with His Other Prison Writings

The Jail Notebook should not be analyzed in isolation but rather in conjunction with Singh's other writings, such as "Why I Am an Atheist," "To Young Political Workers," his court statements, "To Make the Deaf Hear," and letters to family and comrades, along with documents related to his hunger strike and the treatment of political prisoners [53]. The 2007 edition intentionally consolidates these various works [54]. "Why I Am an Atheist" highlights Singh's commitment to rational inquiry and intellectual autonomy [55]. "To Young Political Workers" reflects his dedication to the future organization and political education of the revolutionary movement, while his court statements transformed the colonial courtroom into a political platform [56]. Collectively, these writings illustrate a revolutionary increasingly focused on mass politics, advocating for workers and peasants, pursuing social equality, secularism, rationalism, and exploring the link between political freedom and social change [57].

The Last Book: Lenin at the Threshold of Death

The final chapters of Bhagat Singh's intellectual journey are noteworthy, particularly in relation to Clara Zetkin's Reminiscences of Lenin [58]. Scholarship indicates that this was the book Bhagat Singh was reading just prior to his execution [59]. According to Chaman Lal's The Bhagat Singh Reader, the Jail Notebook concludes with a partially read copy of this work on 23 March 1931, coinciding with the execution of Bhagat Singh, Rajguru, and Sukhdev [60]. Retrospective accounts consistently highlight Reminiscences of Lenin as the final book he engaged with [61]. This detail carries both symbolic and scholarly significance [62]. It underscores Bhagat Singh's commitment to intellectual engagement, even in the face of death [63]. His identity as a reader remained integral to his revolutionary spirit [64]. The common portrayal of Bhagat Singh reading about Lenin before his execution should therefore be viewed as more than a mere heroic anecdote; it represents the culmination of a well-documented intellectual journey [65].

Bhagat Singh as Reader, Thinker, and Revolutionary

The Jail Notebook challenges a simplistic distinction between the roles of "thinker" and "activist" in Bhagat Singh's life [66]. He embodied both aspects; his reading profoundly shaped his political practice, while his revolutionary experiences influenced his inquiries into the texts he studied [67]. Over time, his understanding of revolution expanded beyond just the replacement of colonial governance [68]. For him,

revolution entailed a fundamental transformation of social and economic relations [69]. Consequently, his writings address issues of capitalism, class exploitation, communalism, caste, religion, political organization, and the empowerment of ordinary people [70]. This intellectual evolution sets Bhagat Singh apart from a purely romantic notion of revolutionary action [71]. He emphasized the importance of organization, political education, and mass involvement, arguing that revolutionary endeavors devoid of political consciousness could not lead to sustainable social change [72].

Relevance of the Jail Notebook Today

The relevance of Bhagat Singh's Jail Notebook extends beyond commemorating a martyr; it highlights the critical need for reading, critical thinking, and social responsibility [73]. In today's context, where public discourse is often marred by political polarization, misinformation, and blind acceptance of prevailing ideas, Bhagat Singh's approach to examining a wide array of texts, questioning established norms, and comparing diverse schools of thought remains vital [74]. His engagement was not limited to one author or ideology; he explored the works of Marx, Engels, Lenin, Rousseau, Paine, Locke, Hugo, Dostoevsky, Gorky, Tagore, among others [75]. Bhagat Singh's intellectual journey serves as a reminder for students and young people that patriotism does not equate to rejecting critique [76]. It illustrates that meaningful social change necessitates both knowledge and organized effort [77]. His emphasis on workers, peasants, economic inequality, communal harmony, secularism, rationalism, and social justice enhances the ongoing relevance of the Jail Notebook in contemporary India [78]. Ultimately, it conveys that freedom transcends mere political independence from foreign dominance; it also involves addressing issues of equality, dignity, and justice within society [79]. Thus, honoring Bhagat Singh entails fostering the spirit of inquiry, rationality, courage, and commitment to social justice that his writings so powerfully embody [80].

Conclusion

The Jail Notebook stands as a testament to Bhagat Singh's intellectual rigor and revolutionary commitment [81]. It reveals a mind that refused to accept dogma, instead engaging critically with diverse intellectual traditions to develop a comprehensive understanding of society and revolution [82]. The notebook challenges us to reconsider the relationship between thought and action, demonstrating that revolutionary practice requires theoretical grounding and that intellectual inquiry can itself be a form of revolutionary activity [83]. In an era marked by polarization and misinformation, Bhagat Singh's example of critical reading and comparative analysis remains profoundly relevant [84]. His intellectual journey from revolutionary nationalism to socialism, his engagement with Marxism and rationalism, and his commitment to social justice continue to inspire scholars, students, and activists worldwide [85]. The Jail Notebook is not merely a historical document; it is a living testament to the power of ideas in shaping revolutionary consciousness and action [86].

References

1. Elam, J. D. (2016). Commonplace anti-colonialism: Bhagat Singh's jail notebook and the politics of reading. South Asia: Journal of South Asian Studies, 39(3), 592–607. https://doi.org/10.1080/00856401.2016.1193796
2. Elam, J. D. (2020). Bhagat Singh's Jail Notebook. In World literature for the wretched of the earth: Anticolonial aesthetics, postcolonial politics (pp. 92–112). Fordham University Press. https://doi.org/10.5422/fordham/9780823289790.003.0005
3. Hooja, B. (Ed.). (1994). A martyr's notebook: Notes and extracts from books read by Shaheed Bhagat Singh during his prison days (1929–31). Indian Book Chronicle.
4. Lal, C. (2007). Revolutionary legacy of Bhagat Singh. Economic and Political Weekly, 42(37), 3712–3718.
5. Lal, C. (Ed.). (2007). The jail notebook and other writings. LeftWord Books.
6. Lal, C. (Ed.). (2019). The Bhagat Singh reader: Writings, letters, and essays. LeftWord Books.
7. Mitrokhin, L. V. (1971). The books read by Bhagat Singh. In India on Lenin. [Soviet scholarly publication].
8. Mitrokhin, L. V. (1981). Lenin and India. [Soviet scholarly publication].
9. Raikov, A. V. (1971). Bhagat Singh and his ideological legacy. [Russian scholarly publication].
10. Singh, B. (2011). Shaheed-e-Azam Bhagat Singh Ki Jail Diary. Unistar Publications/Kulbir Singh Memorial Foundation.
11. Zetkin, C. (1929). Reminiscences of Lenin. Modern Books.
12. Kumari, M. (2024). Relevance of Bhagat Singh's Thoughts [PhD Thesis]. BMU, Asthal Bohar, Rohtak.
13. Lal, R. (2025, September 30). Bhagat Singh: A great inspiration for students and youth: A scientific perspective. Samaj Weekly UK.
14. Lal, R. (2025, September 26). Shaheed-e-Azam Bhagat Singh: The importance of secularism – A new look. Samaj Weekly UK.
15. Lal, R. (2025, April 14). Amar Shaheed Sukhdev: A glorious golden page of the socialist revolutionary movement – An analysis. Samaj Weekly UK.
16. Ambedkar, B. R. (2025, March 24). Ambedkar on Bhagat Singh. Samaj Weekly.
17. Lal, R. (2025, October 5). Bhagat Singh: A great inspiration for students and youth: A scientific perspective. Asian Independent UK.
18. Lal, R. (2025). Shaheed-e-Azam Bhagat Singh: The importance of secularism – A new look. Samaj Weekly UK / Asian Independent UK.
19. Lal, R. (2025). I pay tribute to the great martyr and revolutionary Shaheed-e-Azam Udham Singh. The Asian Independent. https://theasianindependent.co.uk/i-pay-tribute-to-the-great-martyr-and-revolutionary-shaheed-e-azam-udham-singh/
20. Lal, R. (2025, December 25). Shaheed-e-Azam Udham Singh: A realistic socialist revolutionary. Pratibimb Media. https://pratibimbmedia.com/shaheed-e-azam-udham-singh-a-realistic-socialist-revolutionary/
21. Lal, R. (2025, December 25). Shaheed-e-Azam Udham Singh: A socialist revolutionary. The Asian Independent. https://theasianindependent.co.uk/shaheed-e-azam-udham-singh-a-socialist-revolutionary/
22. Lal, R. (2025, January 30). Bhagat Singh ki phansi ke virudh the Gandhi. Dainik Tribune, Chandigarh, p. 4.
23. Lal, R., & Kumari, M. (2025, September 26). Shaheed-e-Azam Bhagat Singh: The importance of secularism – A new look. Samaj Weekly. https://samajweekly.com/shaheed-e-azam-bhagat-singh-the-importance-of-secularism-a-new-look/
24. Lal, R. (2025, January 29). Mahatma Gandhi: The best effort to save Bhagat Singh, Rajguru and Sukhdev – A review. Samaj Weekly. https://samajweekly.com/mahatma-gandhi-the-best-effort-to-save-bhagat-singh-rajguru-and-sukhdev-a-review/
25. Lal, R. (2025, May 14). Amar Shaheed Sukhdev: Catalyst of socialist revolutionary movement – An analysis. Samaj Weekly. https://samajweekly.com/amar-shaheed-sukhdev-catalyst-of-socialist-revolutionary-movement-an-analysis/
26. Lal, R. (2025, May 14). Amar Shaheed Sukhdev: Catalyst of socialist revolutionary movement. The Asian Independent. https://theasianindependent.co.uk/amar-shaheed-sukhdev-catalyst-of-socialist-revolutionary-movement/
27. Lal, R. (2026, July 18). I pay tribute to the great martyr and revolutionary Shaheed-e-Azam Udham Singh. The Asian Independent. https://theasianindependent.co.uk/i-pay-tribute-to-the-great-martyr-and-revolutionary-shaheed-e-azam-udham-singh/
28. Lal, R. (2026, September 27). Bhagat Singh: Life and ideology – Dhruv Tara, revolutionary socialist and prince of youth. Pratibimb Media. https://pratibimbmedia.com/bhagat-singh-life-and-ideology-dhruv-tara-revolutionary-socialist-and-prince-of-youth/
29. Lal, R. (2026, September 27). Bhagat Singh: Life, ideology, pole star revolutionary socialist, and prince of youth: A review. The Asian Independent. https://theasianindependent.co.uk/bhagat-singh-life-ideology-pole-star-revolutionary-socialist-and-prince-of-youth-a-review/
30. Lal, R. (2026, September 27). Bhagat Singh: Life, ideology, pole star revolutionary socialist, and prince of youth: A review. Samaj Weekly. https://samajweekly.com/bhagat-singh-life-ideology-pole-star-revolutionary-socialist-and-prince-of-youth-a-review/
31. Lal, R. (2026, September 28). Shaheed-e-Azam Bhagat Singh: Dhruv Tara, krantikari samajwadi aur yuvaon ko pyara. Karnal Kesari (Karnal Edition – Punjab Kesari), p. 2.

@ 2026 Wah Academia Journal of Society, Culture and Policy. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license https://creativecommons.org/licenses/cc-by/4.0

32. Lal, R. (2026, September 29). Bhagat Singh: Jail Notebook (Jail Diary 12.9.1929–23 March 1931) – Ek krantikari ke bauddhik nirman ki yatra. Pratibimb Media. https://pratibimbmedia.com/bhagat-singh-jail-notebook-jail-diary-12-9-1929-23-march-1931-the-journey-of-a-revolutionarys-intellectual-formation/

Declarations:

Authors' Contribution:

- All Authors: Conceptualization, data collection, interpretation, drafting of the manuscript and intellectual revisions
- The authors agree to take responsibility for every facet of the work, making sure that any concerns about its integrity or veracity are thoroughly examined and addressed

Conflict of Interest: NIL

Funding Sources: NIL

Intersections of Knowledge: Dialogues Across Disciplines
https://org.wahacademia.com/publications/

Chapter Eight

Bhagat Singh: Life, Ideology, Pole Star Revolutionary Socialist, and Prince of Youth: A Review

Dr. Ramjilal[1]

[1] Social Scientist, Former Principal, Dyal Singh College, Karnal, Haryana, India

Keywords

Jallianwala Bagh massacre of 1919, Romantic Nationalism, Russian Revolution, Marxism, socialism, Marx, Engels, and Lenin, Ganesh Shankar Vidyarthi, journalist, Bharat Naujawan Sabha, Hindustan Socialist Republican Association (HSRA), imperialism

Abstract

Bhagat Singh holds a significant position in the narrative of India's freedom struggle. While he is often remembered as a young revolutionary who made the ultimate sacrifice at the tender age of 23, his contributions extend far beyond this singular event. He was a profound thinker, journalist, political organizer, rationalist, and socialist ideologue who critically examined elements such as communalism, caste oppression, and economic exploitation [13]. His legacy is enriched by a body of work that includes writings, a prison notebook, political engagements, courtroom declarations, and correspondence, which collectively illustrate his intellectual evolution from a romantic view of revolutionary nationalism to a more sophisticated understanding of socialist revolution and socio-economic transformation [14]. This article examines Bhagat Singh's life, ideological development, organizational contributions, journalistic work, and enduring relevance as a pole star for youth and a revolutionary socialist [15]. It argues that Bhagat Singh's significance lies not merely in his martyrdom but in the intellectual trajectory of his life - his transformation from a nationalist to a socialist, from an activist to a scholar of history and political philosophy [16]. His writings on atheism, communalism, caste, youth, imperialism, and socialism reflect a profound refusal to accept inherited beliefs without scrutiny, and his questions about the relationship between political freedom and social equality remain profoundly relevant in the contemporary neo-imperialist era [17].

Introduction

Bhagat Singh's life and thought have been subjects of extensive scholarly inquiry, yet the full dimensions of his intellectual journey remain under-explored in popular discourse [1]. While his martyrdom at the age of twenty-three has been commemorated extensively, the depth of his engagement with political theory, philosophy, and literature has often been overshadowed by his iconic status as a revolutionary [9]. The historical figure of Bhagat Singh and his popular images are interconnected but not identical [9]. His recognizable likeness—characterized by a hat, moustache, and youthful demeanour—has become one of modern India's most iconic political symbols [9]. The role of the media was crucial in shaping this image [9]. Historian Kama Maclean notes that revolutionary politics engaged with violence, image, voice, and text [9]. Bhagat Singh's prominence can be attributed to his impactful courtroom statements, literary contributions, compelling photographs, and martyrdom, which collectively amplified his influence [9]. Acknowledging this constructed image does not undermine his historical accomplishments; rather, it emphasizes that political memory is shaped by a combination of newspapers, literature, photographs, cinema, political movements, and public commemorations [9]. This article seeks to examine Bhagat Singh's life, ideology, and legacy, arguing that his true significance lies in the intellectual trajectory of his life rather than merely in the circumstances of his death [1, 2].

Early Life and Influences

Born on September 28, 1907, in Banga, Lyallpur district, in undivided Punjab, Bhagat Singh was raised in a politically active family [7]. The socio-political environment of Punjab at the time greatly influenced his formative years [7]. A pivotal moment in his life was the Jallianwala Bagh massacre of 1919, which instilled in him the belief that India's liberation required more than a mere change of rulers; it necessitated a comprehensive transformation of the social and economic fabric of the nation [7]. This early exposure to colonial violence shaped his understanding of the relationship between political oppression and social transformation, laying the foundation for his later embrace of socialist ideology [14].

Political Development: From Romantic Nationalism to Revolutionary Politics

Bhagat Singh's early political maturation was shaped by the revolutionary ethos prevalent in Punjab, drawing inspiration from figures such as Kartar Singh Sarabha and Lala Lajpat Rai, as well as the broader anti-colonial movements [7]. His education at National

Address correspondence to Dr. Ramjilal, Social Scientist, Former Principal, Dyal Singh College, Karnal, Haryana, India
drramjilal1947@gmail.com (Dr. Ramjilal).

ISBN 978 627 7901 23 3
@ 2026 Intersections of Knowledge: Dialogues Across Disciplines. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/cc-by/4.0/).

College, Lahore, was critical, exposing him to a stimulating environment where historical and political discussions flourished, allowing students to critically engage with colonial rule [7]. A voracious reader, Bhagat Singh delved into an array of topics beyond nationalist literature [1]. His studies encompassed European revolutionary movements, the Russian Revolution, Marxism, socialism, anarchism, Irish nationalism, and Indian history [1]. His prison notebook serves as a testament to the breadth of his intellectual pursuits, containing references to influential thinkers like Marx, Engels, and Lenin [4]. This intellectual evolution is essential for understanding the transition from the youthful revolutionary of the early 1920s to the mature socialist revolutionary by the late 1920s [14]. As Dr. Ramjilal has argued, Bhagat Singh's intellectual journey reflects a significant transformation over time, with his revolutionary nationalism increasingly adopting a socialist perspective [14].

Bhagat Singh—A Remarkable Journalist

His journalistic career began in the early 1920s and was associated with publications including Pratap, Kirti, Maharathi, Vir Arjun, Matwala, Prabha, Akali, Chand, and Bande Mataram [3]. He wrote under pseudonyms, including Balwant Singh and Vidrohi, partly because colonial surveillance made open political writing dangerous [3]. His journalism covered revolutionaries, communalism, youth, workers, peasants, untouchability, imperialism, youth engagement, politics, social justice, political strategy, and the freedom struggle [3]. His work with Pratap (Kanpur) under Ganesh Shankar Vidyarthi was particularly significant [3]. He also translated revolutionary literature, thereby helping bring international revolutionary experiences to Indian readers [3]. For Bhagat Singh, journalism was not simply reporting [3]. The printed word was an instrument for political education [3]. He wanted readers to understand why people rebelled, what social conditions produced oppression, and what kind of society the revolutionaries wished to create [3].

Notably, his 1928 article on communal riots, published in Kirti, highlights his perspective that mere appeals to religious leaders could not resolve deep-seated communal conflicts [2]. He asserted that political and economic conditions, along with colonial policies and societal prejudices, must be confronted to achieve lasting solutions [2]. His writings emphasized that the interests of workers and ordinary people transcend religious divides [2]. Furthermore, his commentary on Untouchability underlines his belief that political freedom alone was not sufficient; it was imperative to challenge social oppression alongside imperialism [3]. This dimension of his thought has gained renewed attention in modern scholarship, including articles by Dr. Ramjilal featured in publications such as Samaj Weekly UK, The Asian Independent UK, and Pratibimb Media, Chandigarh [14, 15].

Political Organization: Bharat Naujawan Sabha

Bhagat Singh recognized the necessity of organized public participation in revolutionary politics [14]. In 1926, he, along with his comrades, established the Naujawan Bharat Sabha in Lahore, aiming to mobilize youth around key issues such as imperialism, communalism, social inequality, and political freedom [14]. The Sabha's political program is significant, as it illustrates Bhagat Singh's evolving conception of revolution, which extended beyond mere individual acts of violence [14]. The primary goal was to educate the youth, enhance political consciousness, and foster a movement capable of challenging systemic exploitation [14]. This organizational strategy eventually transitioned into the Hindustan Socialist Republican Association (HSRA) [14]. In 1928, the term "Socialist" was intentionally included in the organization's name, reflecting an important ideological shift that linked political independence with social and economic transformation [14]. As Dr. Ramjilal has noted, this organizational strategy demonstrates Bhagat Singh's emphasis on political education, mass involvement, and the importance of organization in revolutionary politics [14].

Lala Lajpat Rai, Saunders, and the Revolutionary Crisis

The death of Lala Lajpat Rai, following a violent lathi charge during an anti-Simon Commission demonstration in Lahore in October 1928, marked a critical turning point [46]. Revolutionaries believed that the British authorities who were responsible for this assault should be held politically accountable [47]. On December 17, 1928, Bhagat Singh and Rajguru assassinated Assistant Superintendent of Police J. P. Saunders, mistakenly identifying him as James Scott, the officer involved in the lathi charge [48]. This incident became central to the Lahore Conspiracy Case and should be contextualized historically, as an act of revolutionary violence shaped by the repressive colonial environment, which ultimately led to the arrests of Bhagat Singh, Sukhdev, and Rajguru [49].

The Assembly Bombing: Political Communication

On April 8, 1929, Bhagat Singh and B.K. Dutt threw smoke bombs in the Central Legislative Assembly in Delhi, intentionally designed to avoid mass casualties [50]. After carrying out the act, the revolutionaries did not flee; instead, they shouted revolutionary slogans and distributed leaflets, welcoming their arrest [51]. This event was pivotal in Bhagat Singh's political evolution [52]. They effectively used the courtroom and prison as platforms to communicate revolutionary ideals [53]. The slogan "Inquilab Zindabad" (Long Live Revolution), initially coined by famous Urdu poet and freedom fighter Maulana Hasrat Mohani in 1921, gained prominence through Bhagat Singh and his comrade B.K. Dutt during the Assembly incident [54]. Bhagat Singh further popularized it through his speeches and writings, ultimately making it emblematic of the Hindustan Socialist Republican Army [55]. Although often closely identified with him, the slogan symbolizes broader political awakening and resonates powerfully in various movements throughout the pre- and post-independence era [56]. Bhagat Singh's actions reflect his commitment to engaging with the masses [57]. Thus, the Assembly incident transcends being merely an act of bombing; rather, it served as a well-crafted political intervention aimed at drawing public attention to imperialist repression and revolutionary thought [58].

Sukhdev and Rajguru: The Collective Nature of Revolution

It is essential to acknowledge that Bhagat Singh's popularity does not overshadow the critical contributions of Sukhdev Thapar and Shivram Hari Rajguru [59]. Together, they were executed on March 23, 1931, with their political lives intricately linked [60]. Sukhdev was a key organizer and intellectual within the revolutionary movement, making significant contributions to both the Naujawan Bharat Sabha and the HSRA [61]. While historical accounts frequently center on Bhagat Singh, Sukhdev's organizational role has often received less recognition [62]. Meanwhile, Rajguru, hailing from Maharashtra, was a vital associate of Bhagat Singh, who played an essential role in the Saunders assassination [63]. The history of the revolutionary movement should be framed as a collective narrative rather than the biography of a single individual [64]. The trio—Bhagat Singh, Sukhdev, and Rajguru—epitomized the inter-regional character of revolutionary nationalism, connecting diverse linguistic and social backgrounds from Punjab and Maharashtra [65]. As Dr. Ramjilal has argued in his analysis of Sukhdev, the revolutionary movement was a collective effort, and understanding it requires attention to the contributions of all its participants [66].

The Lahore Conspiracy Case (1929-1930): An Overview

The Lahore Conspiracy Case (1929-1930) played a crucial role in revealing the interconnected lives and shared ideologies of revolutionaries in colonial India, emphasizing their collective contributions to the freedom struggle [67]. It became one of the most significant political trials of the era, wherein the British government employed extraordinary legal tactics against the accused [68]. A special tribunal was established to oversee the case, indicating the gravity with which the colonial authorities approached the matter [69]. The prosecution utilized testimonies from former associates who turned government witnesses, highlighting the problematic nature of the judicial process [70]. Key witnesses, such as Hans Raj Vohra and Jai Gopal, have become important subjects for historical analysis regarding the trial [71]. The reliance on approvers, police evidence, and extraordinary judicial practices showcased the colonial state's commitment to dismantling revolutionary organizations [72]. This trial also offered Bhagat Singh and his comrades a platform to challenge the legitimacy of colonial governance, transforming the courtroom into a venue for political discourse [73].

Prison as a University of Political Thought

Bhagat Singh's time in prison became a pivotal period for his intellectual development [74]. Instead of stifling his creativity, imprisonment fostered significant reading, writing, and political reflection [75]. His hunger strike against the discriminatory treatment of Indian political prisoners garnered national attention and highlighted the demand for prisoner rights, including improved food, clothing, reading materials, and basic amenities [76]. This protest emphasized that Bhagat Singh's revolutionary approach extended beyond covert conspiracies; it became increasingly focused on public mobilization and political discourse [77]. His prison writings, including letters and notebooks, reveal a thinker deeply engaged with history, philosophy, economics, and revolutionary ideology [78]. The Jail Diary is especially notable, as it offers insights into the intellectual landscape that influenced Bhagat Singh's thoughts [79]. As Dr. Ramjilal has argued, the Jail Notebook challenges a simplistic distinction between the roles of "thinker" and "activist" in Bhagat Singh's life [80]. He embodied both aspects; his reading profoundly shaped his political practice, while his revolutionary experiences influenced his inquiries into the texts he studied [81].

"Why I Am an Atheist?": A Rationalist Perspective

Bhagat Singh's essay, "Why I Am an Atheist?", is one of his most acclaimed works [82]. It should not simply be viewed as a critique of religion but rather as a call for reason, critical inquiry, and intellectual autonomy [83]. Bhagat Singh rejected the notion that revolutionary commitment necessitated blind faith, advocating instead for a rational examination of beliefs, rather than accepting them uncritically based on tradition [84]. This rationalist viewpoint was inherently linked to his political philosophy [85]. He argued that superstition, communal bias, and political oppression were interrelated barriers to human freedom [86]. As Dr. Ramjilal has noted, Bhagat Singh's commitment to rational inquiry and intellectual autonomy was integral to his revolutionary politics [87].

Secularism and Communalism

Bhagat Singh's secular beliefs were particularly relevant amid the communal tensions of the 1920s [88]. He recognized the potential for manipulation of religious identities for political gain and understood that communal divides hindered unified struggle [89]. In his article "Communal Riots and Their Cure," he expressed concern over the escalating Hindu-Muslim conflicts, positing that political organization grounded in class interests, rational thought, and shared social goals could bridge communal divisions [90]. Rather than advocating mere religious tolerance, Bhagat Singh sought to forge a political identity that enabled the collaboration of workers, peasants, and youth across religious boundaries [91]. This aspect of his thought continues to resonate in contemporary discussions about secularism and societal cohesion, as explored in recent publications by Dr. Ramjilal in Samaj Weekly UK, The Asian Independent UK, and Pratibimb Media, Chandigarh [92].

Caste and the Question of the Oppressed

Bhagat Singh also addressed the issue of untouchability and social oppression in his writing on the "Untouchable Question" [93]. He recognized that social inequities posed significant obstacles to national liberation, making it vital that revolutionary nationalism aligned with the pursuit of social equality [94]. He argued that political independence without the dismantling of social humiliation would exclude a substantial segment of India's population from the broader definition of freedom [95]. It is important to study Bhagat Singh's writings contextualized within his time, as he was still developing his ideas [96]. His significance lies not only in his conclusions but also in the questions he raised and the trajectory of his political thought [97].

Efforts of Mahatma Gandhi to Save Bhagat Singh, Rajguru, and Sukhdev

The relationship between Mahatma Gandhi and Bhagat Singh offers a complex view of the Indian freedom struggle, marked by distinct ideological differences [98]. Gandhi championed non-violent civil disobedience, while Bhagat Singh and the Hindustan Socialist Republican Association (HSRA) pursued a revolutionary approach [99]. Despite their differing philosophies, they should not be seen purely as antagonistic figures [100]. After Bhagat Singh, Sukhdev, and Rajguru were sentenced to death, a significant wave of public outcry emerged, demanding the commutation of their sentences [101]. During the negotiations of the Gandhi-Irwin Pact, Gandhi met with Viceroy Lord Irwin and raised the issue of their impending executions [102]. Historical accounts vary regarding the effectiveness of Gandhi's interventions, but documentary evidence confirms that he consistently appealed for clemency [103]. Ultimately, however, the death sentences were not commuted [104]. The key question for historians is not whether the executions were halted—since they were not—but rather how Gandhi's efforts can be understood within the broader political context of early 1931 [105]. Gandhi made earnest attempts to save the lives of these revolutionaries, as indicated by historical documentation [106]. In recent writings, published in Samaj Weekly UK, The Asian Independent UK, Pratibimb Media, Chandigarh, and Dainik Tribune, Chandigarh, and other newspapers, Dr. Ramjilal, after examining various documents, has categorically stated that Mahatma Gandhi made the best efforts to save the lives of the three martyrs [107].

The Final Hours and Martyrdom of Bhagat Singh, Sukhdev, and Rajguru

On March 23, 1931, Bhagat Singh, Sukhdev, and Rajguru were executed in Lahore Central Jail, ahead of the scheduled time, amidst heightened public tension [108]. Following their execution, the bodies were secretly transported towards the Sutlej River near Hussaini Wala and cremated hastily [109]. Local residents later discovered their remains and

@ 2026 Wah Academia Journal of Society, Culture and Policy. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license https://creativecommons.org/licenses/cc-by/4.0

conducted the final rites [110]. The news of their executions provoked widespread outrage, prompting protests and demonstrations across India [111]. The three young revolutionaries became enduring symbols of sacrifice, particularly resonating with the youth [112]. Their martyrdom notably transformed Bhagat Singh into a prominent national political figure [113].

Comparison Between Bhagat Singh and Udham Singh

Bhagat Singh and Udham Singh are frequently discussed in tandem, both serving as symbols of Punjabi resistance against British colonial rule [114]. They shared several similarities: both were deeply influenced by colonial violence, rejected passive acceptance of imperialism, adopted revolutionary methods, and ultimately sacrificed their lives [115]. They were also linked to socialist or radical political movements [116]. An article by Dr. Ramjilal highlights Udham Singh's ties to revolutionary and socialist organizations and his admiration for Bhagat Singh [117]. However, their life paths differed significantly [118]. Bhagat Singh was executed at the young age of 23, leaving behind a rich legacy of political writings and a focus on socialism, atheism, rationalism, and mass political mobilization [119]. In contrast, Udham Singh lived until 1940, with his most notable act being the assassination of Michael O'Dwyer in London in 1940, which he viewed as retribution for the atrocities committed in Punjab and during the Jallianwala Bagh massacre [120]. Udham Singh's political journey unfolded through years spent abroad and engagement with international revolutionary networks [121]. Thus, Bhagat Singh is predominantly remembered for his contributions to political theory and socialist thought, while Udham Singh's legacy is tied to his personal commitment to avenging colonial violence [122]. Together, they illustrate the diverse and complex nature of Punjab's revolutionary tradition [123].

The Lasting Impact of Bhagat Singh on Youth: Prince of Youth

Bhagat Singh's legacy is particularly significant in its influence on young people [124]. He championed the idea of intellectual engagement rather than ignorance or blind sacrifice [125]. Singh's own life exemplified this through extensive reading, active debates on political ideologies, a deep study of history, and thoughtful writing that shaped his political views [126]. His message to the youth emphasizes the importance of intellectual independence, courage, active participation in public life, and a stance against injustice [127]. Modern youth can explore Bhagat Singh's contributions in a way that transcends the political landscape of the 1920s [128]. His relevance today is found in his principles of questioning authority, resisting injustice, fostering a scientific outlook, and linking individual freedom with social responsibility [129]. As Dr. Ramjilal has argued, Bhagat Singh's intellectual journey serves as a reminder for students and young people that patriotism does not equate to rejecting critique [130]. It illustrates that meaningful social change necessitates both knowledge and organized effort [131].

From Revolutionary Nationalism to Social Revolution

A pivotal shift in Bhagat Singh's ideology was the transition from revolutionary nationalism to social revolution [132]. Initially, his primary focus was on achieving freedom from British colonial rule [133]. However, as his political thought evolved, he began to consider the type of society that would emerge post-independence [134]. This distinction is essential: if political power merely shifts from one group to another, while issues like poverty, caste discrimination, communalism, economic exploitation, and social inequality persist, then the true essence of revolution remains unfulfilled [135]. His iconic slogan, "Inquilab Zindabad—Long Live Revolution", symbolized not just the desire to overthrow British authority, but also the need for ongoing social and political transformation [136]. As Dr. Ramjilal has noted, Bhagat Singh's understanding of revolution expanded beyond just the replacement of colonial governance [137]. For him, revolution entailed a fundamental transformation of social and economic relations [138]. Consequently, his writings address issues of capitalism, class exploitation, communalism, caste, religion, political organization, and the empowerment of ordinary people [139].

Conclusion: Bhagat Singh Beyond Martyrdom

The historical significance of Bhagat Singh extends beyond the circumstances of his death; it lies in the intellectual trajectory of his life [140]. He transformed from a revolutionary into a thinker, evolving from a nationalist to a socialist and from an activist to a dedicated scholar of history and political philosophy [141]. Even while imprisoned, he continued his self-education and engaged with societal issues [142]. His writings on atheism, communalism, caste, youth, imperialism, and socialism reflect a profound refusal to accept inherited beliefs without scrutiny [143]. Collaborating with peers such as Sukhdev and Rajguru highlighted that his revolutionary politics were a collective effort [144]. It is important to remember Bhagat Singh not merely as an armed revolutionary or a romantic martyr, but as a political intellectual whose ideas were developing at the time of his execution [145]. His unfinished intellectual endeavours pose enduring questions that remain relevant today in the current neo-imperialist era: What is the value of political freedom without social equality? Can democracy exist in a context of communal division? Is economic development meaningful without justice for workers and farmers? How are individual freedom and collective emancipation related? What role can youth play in public life without being manipulated politically? [146]. These enquiries affirm Bhagat Singh's relevance beyond mere commemorative occasions [147]. His true legacy is not a fixed historical narrative but an ongoing encouragement to read deeply, question critically, reason thoughtfully, organize effectively, and strive towards a society founded on principles of freedom, equality, secularism, and social justice [148]. As Dr. Ramjilal has argued, honoring Bhagat Singh entails fostering the spirit of inquiry, rationality, courage, and commitment to social justice that his writings so powerfully embody [149]. In an era marked by polarization and misinformation, Bhagat Singh's example of critical reading and comparative analysis remains profoundly relevant [150]. His intellectual journey from revolutionary nationalism to socialism, his engagement with Marxism and rationalism, and his commitment to social justice continue to inspire scholars, students, and activists worldwide [151].

References

1. Singh, B. (1930). Why I am an atheist.
2. Singh, B. (1928, June). Communal riots and their solution. Kirti.
3. Singh, B. (1928). The untouchable question. Kirti.
4. Singh, B. Jail Notebook / Prison Notes (various editions, including A Martyr's Notebook, edited by Bhupendra Hooja).
5. Singh, K. (Ed.). (2011). Shaheed-e-Azam Bhagat Singh ki Jail Diary. Unistar Books, Chandigarh.
6. Singh, B. Selected Writings (various compilations).
7. Chandra, B. India's Struggle for Independence. Penguin.
8. Panikkar, K. N. Works on nationalism, colonialism and revolutionary politics in India.
9. Maclean, K. (2015). A Revolutionary History of Interwar India: Violence, Image, Voice and Text. Hurst.
10. Noorani, A. G. (1996). The Trial of Bhagat Singh: Politics of Justice. Oxford University Press.
11. Verma, S. Writings and memoirs concerning the HSRA and Bhagat Singh.
12. Yashpal. Sinhavalokan (revolutionary-era memoir).
13. Kumari, M. (2024, May). Relevance of Bhagat Singh's Thoughts [PhD Thesis]. BMU, Asthal Bohar, Rohtak.
14. Lal, R. (2025, September 30). Bhagat Singh: A great inspiration for students and youth: A scientific perspective. Samaj Weekly UK.
15. Lal, R. (2025, September 26). Shaheed-e-Azam Bhagat Singh: The importance of secularism – A new look. Samaj Weekly UK.

16. Lal, R. (2025, April 14). Amar Shaheed Sukhdev: A glorious golden page of the socialist revolutionary movement – An analysis. Samaj Weekly UK.
17. Ambedkar, B. R. (2025, March 24). Ambedkar on Bhagat Singh. Samaj Weekly.
18. Puniyani, R. (2025, July 11). Secularism and socialism in Constitution's Preamble: Eyesore to Hindu nationalists.
19. Lal, R. (2025, October 5). Bhagat Singh: A great inspiration for students and youth: A scientific perspective. Asian Independent UK.
20. Lal, R. (2025). Shaheed-e-Azam Bhagat Singh: The importance of secularism – A new look. Samaj Weekly UK / Asian Independent UK.
21. Lal, R. (2025). I pay tribute to the great martyr and revolutionary Shaheed-e-Azam Udham Singh. The Asian Independent. https://theasianindependent.co.uk/i-pay-tribute-to-the-great-martyr-and-revolutionary-shaheed-e-azam-udham-singh/
22. Lal, R. (2025, December 25). Shaheed-e-Azam Udham Singh: A realistic socialist revolutionary. Pratibimb Media. https://pratibimbmedia.com/shaheed-e-azam-udham-singh-a-realistic-socialist-revolutionary/
23. Lal, R. (2025, December 25). Shaheed-e-Azam Udham Singh: A socialist revolutionary. The Asian Independent. https://theasianindependent.co.uk/shaheed-e-azam-udham-singh-a-socialist-revolutionary/
24. Lal, R. (2025, January 30). Bhagat Singh ki phansi ke virudh the Gandhi. Dainik Tribune, Chandigarh, p. 4.
25. Lal, R., & Kumari, M. (2025, September 26). Shaheed-e-Azam Bhagat Singh: The importance of secularism – A new look. Samaj Weekly. https://samajweekly.com/shaheed-e-azam-bhagat-singh-the-importance-of-secularism-a-new-look/
26. Lal, R. (2025, January 29). Mahatma Gandhi: The best effort to save Bhagat Singh, Rajguru and Sukhdev – A review. Samaj Weekly. https://samajweekly.com/mahatma-gandhi-the-best-effort-to-save-bhagat-singh-rajguru-and-sukhdev-a-review/
27. Lal, R. (2025, May 14). Amar Shaheed Sukhdev: Catalyst of socialist revolutionary movement – An analysis. Samaj Weekly. https://samajweekly.com/amar-shaheed-sukhdev-catalyst-of-socialist-revolutionary-movement-an-analysis/
28. Lal, R. (2025, May 14). Amar Shaheed Sukhdev: Catalyst of socialist revolutionary movement. The Asian Independent. https://theasianindependent.co.uk/amar-shaheed-sukhdev-catalyst-of-socialist-revolutionary-movement/
29. Lal, R. (2026, July 18). I pay tribute to the great martyr and revolutionary Shaheed-e-Azam Udham Singh. The Asian Independent. https://theasianindependent.co.uk/i-pay-tribute-to-the-great-martyr-and-revolutionary-shaheed-e-azam-udham-singh/
30. Lal, R. (2026, September 27). Bhagat Singh: Life and ideology – Dhruv Tara, revolutionary socialist and prince of youth. Pratibimb Media. https://pratibimbmedia.com/bhagat-singh-life-and-ideology-dhruv-tara-revolutionary-socialist-and-prince-of-youth/
31. Lal, R. (2026, September 27). Bhagat Singh: Life, ideology, pole star revolutionary socialist, and prince of youth: A review. The Asian Independent. https://theasianindependent.co.uk/bhagat-singh-life-ideology-pole-star-revolutionary-socialist-and-prince-of-youth-a-review/
32. Lal, R. (2026, September 27). Bhagat Singh: Life, ideology, pole star revolutionary socialist, and prince of youth: A review. Samaj Weekly. https://samajweekly.com/bhagat-singh-life-ideology-pole-star-revolutionary-socialist-and-prince-of-youth-a-review/
33. Lal, R. (2026, September 28). Shaheed-e-Azam Bhagat Singh: Dhruv Tara, krantikari samajwadi aur yuvaon ko pyara. Karnal Kesari (Karnal Edition – Punjab Kesari), p. 2.
34. Lal, R. (2026, September 29). Bhagat Singh: Jail Notebook (Jail Diary 12.9.1929–23 March 1931) – Ek krantikari ke bauddhik nirman ki yatra. Pratibimb Media. https://pratibimbmedia.com/bhagat-singh-jail-notebook-jail-diary-12-9-1929-23-march-1931-the-journey-of-a-revolutionarys-intellectual-formation/
35. Elam, J. D. (2016). Commonplace anti-colonialism: Bhagat Singh's jail notebook and the politics of reading. South Asia: Journal of South Asian Studies, 39(3), 592–607. https://doi.org/10.1080/00856401.2016.1193796
36. Elam, J. D. (2020). Bhagat Singh's Jail Notebook. In World literature for the wretched of the earth: Anticolonial aesthetics, postcolonial politics (pp. 92–112). Fordham University Press. https://doi.org/10.5422/fordham/9780823289790.003.0005
37. Hooja, B. (Ed.). (1994). A martyr's notebook: Notes and extracts from books read by Shaheed Bhagat Singh during his prison days (1929–31). Indian Book Chronicle.
38. Lal, C. (2007). Revolutionary legacy of Bhagat Singh. Economic and Political Weekly, 42(37), 3712–3718.
39. Lal, C. (Ed.). (2007). The jail notebook and other writings. LeftWord Books.
40. Lal, C. (Ed.). (2019). The Bhagat Singh reader: Writings, letters, and essays. LeftWord Books.
41. Mitrokhin, L. V. (1971). The books read by Bhagat Singh. In India on Lenin. [Soviet scholarly publication].
42. Mitrokhin, L. V. (1981). Lenin and India. [Soviet scholarly publication].
43. Raikov, A. V. (1971). Bhagat Singh and his ideological legacy. [Russian scholarly publication].
44. Zetkin, C. (1929). Reminiscences of Lenin. Modern Books.

Declarations:

Authors' Contribution:

- All Authors: Conceptualization, data collection, interpretation, drafting of the manuscript and intellectual revisions
- The authors agree to take responsibility for every facet of the work, making sure that any concerns about its integrity or veracity are thoroughly examined and addressed

Conflict of Interest: NIL

Funding Sources: NIL

@ 2026 Wah Academia Journal of Society, Culture and Policy. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license https://creativecommons.org/licenses/cc-by/4.0

Intersections of Knowledge: Dialogues Across Disciplines
https://org.wahacademia.com/publications/

Chapter Nine

Caste and Politics: The Role of Kambojas in Punjab Politics, 1947–2026

Dr. Ramjilal[1]

[1] Social Scientist, Former Principal, Dyal Singh College, Karnal, Haryana, India

Keywords

Kamboj community, Punjab politics, caste and electoral behaviour, agrarian politics, Congress, Shiromani Akali

Abstract

he political history of Punjab after Independence cannot be fully understood without examining the interaction between caste, community, agrarian interests and political parties [1]. The Kamboj community has been one of the important agrarian communities of Punjab, with political representatives and social organisations associated with Congress, Shiromani Akali Dal, Aam Aadmi Party, BJP and other political formations [2]. Its political history, however, cannot be reduced merely to the number of elected representatives [3]. It also includes participation in the freedom movement, Gurdwara Reform Movement, farmers' organisations, cooperative institutions and local politics [4]. This article examines the political trajectory of the Kamboj community in Punjab from 1947 to 2026, tracing its journey from traditional agrarian and Congress-Akali networks towards a more competitive political environment [5]. It argues that the history of Kamboj politics is best understood not as a story of one permanent political allegiance, but as a history of agrarian identity, social mobility, community representation and changing political choices [6]. The careers of Balwant Singh, Dr. Upinderjit Kaur, Lal Singh, Hardyal Singh Kamboj, Jagdeep "Goldy" Kamboj and Mohammad Jameel Ur Rehman illustrate different phases of this journey [7]. At the same time, the 2020–21 farmers' movement demonstrated that agrarian interests could transcend conventional caste and party boundaries [8]. A methodological point is important: searching only for politicians carrying the surname "Kamboj" can give an incomplete picture [9]. Some leaders have used different surnames, while community and historical sources identify others through their family or social background [10]. The political role of Kambojas, therefore, has to be examined through electoral records, contemporary newspapers, historical accounts and community documentation [11].

Introduction

The relationship between caste, community and political representation in Punjab has been a subject of significant scholarly inquiry [12]. Punjab's political landscape has been shaped by the interaction of agrarian interests, religious identities, regional aspirations and party competition [13]. Within this complex matrix, the Kamboj community has occupied a distinctive position as an important agrarian community with political representatives across major parties [14]. The political history of the Kambojas cannot be understood in isolation from the broader transformations in Punjab's political economy—from the Green Revolution and its consequences to the farmers' movement of 2020–21 [15]. This article seeks to examine the political role of the Kamboj community from 1947 to 2026, analysing its participation in electoral politics, its representation across political parties, and the changing relationship between caste identity and political choice [16]. It argues that caste alone cannot explain electoral behaviour in Punjab; landholding, class, religion, region, occupation, party organisation and immediate agrarian interests also influence political choices [17]. The Kamboj experience thus offers valuable insights into the broader dynamics of caste and politics in contemporary Punjab [18].

Historical Roots and Partition

Kamboj political participation has roots going back to the freedom movement [19]. Sikh and Muslim Kambojas/Kambohs participated in revolutionary activities, the Gurdwara Reform Movement, Akali politics, peasant mobilisation, socialist and communist movements, the Congress movement and the armed forces [20]. Recent research by Dr. Ramjilal, published in Samaj Weekly (U.K.), The Asian Independent (U.K.), and Pratibimb Media, records the participation of Sikh Kambojas in the Gurdwara Reform and Akali movements, agrarian mobilisation, the Ghadar movement, Congress campaigns and other anti-colonial activities [21]. Master Sunder Singh Lyallpuri is among the best-known figures in this history [22].

Partition profoundly changed the community's political and social landscape [23]. Muslim Kamboj/Kamboh families largely moved from Indian Punjab to Pakistan, while Sikh and Hindu Kamboj families

Address correspondence to Dr. Ramjilal, Social Scientist, Former Principal, Dyal Singh College, Karnal, Haryana, India
drramjilal1947@gmail.com (Dr. Ramjilal).

ISBN 978 627 7901 23 3
@ 2026 Intersections of Knowledge: Dialogues Across Disciplines. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/cc-by/4.0/).

moved in the opposite direction [24]. In Indian Punjab, Kamboj families gradually rebuilt their economic and political position in several agricultural districts [25]. The story of Kamboj politics is therefore also a story of Partition [26]. The political traditions developed by Sikh, Hindu and Muslim Kambojas in undivided Punjab were separated by the events of 1947, but their shared historical experience remains an important part of understanding the community's political development on both sides of the Punjab [27].

From Agrarian Society to Electoral Politics

The expansion of Green Revolution agriculture subsequently strengthened the economic and political importance of rural and landholding communities [28]. During the first decades after Independence, Kamboj political participation developed through panchayats, cooperative institutions, market committees, local bodies and the major political parties [29]. Congress remained an important political platform, while the Akali movement provided another significant avenue, particularly where agrarian, Sikh and regional questions intersected [30].

Among the important political figures of the earlier period was Sardar Atma Singh, a senior Akali leader and former Punjab minister [31]. His political legacy was later reflected in the career of his daughter, Dr. Upinderjit Kaur, who represented Sultanpur and subsequently held several ministerial portfolios [32].

Balwant Singh and the Akali Tradition

Balwant Singh, a senior Akali leader and former Finance Minister of Punjab, represented an important phase in the development of Akali politics [33]. During the difficult political period of the 1980s, he participated in negotiations aimed at finding a political settlement to the Punjab crisis [34]. He was among the leaders involved in the negotiations surrounding the Rajiv–Longowal Accord of 1985 [35]. It would be historically excessive to describe any one person as the sole architect of the Accord, since the process involved several leaders and the central government [36]. Nevertheless, Balwant Singh's participation illustrates the presence of Kamboj political leadership at the highest levels of Punjab's Akali politics [37].

Dr. Upinderjit Kaur: Women in Political Representation

Dr. Upinderjit Kaur represents an important phase in the development of women's political representation within Punjab's agrarian political society [38]. She represented Sultanpur for several terms and served in different ministries of the Punjab government [39]. In October 2010, she became Punjab's Finance and Planning Minister [40]. Her career is significant because it demonstrates that Kamboj political representation was not confined to male rural leaders [41]. Her background in education and economics, and her participation in state administration, added another dimension to the community's political presence [42].

Lal Singh and Congress Politics

Congress also produced important Kamboj political figures [43]. Lal Singh, a senior Congress leader and former Punjab minister, remained an influential figure in state politics for several decades [44]. His political role was particularly visible in constituencies where caste and community mobilisation formed part of electoral strategy [45]. During the 2018 Shahkot by-election, contemporary reporting highlighted the importance of the Kamboj vote and the role of senior Kamboj political figures in electoral mobilisation [46]. This illustrates an important characteristic of Punjab politics: caste identity often operates alongside party ideology rather than independently of it [47].

Hardyal Singh Kamboj and Rajpura

Hardyal Singh Kamboj became one of the prominent contemporary Congress representatives of the community [48]. He represented Rajpura and was elected to the Punjab Assembly in 2012 and 2017 [49]. His political career illustrates the continuing role of Kamboj representation within mainstream party politics [50]. At the same time, his experience demonstrates that caste identity cannot automatically be equated with political loyalty [51]. During the 2020–21 farmers' movement, farmers protested a number of political leaders across party lines [52]. Hardyal Singh Kamboj also faced protests in Punjab during this period [53].

Kambojas and the Farmers' Movement, 2020–21

The farmers' movement of 2020–21 was an important moment in understanding the changing relationship between caste, agrarian interests and electoral politics in Punjab [50]. Kamboj farmers, like other sections of the state's rural population, participated in the wider mobilisation against the three central farm laws [35]. The movement developed from protests in Punjab into the historic mobilisation around Delhi, with farmers from Punjab and Haryana forming a major part of the agitation [26].

The movement also demonstrated that community identity did not automatically determine political behaviour [27]. The protests against Hardyal Singh Kamboj provide one documented example [48]. Farmers' organisations opposed political representatives irrespective of their caste background [49]. This suggests that during the farm-law agitation, agrarian interests could cross traditional caste and party boundaries [50]. For Kamboj politics, the movement was significant because community representation increasingly had to be understood alongside questions concerning MSP, agricultural markets, land, farm incomes and rural livelihoods [41]. The episode therefore forms an important link between community politics and wider agrarian politics in contemporary Punjab [22].

Col. C. D. Singh Kamboj and Political Mobility

Col. C. D. Singh Kamboj provides another example of political mobility [13]. He contested the Shahkot Assembly constituency on a Congress ticket and subsequently joined the Shiromani Akali Dal [24]. His political journey illustrates that Kamboj political leaders have not necessarily remained permanently attached to one political party [45]. Such movements between parties are part of the wider transformation of Punjab politics, where local political calculations, electoral alliances and changing public issues frequently influence political careers [46].

AAP and Jagdeep "Goldy" Kamboj

The emergence of the Aam Aadmi Party created a new political space in Punjab [6]. Jagdeep Singh "Goldy" Kamboj is an important example [8]. He joined AAP in 2020 and contested the Jalalabad Assembly constituency in 2022 [29]. He defeated Shiromani Akali Dal president Sukhbir Singh Badal and entered the Punjab Assembly [30]. His rise demonstrated that Kamboj political representation was no longer confined to the traditional Congress-Akali framework [41]. The emergence of AAP provided a new platform through which younger leaders could mobilise voters around changing political and local issues [22].

@ 2026 Wah Academia Journal of Society, Culture and Policy. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license https://creativecommons.org/licenses/cc-by/4.0

Muslim Kambojas and Malerkotla

The political history of Punjab's Kamboj community must also include Muslim Kamboj/Kamboh representation [43]. Malerkotla provides an important contemporary example [44]. Choudhary Mohammad Jameel Ur Rehman won the Malerkotla Assembly seat in 2022, and community historical sources identify him as a Muslim Kamboj [45]. His political presence is significant in the post-Partition history of the community [46]. Malerkotla demonstrates that Muslim Kamboj political identity survived Partition within Indian Punjab and continues to have a place in contemporary electoral politics [37].

BJP, SGPC and Wider Institutional Politics

Kamboj political participation has extended beyond Congress, SAD and AAP [28]. Kamboj political workers and local representatives have also been associated with BJP and other political organisations [39]. However, claims regarding major Punjab-wide BJP leadership or senior SGPC offices should be made only where documentary evidence is available [30]. The community's institutional presence is nevertheless wider than electoral politics [41]. Participation in gurdwara institutions, cooperative bodies, local government, educational organisations and welfare institutions has contributed to the development of political and social networks [42].

Caste, Class, Region and Political Choice

The political experience of Kambojas from 1947 to 2026 demonstrates that caste alone cannot explain electoral behaviour in Punjab [43]. Landholding, class, religion, region, occupation, party organisation and immediate agrarian interests also influence political choices [44]. The Shahkot experience demonstrated the importance of community identity in electoral mobilisation [50]. The farmers' movement showed that agrarian interests could challenge conventional party and caste alignments [46]. Jagdeep Goldy Kamboj's rise through AAP demonstrated political mobility, while the continuing presence of Kamboj leaders in Congress and SAD showed the persistence of older political traditions [17].

It is also important to distinguish between community representation and community voting [18]. A community can produce leaders belonging to different political parties without itself voting uniformly for one party [19]. Political representation should therefore not automatically be interpreted as permanent political loyalty [10].

Conclusion

From 1947 to 2026, Kamboj participation has been an important component of Punjab's political history [11]. The community's political journey has moved from traditional agrarian and Congress-Akali networks towards a more competitive political environment involving Congress, Shiromani Akali Dal, AAP, BJP and other formations [2]. The careers of Balwant Singh, Dr. Upinderjit Kaur, Lal Singh, Hardyal Singh Kamboj, Jagdeep "Goldy" Kamboj and Mohammad Jameel Ur Rehman illustrate different phases of this journey [13]. At the same time, the 2020–21 farmers' movement demonstrated that agrarian interests could transcend conventional caste and party boundaries [34].

The history of Kamboj politics in Punjab is therefore best understood not as a story of one permanent political allegiance, but as a history of agrarian identity, social mobility, community representation and changing political choices [35]. Its future political significance will depend not only on caste arithmetic but also on agriculture, employment, education, rural development, social justice and the changing political economy of Punjab [46].

References

1. Lal, R. (2026, August 9). Role of the Kamboj Sikhs in the Indian freedom movement: 1857 to 1947 – A review. Samaj Weekly.
2. Lal, R. (2026, August 8). The role of the Muslim Kamboj community in the freedom movement (1857–1947): A systematic study and review. The Asian Independent, U.K.
3. The Tribune. (2018, May 21). 2 more AAP leaders join Akali Dal.
4. PRS Legislative Research. Hardyal Singh Kamboj – MLA Track.
5. The Indian Express. (2010, October 21). Upinderjit is new Finance Minister.
6. The Christian Science Monitor. (1985, July). Will India's Sikh Accord hold?
7. The Indian Express. (2021, August). Explained: Why farmers have started protesting against Congress leaders in Punjab.
8. Amar Ujala. (2021, August 8). Farmers protested against MLA Kamboj in Banur.
9. Hindustan Times. (2022, March 10). Riding on AAP wave, Kamboj breaches Sukhbir's bastion.
10. The Indian Express. (2022, March 11). From student Cong leader to AAP candidate.
11. Election Commission of India. (2012). Statistical Report on General Election to the Legislative Assembly of Punjab, 2012.
12. Samaj Weekly and The Asian Independent. Historical studies on Kamboj participation in India's freedom movement.
13. Lal, R. (2026, September 29). Bhagat Singh: Jail Notebook (Jail Diary 12.9.1929–23 March 1931) – Ek krantikari ke bauddhik nirman ki yatra. Pratibimb Media.
14. Lal, R. (2025, September 30). Bhagat Singh: A great inspiration for students and youth: A scientific perspective. Samaj Weekly UK.
15. Lal, R. (2025, September 26). Shaheed-e-Azam Bhagat Singh: The importance of secularism – A new look. Samaj Weekly UK.
16. Lal, R. (2025, April 14). Amar Shaheed Sukhdev: A glorious golden page of the socialist revolutionary movement – An analysis. Samaj Weekly UK.
17. Lal, R. (2025, October 5). Bhagat Singh: A great inspiration for students and youth: A scientific perspective. Asian Independent UK.
18. Lal, R. (2025, December 25). Shaheed-e-Azam Udham Singh: A realistic socialist revolutionary. Pratibimb Media.
19. Lal, R. (2025, December 25). Shaheed-e-Azam Udham Singh: A socialist revolutionary. The Asian Independent.
20. Lal, R. (2025, January 30). Bhagat Singh ki phansi ke virudh the Gandhi. Dainik Tribune, Chandigarh, p. 4.
21. Lal, R. (2025, January 29). Mahatma Gandhi: The best effort to save Bhagat Singh, Rajguru and Sukhdev – A review. Samaj Weekly.
22. Lal, R. (2025, May 14). Amar Shaheed Sukhdev: Catalyst of socialist revolutionary movement – An analysis. Samaj Weekly.
23. Lal, R. (2026, September 27). Bhagat Singh: Life, ideology, pole star revolutionary socialist, and prince of youth: A review. The Asian Independent.
24. Lal, R. (2026, September 28). Shaheed-e-Azam Bhagat Singh: Dhruv Tara, krantikari samajwadi aur yuvaon ko pyara. Karnal Kesari (Karnal Edition – Punjab Kesari), p. 2.
25. Kumari, M. (2024). Relevance of Bhagat Singh's Thoughts [PhD Thesis]. BMU, Asthal Bohar, Rohtak.
26. Ambedkar, B. R. (2025, March 24). Ambedkar on Bhagat Singh. Samaj Weekly.
27. Puniyani, R. (2025, July 11). Secularism and socialism in Constitution's Preamble: Eyesore to Hindu nationalists.
28. Maclean, K. (2015). A Revolutionary History of Interwar India: Violence, Image, Voice and Text. Hurst.
29. Noorani, A. G. (1996). The Trial of Bhagat Singh: Politics of Justice. Oxford University Press.
30. Chandra, B. India's Struggle for Independence. Penguin.
31. Elam, J. D. (2016). Commonplace anti-colonialism: Bhagat Singh's jail notebook and the politics of reading. South Asia: Journal of South Asian Studies, 39(3), 592–607.
32. Elam, J. D. (2020). Bhagat Singh's Jail Notebook. In World literature for the wretched of the earth: Anticolonial aesthetics, postcolonial politics (pp. 92–112). Fordham University Press.
33. Hooja, B. (Ed.). (1994). A Martyr's Notebook: Notes and Extracts from Books Read by Shaheed Bhagat Singh during His Prison Days (1929–31). Indian Book Chronicle.
34. Lal, C. (2007). Revolutionary legacy of Bhagat Singh. Economic and Political Weekly, 42(37), 3712–3718.
35. Lal, C. (Ed.). (2007). The Jail Notebook and Other Writings. LeftWord Books.
36. Lal, C. (Ed.). (2019). The Bhagat Singh Reader: Writings, Letters, and Essays. LeftWord Books.
37. Mitrokhin, L. V. (1971). The books read by Bhagat Singh. In India on Lenin.
38. Mitrokhin, L. V. (1981). Lenin and India.
39. Raikov, A. V. (1971). Bhagat Singh and His Ideological Legacy.
40. Singh, B. (2011). Shaheed-e-Azam Bhagat Singh Ki Jail Diary. Unistar Publications/Kulbir Singh Memorial Foundation.
41. Zetkin, C. (1929). Reminiscences of Lenin. Modern Books.
42. Singh, B. (1930). Why I am an atheist.
43. Singh, B. (1928, June). Communal riots and their solution. Kirti.

44. Singh, B. (1928). The untouchable question. Kirti.
45. Singh, K. (Ed.). (2011). Shaheed-e-Azam Bhagat Singh ki Jail Diary. Unistar Books, Chandigarh.
46. Singh, B. Selected Writings (various compilations).
47. Panikkar, K. N. Works on nationalism, colonialism and revolutionary politics in India.
48. Verma, S. Writings and memoirs concerning the HSRA and Bhagat Singh.
49. Yashpal. Sinhavalokan (revolutionary-era memoir).
50. Samaj Weekly and The Asian Independent. (2026). Historical studies on Kamboj participation in India's freedom movement.

Declarations:

Authors' Contribution:

- All Authors: Conceptualization, data collection, interpretation, drafting of the manuscript and intellectual revisions
- The authors agree to take responsibility for every facet of the work, making sure that any concerns about its integrity or veracity are thoroughly examined and addressed

Conflict of Interest: NIL

Funding Sources: NIL

@ 2026 Wah Academia Journal of Society, Culture and Policy. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license https://creativecommons.org/licenses/cc-by/4.0

Intersections of Knowledge: Dialogues Across Disciplines
https://org.wahacademia.com/publications/

Chapter Ten

From the Window of Ancient Indian Kamboj History: The Kamboj Horses in Ancient India — Breeding, Trade and the Art of War

Dr. Ramjilal[1]

[1] Social Scientist, Former Principal, Dyal Singh College, Karnal, Haryana, India

Keywords

Kamboja, Kamboj horses, ancient India, horse breeding, horse trade, Mahabharata, Kurukshetra War, Sudakshina Kamboja

Abstract

The history of the Kambojas is closely associated with the history of the horse in ancient India [1]. Sanskrit, Buddhist and Jain sources repeatedly connect Kamboja with excellent horses, skilled horsemen and the horse trade of the north-west [2]. The reputation was so strong that Buddhist tradition described Kamboja as a country famous for horses [11]. Kautilya's Arthashastra also placed Kamboja among the important sources of superior horses [4]. The Kamboj horse was therefore not merely an animal of transport; it was an economic commodity, a military resource and a symbol of royal prestige [13]. This article examines the place of the Kamboj horse in ancient Indian history, covering its breeding and qualities, its role as royal gift and diplomatic instrument, its association with the Kurukshetra War and Krishna's chariot, its importance in long-distance trade, the Kamboja-Asvaka resistance against Alexander, and the later appearance of Kamboja ruling families in Bengal [20]. It argues that the Kamboj horse was much more than a celebrated animal; it was part of a wider network connecting commerce, military power, political authority and cultural exchange across ancient India and its north-western and eastern frontiers [21].

Introduction

The horse occupied a central place in the military, economic and ceremonial life of ancient India [14]. Among the regions associated with superior horses, Kamboja holds a distinctive position in Sanskrit, Buddhist, Jain and Greek sources [2]. Ancient Kamboja was situated in the north-western zone of the Indian cultural world, broadly associated with areas towards present-day Afghanistan and adjoining regions [11]. Its exact geographical boundaries changed over different periods [11]. Its location, however, was strategically important because it connected the Indian subcontinent with Afghanistan, Central Asia and the Iranian world [13]. This geographical position helped Kamboja develop a major horse economy [13]. The north-western regions of Kamboja, Gandhara, Sindhu and Bahlika formed an important corridor through which horses reached the Indian plains [13]. Kamboja became known for the production, selection, training and trade of horses [4]. It should therefore be understood not simply as a place where horses were bred but as part of a wider horse culture [1]. This article examines the multiple dimensions of the Kamboj horse tradition—its breeding and qualities, its role in royal gift-exchange, its association with the Mahabharata narrative, its importance in long-distance trade, its military significance during Alexander's invasion, and its later epigraphic presence in Bengal [20, 21].

Kamboja: A Horse-Producing Region

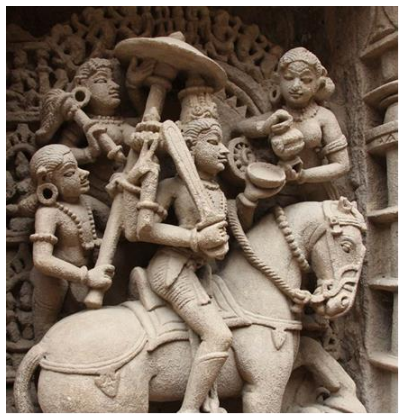


Figure 1.

Ancient sources frequently classified horses according to their geographical origin and qualities [4]. Therefore, the expression "Kamboj horse" should not necessarily be understood as referring to a genetically uniform breed in the modern sense [4]. It generally denoted horses associated with Kamboja and its celebrated horse-producing and trading tradition [4]. Kautilya's Arthashastra classifies horses associated with Kamboja, Sindhu, Aratta and Vanayu among the superior categories [5]. This classification is also discussed in modern studies of

Address correspondence to Dr. Ramjilal, Social Scientist, Former Principal, Dyal Singh College, Karnal, Haryana, India
drramjilal1947@gmail.com (Dr. Ramjilal).

ISBN 978 627 7901 23 3
@ 2026 Intersections of Knowledge: Dialogues Across Disciplines. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/cc-by/4.0/).

ancient Indian horse management [6]. The Arthashastra deals with the classification, registration, native place, breeding and management of horses under the Superintendent of Horses (Aśvādhyakṣa) [4]. The north-western horse-producing zone thus occupied a recognised place in the statecraft and economic administration of ancient India [6]. Vedic and later Sanskrit sources also refer to geographical regions and horses associated with the north-western areas [10]. Buddhist tradition described Kamboja as a country famous for horses, reinforcing the region's reputation [11]. The Kamboja country was thus not merely a source of animals but a centre of specialised knowledge about selection, training and maintenance [20].

Qualities of Kamboj Horses

Ancient literature particularly praised Kamboj horses for speed, strength, endurance and courage [1]. Jain literature describes the trained Kamboja horse as exceptionally swift and difficult to frighten by battlefield noise [2]. Such qualities were essential in an age when horses were central to cavalry and chariot warfare [14]. The Mahabharata gives detailed descriptions of horses presented by the Kamboja king [1]. Their colours, physical appearance and conformation are mentioned, suggesting that ancient horse culture valued both beauty and practical qualities [1]. The importance of training was equally great [2]. A powerful horse could become a successful war animal only through disciplined training and proper care [2]. Kamboja's reputation consequently reflected not merely natural horse qualities but also the knowledge of horsemen who selected, trained and maintained these animals [20]. The combination of good-quality horses and capable riders formed the basis of the Kamboja military tradition [20].

Kamboj Horses as Royal Gifts

The Mahabharata provides some of the most striking evidence for the prestige of Kamboj horses [1]. During Yudhishthira's Rajasuya, the King of Kamboja presented 300 horses among other valuable gifts [1]. The horses are described according to their distinctive varieties and physical characteristics [1]. This was not an ordinary commercial transaction: the presentation of hundreds of valuable horses to a powerful king represented wealth, diplomacy and political recognition [1]. Another remarkable episode occurs during Yudhishthira's consecration [1]. The Mahabharata states that the King of Bahlika brought a golden chariot, while Sudakshina, the Kamboja king, personally yoked four white Kamboja horses to it [1]. This reference is especially significant because it explicitly associates Sudakshina and the royal ceremony with four white horses of Kamboja origin [1]. These episodes show that Kamboj horses occupied a prestigious place in royal life [1]. They could be offered as tribute, diplomatic gifts and symbols of political power [1]. The presentation of horses was thus embedded in the political culture of ancient India, where the quality and number of horses reflected the status of both the donor and the recipient [1].

Maharaja Sudakshina Kamboja and the Kurukshetra War



Figure 2.

The Mahabharata mentions the Kamboja Mahajanapada [2]. It also mentions Bhanumati [2]. Bhanumati was the daughter of the Kamboja king Chitrang Kamboja and Queen Chandramudra Kamboja [2]. She was the sister of Maharaja Sudarshana Kamboja of the Kamboja Mahajanapada and was married to Duryodhana [2]. The Kamboja queen of Jayadratha is also mentioned in the Mahabharata (11.23.11) [2]. One of the wives of King Jayadratha of the Sindhu-Sauvira dynasty was a Kamboja princess [2]. The marriage alliance between the Kamboja dynasty and the Kauravas is a significant example of the political relationship between two royal families [2]. This familial relationship strengthened their political and military ties [2].

Maharaja Sudakshina Kamboja of the Kamboja Mahajanapada supported Jayadratha and Duryodhana in the war, especially to protect the honour and safety of his sister Bhanumati, who was Duryodhana's queen [2]. He commanded an army of approximately 6,000 horsemen, supported by golden chariots and white horses [2]. Along with the Kaurava army, he fought against the Pandavas and Arjuna on the battlefield of Kurukshetra and was martyred on the 13th or 14th day of the war [2]. Sudakshina's importance was not limited to rituals [2]. He appears as a prominent Kamboja ruler and warrior in the Kurukshetra War [2]. He led the Kamboja army fighting on the Kauravas' side, and in the Mahabharata, Kamboja warriors are known for their swift horses and effective cavalry warfare [2]. Another Kamboja king, Parama Kamboja, is said to have supported the Pandavas [2]. He sent his cavalry, equipped with white horses, to assist them [2]. The Pandavas lived with them during their exile and developed a friendly relationship with them [2]. However, Parama Kamboja himself did not directly participate in the Kurukshetra War [2]. Therefore, the Kambojas contributed not only horses but also experienced cavalry to ancient Indian warfare [2]. Their reputation was based on the combination of a good-quality horse and a capable rider [2]. Cavalry could move quickly, attack vulnerable positions, pursue retreating armies, and operate at distances where infantry was less effective [14]. The Kamboja military tradition thus became an essential part of north-western martial culture [20].

Kamboj Horses and Krishna's Chariot



Figure 3.

One of the most memorable references occurs in the Sauptika Parva of the Mahabharata [3]. Krishna's magnificent chariot is described as being yoked to superior Kamboja horses [3]. The four horses are named Shaibya, Sugriva, Meghapushpa and Balahaka [3]. This passage is particularly important because it places the celebrated Kamboja horse tradition in connection with Krishna's royal and military chariot [3]. The horses are presented as exceptional steeds, consistent with the high reputation given to Kamboja horses throughout the epic [3]. It is important, however, to distinguish the origin or quality designation from the individual names [3]. The text describes the team as superior Kamboja horses and then gives the names of the four steeds [3]. Thus,

@ 2026 Wah Academia Journal of Society, Culture and Policy. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license https://creativecommons.org/licenses/cc-by/4.0

the passage provides strong evidence for the prestige of Kamboja horses without requiring the individual names themselves to be treated as the name of a Kamboj breed [3].

Kamboj Horses and Long-Distance Trade

The importance of Kamboj horses extended beyond warfare [13]. The scarcity of high-quality horses in many parts of India created a profitable long-distance trade [13]. Merchants carried horses from the north-west towards the major political and commercial centres of the subcontinent [13]. Kamboja's location on the routes towards Central Asia gave it an important position in this trade [13]. Horses moved alongside merchants, soldiers and political representatives [13]. They were exchanged for wealth and goods and were also presented to rulers as tribute [13]. The horse trade therefore helped connect the north-west with the Gangetic plain and eastern India [13]. The history of Kamboj horses is consequently also a history of ancient India's wider commercial networks [13]. The Arthashastra's attention to the native place and management of horses reflects the state's interest in this trade [4]. Modern studies of the horse trade in north India have examined its socio-economic dimensions and its integration with wider commercial life [13].

The Kamboja-Asvaka Resistance Against Alexander: A Golden Page of Glory



Figure 4.

During Alexander's Indian campaign, the Assakanoi/Assakenoi community in the north-west offered strong resistance [7]. Greek sources mention their queen as Cleophis [7]. Many modern Indian historians and Kamboja historians have attributed Cleophis to the Indian name Kripa/Kripi and linked her to the Kamboja-Asvaka tradition [20]. Dr. R.K. Mukherjee, Dr. V.D. Mahajan, Dr. L.M. Joshi, Dr. Fauja Singh, and especially Dr. J.L. Kamboj and Dr. Ramjilal support this identification [20, 21]. The military importance of the north-western mounted warrior tradition is also evident during Alexander's invasion of 327–326 BCE [8]. Greek writers describe the strong resistance of the Assakanoi/Asvakas in the areas of Massaga and Swat [8]. After the death of the local ruler, Queen Cleophis is associated in classical accounts with continuing the defence [9]. Diodorus wrote that she eventually reached a compromise with Alexander and was restored to her kingdom [7]. Later Indian interpretations have linked the Ashvaka mounted warrior communities to the broader Kamboja tradition [20]. It can be emphasised that the resistance of the great Kamboja queen, Kirpa Kamboja, was serious enough to lead to negotiations [21]. The Kamboja queen and Alexander had to sign a treaty because, on the one hand, the queen did not want to take innocent lives; on the other hand, Alexander's army was tired of constant warfare, and there was a fear of rebellion within his army, as later events proved [21]. As a result, peace and the reign of Queen Kirpa Kamboja were maintained after the agreement [21]. This is a glorious page in ancient Indian history [21].

From Kamboja to Bengal

The Kamboja tradition subsequently appears far beyond its original north-western homeland [15]. Epigraphic evidence establishes the existence of a Kamboja ruling family in parts of Bengal during the later tenth and early eleventh centuries [15]. The Dinajpur pillar inscription refers to a ruler belonging to the Kamboja family as a lord of Gauda, while the Irda copper plate records Kamboja rulers including Rajyapala, Narayanapala and Nayapala [15]. This evidence is historically important [16]. It demonstrates that the Kamboja name and political tradition had become established in eastern India [16]. It also illustrates the remarkable geographical mobility of political and military groups in early medieval India [16]. The horse connection continued as well [17]. The Monghyr inscription of the Pala ruler Devapala has been interpreted as referring to horses connected with Kamboja, showing that the north-western horse-producing region remained linked with eastern India [17]. Thus, Kamboja's historical influence should not be confined to its original homeland [18]. Its political and commercial connections extended across large parts of the subcontinent [18]. Studies of the inscriptions of Bengal provide further evidence concerning the political history of the Kamboja rulers [19]. The Irda Copper Plate and the Dinajpur Pillar Inscription remain important sources for this phase of Kamboja history [15].

Kamboja and Kambuja (Cambodia)

A further question concerns the relationship between Kamboja and Kambuja, the ancient Sanskrit name associated with Cambodia [24]. The similarity has led historians to propose different explanations [24]. The leading scholars of ancient Indian history connected the Cambodian name with the ancient Indian Kambojas [20]. Additionally, the wider Indian cultural influence on early Cambodia is well documented [24]. Sanskrit language, Indian religious traditions and political concepts became deeply embedded in early Khmer civilisation [24]. It is a historical fact that the Kamboja name has an extraordinarily wide geographical history, extending from the north-western frontier of India into eastern India and into the broader cultural world of Southeast Asia [24]. Studies of the Indianized states of Southeast Asia provide the broader context for understanding these connections [24]. The historical discussion of early Cambodia and the development of Khmer civilisation further illuminates this wider cultural world [25].

A Horse Tradition with a Wider Historical Meaning

The history of Kamboj horses reveals the close relationship between animal husbandry, trade, warfare, diplomacy and political power in ancient India [1]. Kamboja's geographical position allowed it to participate in the movement of horses between Central Asia and the Indian plains [13]. Its horsemen developed a reputation for military skill, while its horses became prized possessions of kings [2]. The Mahabharata provides particularly vivid examples: the Kamboja king's gift of 300 horses to Yudhishthira, Sudakshina's four white Kamboja horses, his participation in the Kurukshetra War, and the description of Krishna's chariot with superior Kamboja horses [1, 2, 3]. The later evidence from Bengal shows that the Kamboja tradition did not disappear with the ancient period [15]. Kamboja rulers established themselves in parts of Bengal, while horses continued to travel from the Kamboja country towards eastern India [17]. The tradition thus demonstrates remarkable continuity across time and space [20]. The Kamboja name and its associated horse culture became part of the wider historical memory of ancient India [21].

Conclusion

The Kamboj horse represents an important but often overlooked chapter of ancient Indian history [1]. Kamboja was associated with a

sophisticated tradition of horse breeding, selection, training, trade and warfare [4]. Its horses were valued for speed, endurance and courage and became objects of royal gifts and military use [2]. From the royal ceremonies of the Mahabharata to the battlefield of Kurukshetra, from the horse-warrior resistance encountered by Alexander to the later Kamboja dynasty in Bengal, the historical record reveals a tradition of remarkable geographical reach [1, 2, 7, 15]. The Kamboj horse was therefore much more than a celebrated animal [13]. It was part of a wider network connecting commerce, military power, political authority and cultural exchange across ancient India and its north-western and eastern frontiers [13, 20]. The study of the Kamboj horse thus offers valuable insights into the economic, military and political history of ancient India, and into the remarkable mobility of communities, commodities and cultural traditions across the subcontinent and beyond [21].

References

1. Vyasa. The Mahabharata, Sabha Parva, Book II — passages concerning the Rajasuya sacrifice, the King of Kamboja and the presentation of horses to Yudhishthira.
2. Vyasa. The Mahabharata, Drona Parva, Book VII — references to Sudakshina Kamboja, Kamboja warriors and their participation in the Kurukshetra War.
3. Vyasa. The Mahabharata, Sauptika Parva, Book X, Section XIII — description of Krishna's chariot and the four Kamboja horses: Shaibya, Sugriva, Meghapushpa and Balahaka.
4. Kautilya (Chanakya). Arthashastra, Book II, Chapter XXX, "The Superintendent of Horses" (Aśvādhyakṣa) — classification, registration, native place, breeding and management of horses.
5. Kautilya. Arthashastra, translated by R. Shamasastry, Bangalore, 1929 — the classification of horses associated with Kamboja, Sindhu, Aratta and Vanayu among the superior categories.
6. Chettri, S., & Sangmu, T. (2025). Horses and statecraft in Kautilya's Arthashastra. Journal of Asiatic Society for Social Science Research, 7(1), 150–159. DOI: 10.46700/asssr/2025/v7/i1/150
7. Diodorus Siculus. Bibliotheca Historica, Book XVII — account of Alexander's campaign in the north-western Indian region, including Massaga and Cleophis (Kleophis) of the Assacenians.
8. Arrian. Anabasis of Alexander, Book IV — Alexander's campaigns against the Aspasians and Assacenians/Ashvakas in the north-west of the Indian subcontinent.
9. Curtius Rufus, Q. Historiae Alexandri Magni, Book VIII — the Assakenoi resistance and the role attributed to Cleophis after the death of Assakenos.
10. Macdonell, A. A., & Keith, A. B. (1912). Vedic Index of Names and Subjects, Vol. I–II. London: John Murray.
11. Law, B. C. Tribes in Ancient India. Banaras/Calcutta, various editions.
12. Gode, P. K. Studies in Indian Cultural History — discussion of ancient Indian horse varieties and the classification of Kamboja, Sindhu, Aratta and Vanayu horses in the Arthashastra.
13. Gupta, C. (1983). Horse trade in North India: Some reflections on socio-economic life. Journal of Ancient Indian History, 14, 186–206.
14. Basham, A. L. (1954). The Wonder That Was India. London: Sidgwick & Jackson.
15. Majumdar, N. G. (1933–34). The Irda Copper Plate. Epigraphia Indica, XXII, 150–158.
16. Majumdar, R. C., & Pusalkar, A. D. (Eds.). (1964). The History and Culture of the Indian People: The Age of Imperial Kanauj. Bharatiya Vidya Bhavan.
17. Banglapedia. "Kamboja Gaudapatis" — discussion of the Dinajpur Pillar Inscription and Irda Copperplate, and the Kamboja rulers Rajyapala, Narayanapala and Nayapala in Bengal.
18. Majumdar, R. C. History of Bengal, Vol. I — discussion of early medieval Bengal and the Kamboja rulers.
19. Sen, B. C. Some Historical Aspects of the Inscriptions of Bengal — evidence concerning the political history of Bengal and Kamboja rulers.
20. Kamboj, J. L. (1981). Ancient Kamboja: People and the Country — study of Kamboja geography, political history and cultural traditions.
21. Singh, K. (2005). The Kambojas Through the Ages — discussion of Kamboja history, including the Kamboja-Pala rulers of Bengal.
22. Pusalkar, A. D., & Majumdar, R. C. Studies of the Bangar Charter of Mahipala I and the political changes in Bengal associated with the Kambojas.
23. Industry, Trade and Commerce in Early Medieval Bengal, University of North Bengal repository — discussion of the Kamboja rulers in Bengal, the Irda Copperplate, Dinajpur inscription and the political position of the Kamboja dynasty.
24. Coedès, G. The Indianized States of Southeast Asia. University of Hawai'i Press.
25. Mabbett, I. W., & Chandler, D. P. The Khmers. Blackwell.

Declarations:

Authors' Contribution:

- All Authors: Conceptualization, data collection, interpretation, drafting of the manuscript and intellectual revisions
- The authors agree to take responsibility for every facet of the work, making sure that any concerns about its integrity or veracity are thoroughly examined and addressed

Conflict of Interest: NIL

Funding Sources: NIL

@ 2026 Wah Academia Journal of Society, Culture and Policy. Published by WA (SMC-PVT) Ltd. This is an open access article under the CC BY license https://creativecommons.org/licenses/cc-by/4.0

Intersections *of* Knowledge:

Dialogues Across Disciplines



Contemporary global challenges increasingly transcend traditional disciplinary boundaries, demanding collaborative thinking and integrative scholarship. *Intersections of Knowledge: Dialogues Across Disciplines* seeks to bring together scholars, researchers, practitioners, and policymakers from diverse fields to contribute original chapters that foster intellectual dialogue across disciplines and offer innovative perspectives on pressing social, scientific, technological, environmental, and health-related issues.

This edited volume aims to serve as a platform for advancing multidisciplinary inquiry and showcasing research that bridges disciplinary silos to address complex local and global challenges.

SCIENCE | HUMANITIES | SOCIAL SCIENCES | LAW | TECHNOLOGY | ARTS | ENVIRONMENT | POLICY | PHILOSOPHY

WAH ACADEMIA PUBLISHING
2026
www.wahacademiapublishing.com
info@wahacademiapublishing.com

ISBN 978-627-7901-23-3

INTERSECTIONS OF KNOWLEDGE: DIALOGUES ACROSS DISCIPLINES

2026