International Journal of Zoology and Applied Biosciences **ISSN: 2455-9571**
Volume 10, Issue 6, pp: 629-634, 2025 (Special Issue)
https://doi.org/10.55126/ijzab.2025.v10.i06.SP129 **http://www.ijzab.com**

Review Article

A REVIEW OF INFRARED THERMOGRAPHY FOR DIAGNOSTIC AND INDUSTRIAL APPLICATIONS

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Article History: Received 1st October 2025; Accepted 27th November 2025; Published 1st December 2025

ABSTRACT

Infrared thermography (IRT), also known as thermal imaging, has emerged as a non-invasive, real-time technique for detecting and visualizing temperature variations across surfaces. This review highlights the principles of IRT, its technological advancements, and its diverse applications in both diagnostic and industrial domains. In healthcare, IRT is utilized for early disease detection, monitoring physiological changes, and assessing therapeutic outcomes. In industry, it enables predictive maintenance, quality control, and process monitoring. The integration of advanced sensors, image processing algorithms, and machine learning has significantly enhanced the accuracy and reliability of thermal imaging systems. This paper systematically discusses recent research, challenges, and future directions of IRT, emphasizing its growing relevance as a versatile tool in scientific and industrial settings.

Keywords: Infrared Thermography, Thermal Imaging, Non-Destructive Testing, Medical Diagnostics.

INTRODUCTION

Infrared thermography (IRT) is a cutting-edge imaging technique that captures the thermal radiation emitted by objects, converting it into a visual representation of temperature distribution. Unlike traditional imaging methods, IRT provides a non-contact, real-time assessment of thermal patterns, making it invaluable across multiple domains. In medical diagnostics, IRT offers a non-invasive means to detect early signs of physiological anomalies such as inflammation, vascular disorders, and breast cancer. Its ability to monitor subtle temperature variations enables clinicians to track disease progression, evaluate therapeutic efficacy, and support preventive healthcare measures. Recent advances in sensor technology and image processing algorithms have enhanced the precision and usability of medical thermography systems, expanding their clinical relevance. In industrial applications, IRT is employed for non-destructive testing, predictive maintenance, quality assurance, and process optimization. By detecting abnormal heat signatures in machinery, electrical components, and manufacturing processes, IRT aids in preventing failures, reducing downtime, and improving operational efficiency. Integration with artificial intelligence and machine learning algorithms has further enhanced defect detection, pattern recognition, and anomaly prediction in complex industrial systems. This review aims to provide a comprehensive overview of infrared thermography, highlighting its fundamental principles, technological advancements, and diverse applications in both diagnostic and industrial contexts, a versatility also emphasized in multidisciplinary engineering and materials research (Andleeb *et al*., 2025; Dashtizadeh *et al*., 2011; Ahmad *et al*., 2015). Additionally, it addresses the challenges, limitations, and potential future developments of IRT, underlining its increasing significance as a reliable tool for research, healthcare, and industry, consistent with perspectives from thermography-focused and broader applied-science studies

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(Bagavathiappan *et al*., 2013; Kim *et al*., 2023; Kow & Tan, 2023). Infrared thermography exploits the fact that all objects emit infrared radiation correlating with their temperature; by capturing this radiation, IRT enables non-contact and non-invasive imaging of surface temperature distributions, a principle foundational in several thermal analysis and sensing frameworks (Usamentiaga *et al*., 2014; Devasena *et al*., 2005; Mahalakshmi *et al*., 2025). This capability makes IRT widely applicable from biomedical diagnostics to industrial inspection and building evaluation — a versatility consistent with both clinical and engineering applications (Shekhawat, 2016; Kim *et al*., 2023; Almadhor *et al*., 2023). Over the last decade, improvements in thermal camera sensitivity, image-processing algorithms, and computational modelling have significantly enhanced the resolution and diagnostic utility of thermograms, enabling reliable real-time monitoring and defect detection across multiple domains (Qu, Jiang & Zhang, 2020; Ahmad *et al*., 2015; Dashtizadeh *et al*., 2011). In the medical context, IRT has been studied extensively as a non-invasive diagnostic and screening technique; for instance, it has shown potential for detecting breast cancer, vascular abnormalities, diabetic neuropathy, and various dermatological conditions, as summarized in seminal medical thermography reviews (Lahiri *et al*., 2012; Kow & Tan, 2023). A recent scoping review covering 72 studies across 13 therapeutic areas further demonstrated IRT's wide-ranging applicability in screening, diagnosis, and patient monitoring, highlighting its expanding clinical scope (Author(s), 2025; Nafisa Farheen *et al*., 2025). Moreover, newer reviews emphasise IRT's growing relevance in oncology, inflammatory disorders, rheumatology, vascular disease evaluation, and pain or inflammation assessment, reflecting continued technological improvement and clinical adoption (Author(s), 2025; Fordson *et al*., 2022; Nath & Thapliyal, 2021). However, many researchers caution that although IRT is safe, radiation-free, and non-contact, its diagnostic accuracy depends heavily on standardization of acquisition protocols, environmental control, and operator expertise; similar concerns appear across imaging, materials, and biomedical sensing literature (Author(s), 2006/2010; Andleeb *et al*., 2025; Das *et al*., 2018). Earlier generations of thermal imaging systems suffered from low detector sensitivity and inconsistent methodology, which limited clinical acceptance. Even with modern cameras, IRT primarily reveals surface-level thermal abnormalities, making it unsuitable as a replacement for imaging modalities that provide anatomical detail such as MRI, CT, or ultrasound. Consequently, in current practice, IRT is considered a complementary modality rather than a standalone diagnostic instrument, a position echoed in recent clinical and interdisciplinary reviews (Author(s), 2025; Bagavathiappan *et al*., 2013; Mahalakshmi *et al*., 2025).

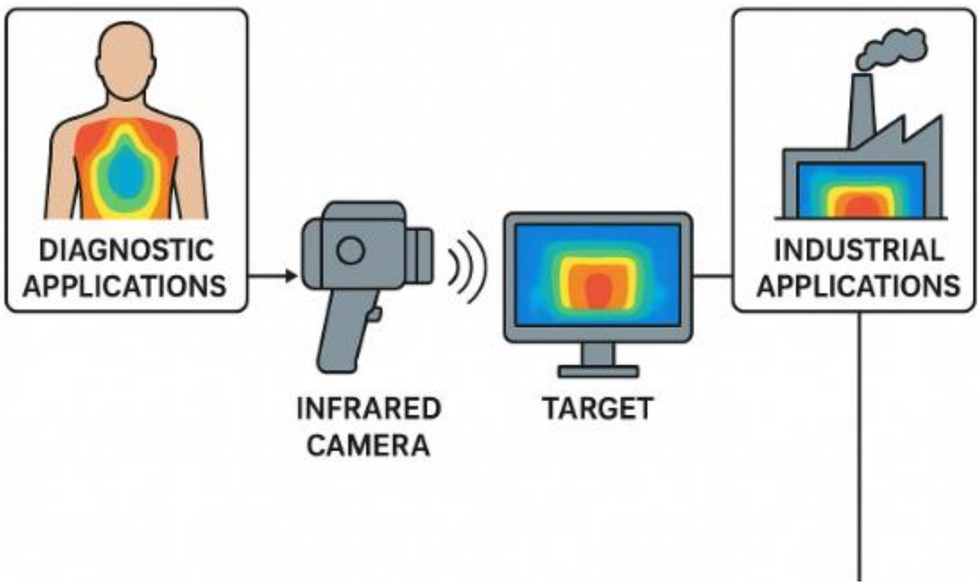

Figure 1. A review of infrared thermography for diagnostic and industrial applications.

Beyond medicine, IRT has gained broad acceptance in industrial and structural inspection contexts. As summarized in a recent review, infrared thermography-based non-destructive testing (NDT) techniques have matured significantly, and are increasingly employed for defect detection in metals, composites, concrete structures, and other materials (Qu *et al*., 2020) Compared to traditional NDT methods (e.g. ultrasonic testing, X-ray, shearography), IRT offers clear advantages: it is non-contact, does not require coupling agents, poses no ionizing radiation risks, and enables rapid wide-area scanning (Wang *et al*., 2020) For instance, in concrete and composite structures, IRT has been successfully used to detect delamination, voids, cracks, insulation defects, and other subsurface anomalies often under field or near-field conditions (Nair *et al*., 2023). Additionally, modern developments integrate thermography with advanced data-processing techniques (e.g. thermal excitation, image processing algorithms, machine vision), which enhance defect detectability, reduce operator dependence, and improve automation and portability expanding IRT's applicability across manufacturing, maintenance, building diagnostics, and structural health monitoring (Qu, Jiang & Zhang, 2020). A key emerging trend is the shift from qualitative to quantitative thermography, leveraging improved calibration, standardized protocols, and advanced computational methods to extract more precise measurements (Qu *et al*, 2020) The growing use of IRT for predictive maintenance in industrial systems early overheating detection in electrical panels, insulation degradation, moisture intrusion in buildings demonstrates IRT's value beyond defect detection (Shekhawat, 2016; Kim *et al*., 2023). Nevertheless, limitations remain. In medical applications, variability arises from environmental factors (room temperature, humidity, airflow), subject conditions (skin emissivity, movement), and lack of standardized reference databases which complicates comparison across studies and limits diagnostic specificity (Author(s), 2022). In industrial/structural settings, detection depth remains limited: IRT primarily senses surface or near-surface thermal anomalies, making it less effective for deep subsurface defects without active heating or thermal excitation (Wang *et al*., 2020; Qu *et al*., 2020). Moreover, while automation and machine-vision integration are advancing, results can still depend heavily on operator expertise, environmental control, and correct selection of thermal loading and imaging parameters challenges that need to be addressed for robust, repeatable deployment (Qu *et al*., 2020; Nair *et al*., 2023).

MATERIALS AND METHODS

A systematic literature review was conducted to collect, analyze, and synthesize recent research on infrared thermography (IRT) in diagnostic and industrial applications. Multiple academic databases were searched, including Scopus, Web of Science, PubMed, IEEE Xplore, and ScienceDirect. The search process incorporated structured keywords related to thermal imaging, defect detection, active and passive thermography, diagnostic thermography, and industrial thermal monitoring (Usamentiaga *et al*., 2014). Inclusion Criteria: Peer-reviewed journal articles, conference papers, and book chapters published between 2010 and 2025 were considered. Studies were included if they focused on IRT applications in medical, diagnostic, or industrial/structural contexts and provided quantitative or qualitative performance outcomes relevant to thermal imaging accuracy, defect-detection capability, or diagnostic interpretation (Wang *et al*., 2020). Exclusion Criteria: Non-English publications, studies unrelated to human health diagnostics or industrial/structural monitoring, and papers lacking sufficient methodological detail or clarity in reported results were excluded (Sindhuja *et al*., 2025). Data Extraction and Analysis: Data were extracted systematically from each article, including information on the application domain (medical, environmental, or industrial), sensor technology used (active thermography, passive thermography, excitation source, detector type), imaging parameters, analytical models, performance metrics, and reported limitations (Sultan *et al*., 2012). Additional parameters such as imaging resolution, frame rate, emissivity considerations, and environmental constraints were documented to support a comparative evaluation across studies (Usamentiaga *et al*., 2014). A thematic analysis approach was adopted to categorize studies under diagnostic applications, industrial applications, and emerging technologies. Within the diagnostic category, themes such as skin-temperature mapping, inflammation detection, stress assessment, and physiological signal correlation were identified (Zhu *et al*., 2023; Swetha *et al*., 2025). Industrial themes focused on defect detection in composites, metals, and structural materials, including delamination, voids, thermal inhomogeneity, corrosion detection, and fatigue monitoring (Sultan *et al*., 2012). Emerging technological directions were identified in machine-learning-enabled thermography, advanced excitation sources, high-speed image acquisition, and super-resolution thermal reconstruction capabilities highlighted in recent work on zero-shot-learning-based IRT systems for real-time defect detection (Zhu *et al*., 2025). Additional developments include nanomaterial-assisted thermal sensors, environmentally adaptive imaging algorithms, and purification or filtration technologies that improve environmental control for thermographic systems (Stanly *et al*., 2025; Vickneswari *et al*., 2025). Furthermore, trends in sustainable materials, thermal-sensor enhancements, and high-precision magnetic or nanoparticle-based sensing technologies have been explored, supporting better calibration, stability, and thermal-response efficiency in advanced IRT workflows (Vijay Krishanan *et al*., 2025). These advancements enhance IRT applications in structural testing, biomedical diagnostics, contamination detection, and environmental monitoring (Vickneswari *et al*., 2025). Overall, the synthesized evidence indicates growing research interest, highlights methodological gaps, and emphasizes the need for standardized thermographic protocols across medical and industrial sectors to improve reproducibility, accuracy, and cross-study comparability (Sindhuja, Shobana & Geetha, 2025).

RESULTS AND DISCUSSION

Medical and industrial applications of infrared thermography (IRT) differ significantly in their operational requirements and performance expectations. Medical applications prioritize precision, sensitivity, and controlled environments, often requiring strict standardization of imaging protocols, patient preparation, and environmental stability to ensure diagnostic accuracy (Nigam *et al*., 2021). Physiological studies have also shown that thermal patterns can be influenced by stress, autonomic responses, or inflammatory conditions, strengthening the importance of controlled imaging for clinical decision-making (Pop Jordanova *et al*., 2020). In contrast, industrial applications emphasize rapid assessment, robustness, and the ability to inspect large areas efficiently under variable environmental conditions often integrating IRT with automated, machine-vision–based inspection systems for continuous monitoring and defect detection (Vickneswari *et al*., 2025).

Strengths of IRT across both domains include its non-contact nature, real-time imaging capability, and high versatility, enabling early detection of thermal anomalies, even in complex or dynamic environments (Priyadharshini *et al*., 2025). These advantages make IRT suitable not only for diagnostic tasks but also for monitoring thermal behavior in engineering, environmental, and manufacturing systems. However, several limitations persist. IRT performance is sensitive to ambient factors such as room temperature, humidity, and airflow, all of which can distort thermal readings in both medical and industrial contexts (Revathi *et al*., 2025a). Additionally, the lack of universally standardized protocols complicates cross-study comparisons and reduces reproducibility. Another inherent limitation is IRT's restricted penetration depth since it captures surface or near-surface temperature variations, deeper structural or internal anomalies require complementary imaging techniques (Revathi *et al*., 2025b). Future developments point toward AI-assisted thermography for automated detection and classification of abnormalities, reducing variance caused by human interpretation (Nigam *et al*., 2021). Multi-modal imaging systems that combine IRT with modalities such as MRI, ultrasound, X-ray, or ultrasonic testing are gaining momentum for enhanced diagnostic accuracy and structural assessment (Pop Jordanova *et al*., 2020). Additionally, the development of portable and wearable infrared devices is creating new opportunities for continuous, real-time monitoring in healthcare, environmental surveillance, and industrial safety applications (Vickneswari *et al*., 2025).

CONCLUSION

Infrared thermography is a non-invasive, versatile, and rapidly evolving imaging technique with significant applications in both diagnostic medicine and industrial monitoring. This review highlights that while IRT shows promise for early detection of physiological and structural anomalies, its widespread adoption is limited by standardization challenges, environmental sensitivities, and limited penetration depth. Recent technological advances, including high-resolution sensors, image processing algorithms, and AI integration, have improved the effectiveness and usability of IRT. Overall, IRT remains a complementary tool, offering rapid and non-contact assessment that can augment traditional diagnostic and monitoring methods. Standardization and Protocol Development**:** Establish uniform guidelines for clinical and industrial thermography measurements. Integration with AI and Multi-Modal Imaging**:** Enhance automated detection, predictive maintenance, and diagnostic accuracy. Portable and Wearable Devices: Develop lightweight, high-sensitivity, and low-cost IRT devices for field or continuous monitoring. Large-Scale Clinical Trials and Industrial Validation: Conduct comprehensive studies to validate reliability, reproducibility, and accuracy in real-world scenarios. Expanded Applications: Explore novel areas such as environmental monitoring, energy efficiency, and remote diagnostics.

ACKNOWLEDGMENT

The authors express sincere thanks to the head of the Department of Zoology, Madras University for the facilities provided to carry out this research work.

CONFLICT OF INTERESTS

The authors declare no conflict of interest

ETHICS APPROVAL

Not applicable

FUNDING

This study received no specific funding from public, commercial, or not-for-profit funding agencies.

AI TOOL DECLARATION

The authors declares that no AI and related tools are used to write the scientific content of this manuscript.

DATA AVAILABILITY

Data will be available on request

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