

Technological Advances in Spectroscopy and Optical Sensors for Non-Invasive Hemoglobin Measurement



A Systematic Review (2015–2025)

Renan Prasta Jenie^{1,2,*}, Ichsan Hardyanto³, Fahmi Noor Fiqri⁴, Nazopatul Patonah Har³, Vania Rahmawaty³, Arga Aridarma⁵, Ageng Prabowo⁵, Aep Setiawan^{3,6}, Ika Rahayu⁷, Ridwan Siskandar⁶, Karlisa Priandana⁴, Husin Alatas³, Rofiqul Umam⁸, Hirotaka Takahashi⁹, Subash Chandra Bose Gopinath¹⁰, Irzaman^{3,*}

¹ Digital Business Department, Binawan University, East Jakarta 13630, Indonesia

² Research, Development, and Innovation Directorate,
Indonesia Artificial Intelligence Society, South Jakarta 12790, Indonesia

³ Physics Department, IPB University, Bogor Regency 16680, Indonesia

⁴ Computer Science Study Program, IPB University, Bogor Regency 16680, Indonesia

⁵ PT Tesena Inovindo, East Jakarta 13750, Indonesia

⁶ Vocational Studies School, IPB University, Bogor City 16128, Indonesia

⁷ Medical Faculty, Universitas Kristen Krida Wacana, West Jakarta 11470, Indonesia

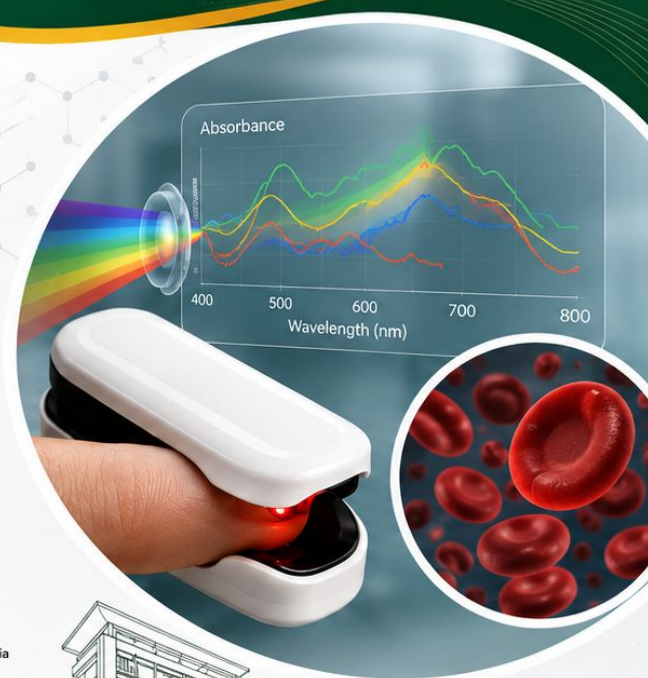
⁸ Institute of Life and Environmental Sciences, University of Tsukuba, Japan

⁹ Faculty of Design and Data Science, Tokyo City University, Japan

¹⁰ Institute of Nano Electronic Engineering, Universiti Malaysia Perlis,
Kangar 01000, Malaysia



*qwerty.user1983@gmail.com; irzaman@apps.ipb.ac.id



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BACKGROUND

Non-invasive hemoglobin (Hb) measurement offers a painless alternative to blood sampling for anemia screening and continuous monitoring.



OBJECTIVE

To systematically review recent advances in spectroscopy and optical sensors for non-invasive Hb measurement, including technologies, algorithms, validation, and performance.



METHODS

- PRISMA 2020 guideline
- Literature 2015–2025
- Search in major databases + citation chaining
- 365 candidate → 344 relevant → 213 highly relevant studies

FOUR MAJOR TECHNOLOGY CATEGORIES



Multi-wavelength Photoplethysmography **37.6%**
PPG-based systems using multiple wavelengths for Hb estimation.



Spectroscopy & Hyperspectral Imaging **30.0%**
Reflectance/absorbance spectroscopy and hyperspectral imaging approaches.



Smartphone-based Imaging **19.7%**
Camera-based solutions leveraging ambient light and AI algorithms.



Calibration & Robustness Strategies **12.7%**
Methods to improve accuracy across skin tones, sites, and conditions.

KEY FINDINGS



MAE as low as
0.25 g/dL



RMSE
0.81–1.88 g/dL



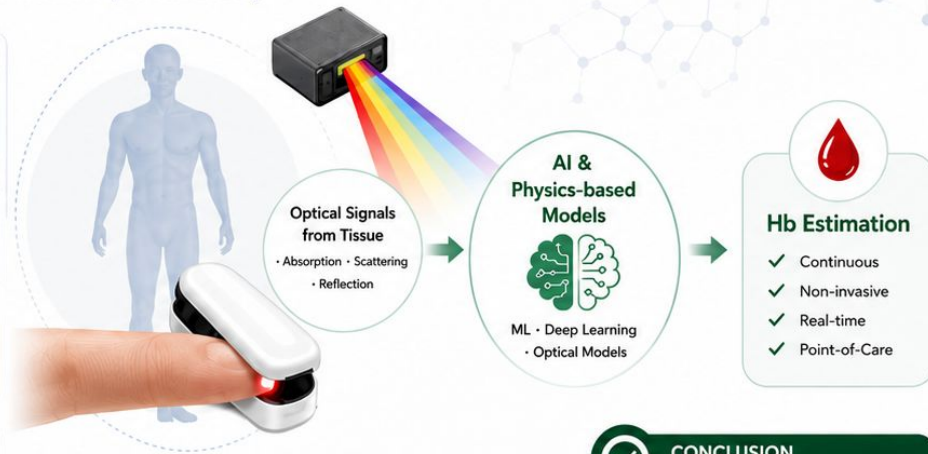
Correlation (r)
up to **0.987**



Diagnostic Accuracy
>99%
(in controlled studies)



Key Challenges:
Skin pigmentation, motion artifacts, illumination variability, site differences, calibration transferability



CONCLUSION

Spectroscopy integrated with artificial intelligence shows strong potential for non-invasive Hb assessment. Standardized protocols, multicenter studies, and improved robustness across diverse populations are essential for widespread clinical adoption.

* Corresponding authors:
qwerty.user1983@gmail.com;
irzaman@apps.ipb.ac.id



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INTRODUCTION



The Need for Non-Invasive Hemoglobin Measurement



BACKGROUND

Hemoglobin (Hb) measurement is essential for anemia screening, diagnosis, and monitoring. Conventional methods rely on invasive blood sampling, which can be painful, time-consuming, resource-intensive, and less suitable for frequent or continuous monitoring.



WHY IT MATTERS

A rapid, accurate, and non-invasive Hb measurement can transform healthcare by enabling point-of-care testing, continuous monitoring, and wider access—especially in resource-limited settings.



EVOLUTION OF OPTICAL APPROACHES



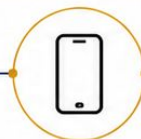
PHOTOPLETHYSMOGRAPHY (PPG)

Early non-invasive monitoring using light absorption changes in blood volume.



SPECTROSCOPY & HYPERSPECTRAL IMAGING

Provides detailed spectral information to estimate Hb concentration.



SMARTPHONE & PORTABLE DEVICES

Expanding accessibility through mobile and low-cost platforms.



AI & ADVANCED MODELS

Enhancing accuracy and robustness through machine learning and physics-based approaches.



OUR GOAL

This systematic review synthesizes technological advances in **spectroscopy and optical sensors** for **non-invasive hemoglobin measurement**, highlighting current achievements, challenges, and opportunities for future research and clinical impact.



METHODS

Systematic Review Approach

This systematic review was conducted in accordance with the PRISMA 2020 guidelines.



SEARCH STRATEGY

- Five search queries executed independently
- Deep Review academic database (indexed >270 million publications)
- Publication filter: 2015–2025



STUDY IDENTIFICATION

- Initial search identified 320 potentially relevant articles
- Backward and forward citation chaining performed
- Additional 45 records identified through citation chaining



ELIGIBILITY CRITERIA

Inclusion based on relevance to non-invasive hemoglobin measurement using spectroscopy and optical sensors, in vivo human studies, algorithm/validation reports, and clinical performance data.



SCREENING & SELECTION

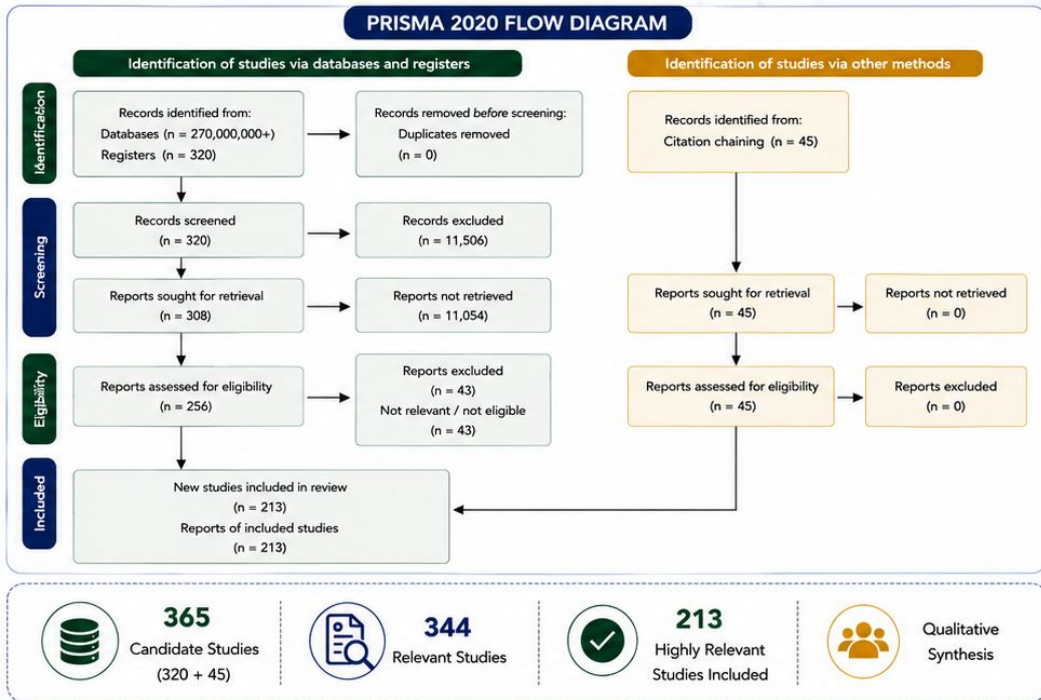
- 365 candidate studies screened
- 344 studies classified as relevant
- 213 studies identified as highly relevant and included in qualitative synthesis



DATA EXTRACTION

Extracted information on sensing technology, optical principles, algorithms, confounder mitigation, validation methods, and diagnostic performance.

PRISMA 2020 FLOW DIAGRAM



RESULTS

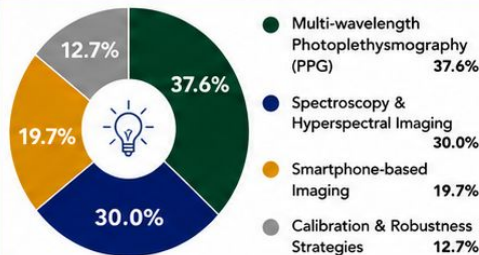
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STUDY INCLUSION (2015–2025)



Followed **PRISMA 2020** Guidelines

TECHNOLOGY CATEGORIES



KEY PERFORMANCE HIGHLIGHTS



MAE (best)

0.25
g/dL



RMSE (range)

0.81 – 1.88
g/dL



Correlation (r)
up to **0.987**



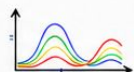
Diagnostic Accuracy
> 99%
(controlled conditions)

METHODS & ALGORITHMS



Machine Learning

- CNN
- SVR
- XGBoost
- Vision Transformers



Spectroscopic Techniques

- UV–Vis–NIR
- Diffuse Reflectance
- Hyperspectral



Wearable / Mobile Platforms

- Portable sensors
- IoT integration



Validation Approaches

- Clinical datasets
- Phantom studies
- Cross-device tests

MAIN FINDINGS

- ✓ Spectroscopy + AI shows strong potential for accurate non-invasive Hb estimation.
- ✓ Performance is influenced by skin pigmentation, motion, illumination, and measurement site.
- ✓ Need for standardized validation, multicenter studies, and robust calibration for real-world application.

KEY CHALLENGES

- ⓘ Population diversity
- ⓘ Illumination & motion artifacts
- ⓘ Cross-device calibration transferability
- ⓘ Dataset heterogeneity

“

Our review highlights significant advances and emerging opportunities to bring non-invasive hemoglobin measurement closer to **practical, reliable, and equitable** healthcare solutions. ”



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DISCUSSION

Interpreting Advances, Challenges, and Future Directions

WHAT THE RESULTS TELL US



Strong Progress

Significant improvements in accuracy and robustness demonstrate the maturity of optical sensing combined with AI for Hb estimation.



Spectroscopy Leads

Spectroscopy and hyperspectral imaging provide richer spectral information, enabling more accurate Hb quantification.



Mobile & Accessible

Smartphone-based solutions expand accessibility and point-of-care potential, especially in resource-limited settings.



AI as a Game Changer

Machine learning and deep learning models capture complex patterns and complement physics-based optical models.

STRENGTHS & LIMITATIONS



STRENGTHS

- Diverse technologies and large body of evidence (213 highly relevant studies).
- Integration of physics-based models with AI improves reliability.
- High diagnostic accuracy reported under controlled conditions.



LIMITATIONS

- Performance drops in real-world, uncontrolled environments.
- Heterogeneity in datasets, devices, and validation methods.
- Limited multicenter clinical studies and population diversity.
- Calibration transferability remains a challenge.

IMPLICATIONS



For Healthcare

Enables non-invasive, continuous, and patient-friendly Hb monitoring and anemia screening.



For Technology

Drives innovation in portable spectroscopy, wearables, and AI models for robust performance.



For Society

Expands access to affordable diagnostics and supports public health initiatives globally.



For Policy

Supports guideline development, standardization, and regulatory pathways for adoption.

FUTURE DIRECTIONS



Multicenter, multi-ethnic, real-world clinical studies.



Standardization of devices, protocols, and datasets.



Hybrid models combining physics-based and AI approaches.



Next-generation sensors with improved stability and calibration transferability.



Integration with digital health platforms and IoT for continuous monitoring.

KEY CHALLENGES



Population Diversity

Skin pigmentation and anatomical differences affect optical signals and model generalizability.



Motion & Illumination Artifacts

Movement and varying light conditions remain major sources of error in practical use.



Measurement Site Variability

Different sites and contact pressures influence optical pathlength and accuracy.



Calibration & Standardization

Lack of standardized protocols hinders device comparison and clinical adoption.



Clinical Validation Gap

Need for large-scale, multicenter trials with diverse populations and real-world validation.

OVERALL TAKEAWAY



Spectroscopy integrated with artificial intelligence has achieved remarkable progress toward **accurate** non-invasive hemoglobin measurement. However, bridging the gap between controlled performance and real-world applicability requires **standardization, robust validation, and inclusive research** across diverse populations.



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THANK YOU

FOR YOUR ATTENTION

Together, through innovation in spectroscopy and optical sensors, we move closer to accurate, accessible, and equitable non-invasive hemoglobin measurement for better health outcomes.

KEY TAKEAWAYS



STRONG POTENTIAL
Spectroscopy and optical sensors show excellent potential for non-invasive Hb assessment.



ACCURACY & ROBUSTNESS
Advances in technology and AI improve accuracy, yet robustness across diverse populations remains key.



STANDARDIZATION
Standardized validation protocols and multicenter studies are essential for clinical adoption.



COLLABORATION
Interdisciplinary collaboration between academia, industry, and healthcare is crucial to translate innovation.



BETTER IMPACT
Our work contributes to better health outcomes and a more inclusive healthcare future.



Let's continue turning science and technology
into meaningful impact for society.



 qwerty.user1983@gmail.com

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