https://jsras.rcc.edu.ly/
Vol.3 No.0 (2026), 30-41
Article history:
Received: 29 Apr. 2026
Accepted: 26 Jun. 2026
Published: 6 Aug. 2026

Journal of Sustainable Research in Applied Sciences

JSRAS

The Role of Modern Imaging Technologies in Supporting Sustainable Development Goals: A Comparison Between Microwave Imaging and Mammography

Dalal Ammar Alakhdhar Ali[1,*], da.a@liaonsrt.ly, Musrafa A. Ben Hkoma[2], m_hkoma2017@yahoo.com
Yasser Fathi Nassar[3], y.nassar@wau.edu.ly
[1]Libyan Authority for Scientific Research, Tripoli, Libya
[2]Sustainable Development Research Center
[3]Mechanical and Renewable Energy Engineering Department, Engineering Faculty, Wadi Alshatti University, Brack Alshatti, Libya
DOI: https://doi.org/10.36602/jsras.2026.3.0.4
* Corresponding author da.ali@aonsrt.ly

Index Terms

Breast Cancer, Mammography, Microwave Imaging, Medical Physics, Artificial Intelligence, Sustainable Healthcare.

Abstract

Breast cancer remains a major global health challenge, emphasizing the need for accurate, safe, and sustainable imaging technologies for early detection. This study presents a comparative descriptive and critical review of mammography and microwave imaging from the perspectives of medical physics, diagnostic performance, image reconstruction, artificial intelligence, and healthcare sustainability. The analysis shows that mammography remains the clinical reference standard because of its high spatial resolution and effective detection of microcalcifications through X-ray attenuation governed by the Beer–Lambert law. In contrast, microwave imaging provides functional tissue characterization based on dielectric permittivity and electrical conductivity described by Maxwell's equations, offering radiation-free imaging with particular advantages for dense breast tissue. Recent advances in computational electromagnetics and physics-informed artificial intelligence have significantly improved microwave image reconstruction and diagnostic capability. The study concludes that microwave imaging should complement rather than replace mammography, supporting safer, more accurate, and sustainable breast cancer diagnosis while contributing to Sustainable Development Goal 3.

دور تقنيات تصوير الثدي الحديثة في دعم أهداف التنمية المستدامة: تحليل مقارن للتصوير بالموجات الميكروية والماموغرافيا

دلال عمار الأخضر علي[1،*]، مصطفى أحمد بن حكومة[2]، ياسر فتحي نصار[3]
[1]الهيئة الليبية للبحث العلمي، طرابلس، ليبيا، da.ali@aonsrt.ly
[2]مركز أبحاث التنمية المستدامة، m_hkoma2017@yahoo.com
[3]جامعة وادي الشاطئ، كلية الهندسة، قسم الهندسة الميكانيكية والطاقات المتجددة، براك الشاطئ، ليبيا، y.nassar@wau.edu.ly
DOI: https://doi.org/10.36602/jsras.2026.3.0.4
* المؤلف المراسل da.ali@aonsrt.ly

الكلمات المفتاحية

سرطان الثدي، التصوير الشعاعي للثدي، التصوير بالموجات الميكروية، الفيزياء الطبية، الذكاء الاصطناعي، الرعاية الصحية المستدامة.

الملخص

لا يزال سرطان الثدي يمثل تحديًا صحيًا عالميًا رئيسًا، مما يؤكد الحاجة إلى تقنيات تصوير دقيقة وآمنة ومستدامة للكشف المبكر. تقدم هذه الدراسة مراجعة وصفية مقارنة ونقدية للتصوير الشعاعي للثدي والتصوير بالموجات الميكروية من منظور الفيزياء الطبية، والأداء التشخيصي، وإعادة بناء الصور، والذكاء الاصطناعي، واستدامة الرعاية الصحية. يُظهر التحليل أن التصوير الشعاعي للثدي لا يزال المعيار المرجعي السريري بفضل دقته المكانية العالية وفعاليته في كشف التكلسات الدقيقة من خلال توهين الأشعة السينية المحكوم بقانون بير–لامبرت. في المقابل، يوفر التصوير بالموجات الميكروية توصيفًا وظيفيًا للأنسجة يعتمد على السماحية العازلة والموصلية الكهربائية الموصوفتين بمعادلات ماكسويل، مع إتاحة التصوير دون استخدام الإشعاع المؤين وإمكانات خاصة في تصوير الثدي الكثيف. كما أسهمت التطورات الحديثة في الكهرومغناطيسية الحاسوبية والذكاء الاصطناعي المستند إلى المبادئ الفيزيائية في تحسين إعادة بناء الصور الميكروية والقدرات التشخيصية. وتخلص الدراسة إلى أن التصوير بالموجات الميكروية ينبغي أن يُستخدم بوصفه تقنية مكملة للتصوير الشعاعي للثدي لا بديلًا عنه، بما يدعم تشخيصًا أكثر أمانًا ودقة واستدامة لسرطان الثدي ويسهم في تحقيق الهدف الثالث من أهداف التنمية المستدامة.

1. INTRODUCTION

Breast cancer remains the most frequently diagnosed malignancy among women and a major global health burden, making early detection central to improving clinical outcomes (Sung et al., 2021). In the United States alone, 310,720 new cases of invasive breast cancer and 42,250 deaths among women were projected for 2024 (Giaquinto et al., 2024). Medical imaging is therefore central to breast cancer screening and diagnosis, but current evaluation increasingly extends beyond diagnostic accuracy to include patient safety, accessibility, and resource use. These considerations are also relevant to Sustainable Development Goal 3 (SDG 3), which emphasizes health and well-being.

Mammography remains the established screening modality for average-risk women because of its clinical validation and ability to detect early structural abnormalities (Marcon et al., 2024). It uses low-energy ionizing X-rays to generate high-resolution images through differences in tissue attenuation, enabling detection of microcalcifications and architectural distortion (Fico et al., 2023). This strength is accompanied by two physics-based limitations. First, repeated screening requires continued dose optimization despite the low risk associated with individual examinations (Yaffe & Mainprize, 2011). Second, overlapping attenuation characteristics of fibroglandular tissue and non-calcified lesions can reduce lesion conspicuity in dense breasts (Destounis et al., 2020).

Microwave breast imaging uses a different physical contrast mechanism. Non-ionizing electromagnetic waves interact with tissue-dependent dielectric properties, mainly relative permittivity and electrical conductivity, which affect propagation, attenuation, phase, and scattering. Experimental studies have established measurable dielectric differences among breast tissue types, providing the physical basis for microwave tissue characterization (Lazebnik et al., 2007). Current systems generally use radar-based or tomographic approaches to localize scattering responses or reconstruct dielectric-property distributions (Aldhaeebi et al., 2020; Wang et al., 2023).

The main technical challenge in microwave imaging is that measured scattered fields must be related to an unknown, heterogeneous dielectric distribution. Multiple scattering, tissue variability, measurement noise, calibration error, and model mismatch make quantitative reconstruction nonlinear and ill-posed. Regularization, computational optimization, and data-driven methods are therefore central to improving reconstruction stability and efficiency (Ambrosanio et al., 2022; Costanzo & Flores, 2022). Recent AI-based approaches have further supported signal processing, reconstruction, and classification, but results from simulations, phantoms, or limited datasets should not be equated with established clinical effectiveness (Reimer & Pistorius, 2023; Aragão et al., 2024).

The comparison also has implications for patient safety and sustainable healthcare. Microwave imaging avoids ionizing-radiation exposure, and some systems have demonstrated compact or portable configurations (Janjic et al., 2021; Adachi et al., 2022). However, non-ionizing operation does not by itself establish lower energy use, cost, or environmental impact. Such claims require direct evidence from energy measurements and life-cycle assessment covering equipment manufacture, operation, infrastructure, maintenance, and end-of-life processes (Thiel et al., 2024). Sustainability should therefore be treated as an evidence-based comparative domain rather than an assumed advantage of either modality.

Current evidence supports mammography as the clinically established screening modality, whereas microwave imaging remains an emerging technology with a distinct dielectric contrast mechanism and potential complementary value (Aragão et al., 2024). Previous reviews have largely emphasized microwave hardware, antenna design, system development, or reconstruction algorithms. The present study instead compares mammography and microwave imaging within a medical-physics framework that links tissue interaction and image formation with diagnostic performance, radiation safety, computational reconstruction, artificial intelligence, and sustainability-related evidence. This approach aims to distinguish established clinical evidence from technological potential while examining the relevance of both modalities to SDG 3.

2. RESEARCH PROBLEM

There is insufficient understanding of the comparative physical performance, diagnostic capabilities, radiation safety, and sustainability contributions of microwave imaging and mammography in supporting modern breast cancer detection and achieving sustainable healthcare development.

2.1.Research Questions

- How do mammography and microwave imaging differ in physical principles, image formation, diagnostic performance, and radiation safety?
- What is the potential contribution of both modalities to sustainable healthcare and SDG 3?
- How do advanced reconstruction methods and AI influence the performance and clinical potential of microwave breast imaging?

3. RESEARCH HYPOTHESES

H1: Mammography and microwave imaging differ in their physical mechanisms, image formation, diagnostic capabilities, and radiation characteristics.

H2: Microwave imaging may complement mammography by providing non-ionizing, dielectric-based tissue information with potential benefits for patient safety and sustainable healthcare.

4. RESEARCH OBJECTIVES

- To compare the physical principles, image formation mechanisms, and tissue contrast of mammography and microwave breast imaging.
- To evaluate both modalities in terms of diagnostic performance, radiation safety, and patient protection.
- To assess their relevance to sustainable healthcare and SDG 3, including accessibility and resource use.
- To examine the role of AI and advanced reconstruction methods in improving microwave imaging performance.

5. SIGNIFICANCE OF THE STUDY

This study offers a medical-physics-based comparison of mammography and microwave breast imaging, focusing on how their different physical mechanisms affect image formation, diagnostic performance, and radiation safety. It examines the roles of X-ray attenuation, tissue dielectric properties, electromagnetic scattering, and image reconstruction in defining the strengths and limitations of each modality. The study also considers how advanced reconstruction methods and AI may improve microwave imaging and assesses its potential role alongside mammography. By linking imaging physics with clinical evidence and sustainability-related considerations, the study provides a focused basis for future research in breast imaging and its contribution to SDG 3.

6. SCOPE AND LIMITATIONS OF THE STUDY

Scope

The study compares mammography and microwave breast imaging in terms of physical principles, image formation, diagnostic performance, radiation safety, reconstruction methods, AI applications, and sustainability-related implications.

Limitations

- The review primarily covers peer-reviewed literature published between 2020 and 2026, with selected earlier studies retained for essential physical foundations.
- Comparative interpretation is limited by the small number of large-scale clinical studies and the heterogeneity of microwave imaging systems, acquisition protocols, and reconstruction methods.
- Technical and engineering aspects are considered only where they directly affect imaging performance or clinical translation.

7. OPERATIONAL DEFINITIONS

7.1 Mammography

A breast imaging modality that uses low-dose ionizing X-rays to produce anatomical contrast through differences in tissue attenuation.

7.2 Microwave Breast Imaging

A non-ionizing imaging approach that detects tissue abnormalities through dielectric contrast and electromagnetic scattering.

7.3 X-ray Attenuation

The reduction in X-ray intensity during tissue passage, forming the physical basis of mammographic contrast.

7.4 Dielectric Properties

Tissue electromagnetic properties, mainly relative permittivity and electrical conductivity, that govern microwave propagation and scattering.

7.5 Electromagnetic Scattering

Changes in microwave propagation caused by spatial variations in tissue dielectric properties.

7.6 Inverse Scattering Problem

The reconstruction of internal tissue properties from measured scattered fields; typically nonlinear and ill-posed.

7.7 Diagnostic Performance

The ability to detect and characterize abnormalities using measures such as sensitivity, specificity, lesion detectability, and image quality.

7.8 Sustainable Healthcare

Healthcare delivery that considers clinical benefit alongside resource use, environmental impact, cost, and accessibility.

8. PREVIOUS STUDIES

The evidence base differs substantially in maturity between mammography and microwave breast imaging. Mammography is integrated into established multimodal screening and diagnostic pathways, whereas microwave imaging remains dominated by technical reviews, system-development studies, and early clinical investigations (Elhatw et al., 2023; Aldhaeebi et al., 2020; Wang, 2023; Aragão et al., 2024; Safdar et al., 2026). This distinction is methodologically important: demonstrating dielectric contrast, improved signal quality, or successful image reconstruction establishes technical feasibility but not diagnostic equivalence to mammography.

The two modalities also differ fundamentally in image-formation physics. Mammography derives contrast from differential X-ray attenuation, whereas microwave imaging responds to frequency-dependent tissue properties, particularly dielectric permittivity and conductivity. The latter mechanism is consistently supported across the microwave literature (Aldhaeebi et al., 2020; Wang, 2023; Aragão et al., 2024; Safdar et al., 2026), but its clinical translation is constrained by breast heterogeneity, acquisition geometry, antenna coupling, calibration, noise, model mismatch, and reconstruction error. Thus, current evidence more firmly establishes a distinct physical source of contrast than superior diagnostic performance under comparable clinical conditions.

Microwave image quality depends on the entire measurement and reconstruction chain. Persistent limitations in spatial resolution and inverse reconstruction have been reported alongside advances in antenna design, signal processing, calibration, electromagnetic shielding, and AI-assisted analysis (Aldhaeebi et al., 2020; Wang, 2023; Aragão et al., 2024; Papatrechas et al., 2025). Because system architecture and reconstruction methods vary considerably, reported improvements are not directly interchangeable. Engineering optimization may improve signal fidelity and lesion visibility, but it does not by itself demonstrate mammography-equivalent spatial resolution or patient-level diagnostic performance. The continued emphasis on reconstruction and tissue heterogeneity in later reviews suggests that these remain intrinsic translational challenges rather than isolated software limitations (Aragão et al., 2024; Safdar et al., 2026).

Artificial intelligence has been applied to reconstruction, signal interpretation, and classification, but the supporting evidence remains uneven (Wang, 2023; Aragão et al., 2024). The MammoWave protocol, for example, includes a planned AI-based classification assessment but reports no completed diagnostic outcomes (Sánchez-Bayuela et al., 2024). Algorithmic gains should therefore not be interpreted as clinical benefit without independent patient-level validation, external reproducibility, and stable performance across acquisition systems. At present, AI is better supported as a computational component of microwave imaging than as evidence of routine clinical effectiveness.

Clinical studies provide stronger translational evidence but remain heterogeneous in design and purpose. The prospective multicentre MammoWave investigation moved evaluation to the patient level, although its single-arm design and study population limit inference about comparative effectiveness in population-based screening (Sánchez-Bayuela et al., 2023). The subsequent multicentre protocol in asymptomatic women defines a broader validation framework but cannot support claims of achieved diagnostic performance (Sánchez-Bayuela et al., 2024). Other studies address different applications: Fasoula et al. (2025) examined three-dimensional Wavelia imaging with radiomic analysis, whereas Smith et al. (2023) explored treatment-related tissue changes in a pilot monitoring context. These studies indicate expanding clinical investigation, but differences in devices, populations, endpoints, and intended use preclude a unified claim of diagnostic readiness.

The non-ionizing nature of microwave imaging may be advantageous when repeated measurements are required, but this should not be equated with absence of all biological or operational risk, nor can it compensate for inadequate diagnostic performance (Aldhaeebi et al., 2020; Sánchez-Bayuela et al., 2023; Smith et al., 2023). Similarly, non-ionizing operation does not establish environmental superiority. Comparative sustainability requires direct evidence on energy consumption, equipment lifespan, maintenance, consumables, operational costs, throughput, and carbon footprint, which remains limited in the reviewed literature.

The principal gap is therefore a lack of comparable evidence rather than a simple lack of studies. Microwave investigations vary in acquisition protocols, frequency ranges, antenna configurations, calibration, reconstruction methods, AI pipelines, populations, and endpoints, limiting reproducibility and direct quantitative comparison (Aldhaeebi et al., 2020; Aragão et al., 2024; Safdar et al., 2026). Head-to-head evaluations against mammography under equivalent populations, clinical endpoints, and reference standards remain scarce, while evidence on energy use, cost-effectiveness, carbon footprint, portability, and implementation in resource-limited settings is insufficient. The present study addresses these limitations through an integrated comparative analysis of image-formation physics, diagnostic performance, radiation safety, computational requirements, clinical readiness, and sustainability in relation to SDG 3, without assuming superiority of either modality in the absence of direct evidence.

9. RESEARCH METHODOLOGY

This study adopts a comparative descriptive and critical review methodology to evaluate the role of modern imaging technologies in supporting sustainable healthcare through a comparison between microwave imaging and mammography.

This research is based exclusively on a comprehensive review and critical comparative analysis of recent peer-reviewed scientific research published between 2020 and 2026, selectively including earlier pioneering studies to identify fundamental physical principles, historical evidence related to dielectric properties, and key developments in microwave mammography. This data was drawn from internationally recognized databases, including Google Scholar, PubMed, Scopus, IEEE Xplore, and Web of Science. The selected studies are analyzed to compare the two imaging modalities in terms of their underlying physical principles, image formation mechanisms, diagnostic performance, radiation safety, dielectric tissue characterization, image reconstruction techniques, artificial intelligence applications, and contributions to Sustainable Development Goal 3 (Good Health and Well-being).

The methodology further involves a critical evaluation of similarities, differences, strengths, limitations, and research gaps identified in the previous literature to establish a comprehensive scientific understanding of the current state of knowledge. Rather than conducting experimental or clinical investigations, the study synthesizes and interprets existing evidence to assess the clinical, physical, technological, and sustainability implications of microwave imaging and mammography, thereby providing an integrated framework for future research and the development of safer and more sustainable breast cancer imaging technologies.



Figure 1. Systematic Comparative Analytical Framework for Evaluating Mammography and Microwave Breast Imaging in the Context of Sustainable Breast Cancer Diagnostics.

10. RESULTS AND DISCUSSION

10.1 Evolution of Breast Imaging Technologies: From Anatomical Detection to Multidimensional Tissue Characterization

The comparative synthesis indicates that the evolution of breast imaging has been shaped not only by the pursuit of higher diagnostic accuracy but also by advances in medical physics, computational science, biomedical engineering, and patient-centered healthcare. Mammography remains the cornerstone of population-based breast cancer screening because of its standardized acquisition protocols, high spatial resolution, and extensive clinical validation. However, its diagnostic performance is influenced by breast density, and persistent concerns regarding lesion masking in dense fibroglandular tissue have stimulated the development of supplemental and alternative imaging approaches (Butler et al., 2020; Hussein et al., 2023).

This finding should be interpreted in relation to the physical mechanism of mammographic image formation. Mammography derives contrast primarily from differences in X-ray attenuation; therefore, its limitations in dense breasts are not attributable solely to observer performance or clinical workflow. Dense fibroglandular tissue and many non-calcified lesions may exhibit overlapping radiographic appearances, while projection imaging introduces anatomical superposition. The clinical limitation is thus partly rooted in the physics of attenuation-based imaging. This interpretation is important because it explains why improvements in detector technology alone cannot fully eliminate density-related masking and why alternative contrast mechanisms continue to attract research interest.

Within this context, microwave breast imaging represents an emerging technology based on a fundamentally different interaction between electromagnetic fields and biological tissues. Rather than measuring X-ray attenuation, microwave systems exploit spatial variations in dielectric properties, particularly relative permittivity and electrical conductivity, which influence wave propagation, attenuation, phase behavior, and scattering (Wang, 2023; Reimer & Pistorius, 2023). The principal significance of this finding is that microwave imaging does not merely reproduce mammographic information using a different radiation source; instead, it interrogates breast tissue through a distinct physical contrast mechanism.

Nevertheless, the distinction between anatomical and dielectric information should not be overstated. Although microwave imaging is frequently described as providing "functional" information, the available evidence more directly supports the terms dielectric-property-sensitive imaging or electromagnetic tissue characterization. The clinical meaning of reconstructed dielectric abnormalities remains dependent on system architecture, tissue heterogeneity, reconstruction accuracy, and pathological validation. Therefore, the broader evolution of breast imaging should be interpreted as a movement toward multidimensional tissue characterization rather than as evidence that microwave imaging has already achieved clinically validated functional imaging capability.

Advances in computational electromagnetics, inverse scattering, artificial intelligence, and high-performance computing have accelerated this technological transition. Data-driven reconstruction strategies have demonstrated the potential to reduce computational burden and improve dielectric-property estimation under defined numerical or experimental conditions (Ambrosanio et al., 2022; Aragão et al., 2024). However, much of this evidence remains derived from simulations, numerical breast models, phantom experiments, or early-stage investigations. Consequently, improved computational performance should not be interpreted as equivalent to improved patient-level diagnostic outcomes.

The broader implication is that contemporary breast imaging is evolving toward closer integration of physical measurement, computational reconstruction, and data-driven analysis. Yet the maturity of evidence differs substantially across modalities. Mammography is supported by established screening pathways and extensive clinical experience, whereas microwave imaging remains heterogeneous in hardware design, acquisition geometry, reconstruction strategy, and validation methodology. This asymmetry must remain explicit throughout any comparative interpretation.

10.2 Physical Basis of Image Formation: X-Ray Attenuation versus Electromagnetic Scattering

The comparative analysis demonstrates that the most fundamental difference between mammography and microwave breast imaging lies in their interaction with biological tissue. Mammographic image formation is governed primarily by the attenuation of low-energy X-ray photons and may be represented by the Beer–Lambert relationship:

$$I = I_0 exp(-\mu x) \quad (1)$$

where:

(I_0) = incident X-ray intensity,

(I) = transmitted X-ray intensity,

(μ) = linear attenuation coefficient (cm^{-1}),

(x) = tissue thickness (cm).

This relationship explains why differences in tissue composition and thickness generate radiographic

contrast. Calcium-rich microcalcifications attenuate X-rays more strongly than surrounding soft tissues and can therefore be detected with the high spatial resolution of mammography. This result confirms a major clinical strength of mammography: its ability to visualize fine structural abnormalities that remain difficult for current microwave systems.

However, the same attenuation-based mechanism also explains an important limitation. Dense fibroglandular tissue can reduce lesion conspicuity because radiographically dense normal structures may overlap with non-calcified abnormalities, while the two-dimensional projection of three-dimensional anatomy further increases masking. Thus, the physical mechanism that enables high-resolution structural imaging simultaneously contributes to reduced detectability under specific tissue conditions (Yaffe & Mainprize, 2011; Butler et al., 2020). This represents a central example of how image-formation physics directly shapes clinical performance.

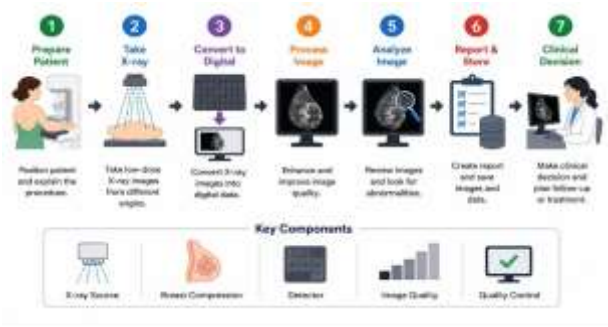


Figure 2. Digital Mammography Imaging Workflow and Key System Components.

In contrast, microwave imaging is governed by electromagnetic wave propagation and scattering through heterogeneous biological media. Its physical behavior is described by Maxwell's equations:

$$\nabla \times E = -\partial B/\partial t \qquad (2)$$

$$\nabla \times H = J + \partial D/\partial t \qquad (3)$$

where:

E = electric field intensity ($V.m^{-1}$),

H = magnetic field intensity ($A.m^{-1}$),

D = electric flux density ($C.m^{-2}$),

B = magnetic flux density (T),

J = electric current density ($A.m^{-2}$).

Unlike mammography, microwave imaging seeks to infer tissue-dependent electromagnetic properties rather than transmitted photon intensity. A commonly used representation is the complex permittivity:

$$\varepsilon^*(r) = \varepsilon'(r) - j\varepsilon''(r) \qquad (4)$$

where:

ε^*= complex permittivity of the biological tissue

$r = (x, y, z)$ = spatial position vector within the imaging domain

$\varepsilon'(r)$ = real part of the permittivity (dielectric constant)

$\varepsilon''(r)$ = imaginary part of the permittivity (dielectric loss factor)

$j = \sqrt{(-1)}$ = imaginary unit

and, depending on the adopted time-harmonic convention, conductivity may be incorporated as:

$$\varepsilon^*(r) = \varepsilon_r(r)\varepsilon_0 - j\frac{\sigma(r)}{\omega} \qquad (5)$$

where:

ε_r = relative permittivity of the tissue (dimensionless)

ε_0= permittivity of free space ($8.854\times10^{-12}\ F\,m^{-1}$)

σ = electrical conductivity of the tissue ($S\,m^{-1}$)

ω = ($2\pi f$) angular frequency ($rad\,s^{-1}$)

The reviewed evidence indicates that breast tissues exhibit measurable dielectric heterogeneity and that differences exist among adipose, fibroglandular, benign, and malignant tissue classes (Joines et al., 1994; Lazebnik et al., 2007; Wang, 2023). However, a critical interpretation is necessary. The malignant-to-normal dielectric contrast is not universally large and depends strongly on frequency, tissue composition, measurement conditions, and the reference tissue used for comparison. In particular, comparisons between malignant and adipose tissue may yield stronger contrast than comparisons between malignant and fibroglandular tissue.

This limitation has direct implications for clinical translation. A simplified assumption that malignant tissue always exhibits markedly higher permittivity than all surrounding normal tissues risks overstating lesion separability. The relevant physical problem is not merely the existence of dielectric contrast but whether that contrast remains detectable within heterogeneous, patient-specific breast environments under realistic noise, coupling, calibration, and reconstruction conditions.



Figure 3. Microwave Breast Imaging Workflow and Diagnostic Processing Pipeline.

The reviewed evidence further identifies the inverse scattering problem as a major physical and computational barrier. A simplified operator representation may be written as:

$$E_s = G(\varepsilon)\, E_i \qquad (6)$$

where:

E_i= incident electric field

E_s ==scattered electric field

$G(\varepsilon)$= nonlinear forward operator dependent on the dielectric distribution.

In heterogeneous breast tissue, measured signals are influenced by reflection, refraction, attenuation, phase changes, multiple scattering, antenna coupling, and model mismatch. Therefore, reconstruction of internal dielectric properties is nonlinear and ill-posed rather than a straightforward inversion of measured data. Numerical methods such as finite-element modeling, finite-difference time-domain methods, iterative optimization, regularization, and data-driven reconstruction are consequently central to quantitative microwave imaging (Ambrosanio et al., 2022; Aragão et al., 2024).

The critical implication is that microwave image quality depends on a coupled chain of factors: hardware performance, calibration accuracy, forward-model fidelity, noise characteristics, regularization, and reconstruction strategy. This differs from mammography, where image formation and clinical quality assurance are substantially more standardized. Current evidence therefore supports the interpretation that the two modalities are physically complementary but clinically asymmetric in maturity.

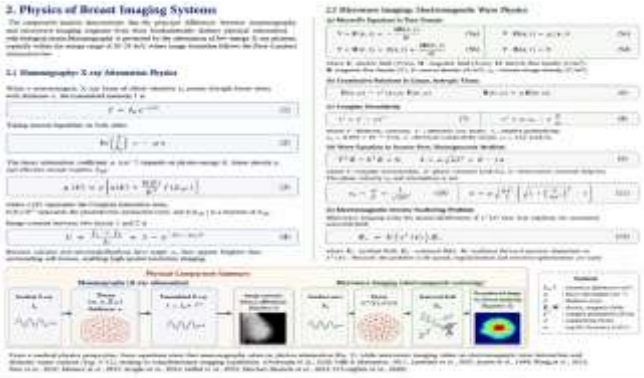


Figure 4. Comparative Physical Framework of Mammography and Microwave Breast Imaging: X-ray Attenuation and Electromagnetic Wave Scattering Principles.

10.3 Mammography: Established Clinical Performance and Physics-Based Limitations

The evidence synthesis confirms that mammography remains the most established modality for population-based breast cancer screening. Its principal strengths are high spatial resolution, standardized acquisition protocols, mature quality-assurance frameworks, and extensive clinical validation. From a medical physics perspective, these strengths arise from optimized X-ray spectra, detector performance, breast compression, scatter control, and digital image processing, enabling visualization of microcalcifications and subtle structural abnormalities.

This result should not be interpreted as evidence that mammographic performance is uniform across all patient groups. Image quality depends on beam quality, breast thickness, tissue composition, detector efficiency, scatter, and noise. Selection of tube potential and target/filter combinations involves an optimization trade-off: higher-energy photons improve penetration but may reduce differential soft-tissue contrast, whereas lower-energy spectra can enhance contrast while increasing absorption. The balance between diagnostic image quality and radiation dose therefore remains a fundamental medical-physics problem (Yaffe & Mainprize, 2011).

A major finding of the reviewed evidence is the persistent limitation associated with dense breast tissue. Dense fibroglandular structures can obscure non-calcified lesions because both may appear radiographically attenuating. This finding is consistent with continuing clinical concern regarding breast density and supplemental screening strategies (Butler et al., 2020; Hussein et al., 2023).

The critical interpretation is that density-related reduction in sensitivity is partly intrinsic to projection-based attenuation imaging. It should therefore not be framed simply as a technological failure of mammography. Rather, it reflects the interaction between tissue composition, photon attenuation, anatomical overlap, and lesion morphology. Digital breast tomosynthesis can reduce some superposition effects through quasi-three-dimensional reconstruction, but it does not eliminate all density-related limitations and introduces additional considerations involving dose, interpretation, availability, and clinical context (Hussein et al., 2023).

Ionizing-radiation exposure represents another important distinction. Modern mammography uses low doses, and the population-level benefit of appropriately implemented screening generally outweighs the associated radiation risk. Nevertheless, repeated examinations contribute to cumulative exposure, making dose optimization relevant in repeated imaging pathways and younger high-risk populations (Yaffe & Mainprize, 2011).

The appropriate interpretation is therefore balanced: mammography should neither be portrayed as unsafe because it uses ionizing radiation nor treated as physically unrestricted because individual examination doses are low. Its clinical value is well established, while optimization remains a continuing requirement. This distinction is particularly important when comparing mammography with non-ionizing emerging technologies.

10.4 Microwave Breast Imaging: Diagnostic Potential versus Translational Uncertainty

The reviewed literature indicates that microwave breast imaging provides a distinct mechanism of tissue interrogation based on spatial variations in relative permittivity and electrical conductivity. Foundational dielectric studies support measurable differences among breast tissue classes, establishing the physical basis for microwave sensing and imaging (Joines et al., 1994; Lazebnik et al., 2007).

Depending on system architecture, microwave signals are transmitted toward or through the breast and scattered fields are recorded by receiving antennas. Radar-based approaches generally seek to localize scattering responses, whereas tomographic systems attempt to reconstruct qualitative or quantitative maps related to tissue dielectric properties (Wang, 2023; Reimer & Pistorius, 2023).

The principal diagnostic implication is that microwave imaging may provide information not directly available from X-ray attenuation. However, this theoretical complementarity must be separated from demonstrated clinical benefit. Electromagnetic propagation within the breast is strongly affected by tissue heterogeneity, attenuation, multiple scattering, phase distortion, coupling conditions, breast geometry, and patient-specific dielectric variation. Clinical case studies indicate that inaccurate patient-specific property estimation can degrade image quality and lesion detection (O'Loughlin et al., 2021).

This finding is important because it challenges overly simplified claims that dielectric contrast alone guarantees reliable tumor detection. The existence of a physical contrast mechanism is necessary but insufficient. Clinically useful imaging additionally requires stable measurement, reproducible reconstruction, adequate lesion localization, standardized interpretation, and validated diagnostic thresholds.

The evidence also indicates continuing progress in antennas, ultra-wideband acquisition, calibration, patient-specific modeling, and computational reconstruction. Nevertheless, studies remain heterogeneous across hardware platforms, acquisition geometries, reconstruction algorithms, and clinical endpoints (O'Loughlin et al., 2021; Reimer & Pistorius, 2023). Such heterogeneity restricts direct comparison and prevents strong generalization from one system to microwave breast imaging as a whole.

A clear advantage of microwave imaging is its use of non-ionizing electromagnetic radiation. Several system designs also avoid the breast compression required in conventional mammography, potentially improving tolerability. Yet these characteristics should not be equated with diagnostic equivalence. Non-ionizing operation is a safety characteristic, not evidence of equivalent sensitivity, specificity, or screening effectiveness.

Despite substantial progress, microwave imaging has not achieved the clinical maturity or standardized performance required to replace mammography as the primary population-screening modality. Persistent barriers include system-dependent spatial resolution, inverse-problem instability, calibration uncertainty, heterogeneous tissue properties, limited standardization, and insufficient large-scale prospective multicenter validation (Aragão et al., 2024; Safdar et al., 2026; Yurtseven et al., 2025).

The strongest defensible conclusion is therefore one of technological promise accompanied by substantial translational uncertainty. Current evidence supports microwave breast imaging primarily as an emerging complementary technology with potential applications in tissue characterization, lesion detection, and selected monitoring scenarios rather than as a validated replacement for established mammographic screening.

10.5 AI-Assisted Reconstruction: Computational Opportunity and Evidence Limitations

The comparative synthesis indicates that artificial intelligence is becoming increasingly important in microwave breast imaging because reconstruction performance is closely coupled to the solution of complex inverse problems. In mammography, AI is commonly applied to detection, classification, triage, and workflow support. In quantitative microwave imaging, by contrast, data-driven methods may contribute directly to estimation of dielectric-property distributions from electromagnetic measurements.

A generic regularized reconstruction problem may be represented as:

$$\hat{\varepsilon} = arg\ min\{\| E_s^{measured} - F(\varepsilon)\ E_i \|_2^2 + \lambda R(\varepsilon)\} \quad (7)$$

where:

($\hat{\varepsilon}$) is the reconstructed dielectric distribution,

(ε)= unknown dielectric distribution to be estimated,

(E_i) is the incident electromagnetic field,

($E_s^{measured}$) is the experimentally measured scattered field,

(F(ε)) represents the nonlinear forward electromagnetic operator,

(R(ε)) is a regularization function that stabilizes the inverse solution,

(λ) is the regularization parameter controlling the trade-off between data fidelity and solution smoothness,

$\|\cdot\|_2$ = Euclidean (L2) norm.

The analysis indicates that conventional iterative methods may be computationally expensive and sensitive to measurement noise, model mismatch, initialization, and regularization choices. This provides a strong rationale for investigating neural networks and hybrid reconstruction strategies. Ambrosanio et al. (2022), for example, investigated an end-to-end deep-learning framework aimed at accelerating quantitative microwave breast imaging.

The result is technologically important but should be interpreted cautiously. Faster reconstruction in numerical datasets does not establish improved clinical diagnosis. AI models may be sensitive to training-data representativeness, domain shift, simulated-to-clinical discrepancies, acquisition-system changes, and patient heterogeneity. A network trained on idealized numerical breast models may perform differently when exposed to real measurements affected by antenna coupling, calibration drift, motion, noise, and anatomical variability.

Accordingly, the current evidence does not support the conclusion that AI has solved the microwave inverse problem. A more defensible interpretation is that AI-assisted reconstruction can improve selected computational metrics and reduce processing time under defined conditions. Clinical translation will require external validation, uncertainty quantification, realistic patient-specific modeling, and explicit testing across hardware platforms and populations (Ambrosanio et al., 2022; Wang, 2023; Aragão et al., 2024).

Hybrid and physics-informed approaches may be particularly relevant because they can integrate electromagnetic constraints with data-driven representation learning. However, their value should ultimately be assessed through patient-level diagnostic endpoints rather than reconstruction speed or image-similarity metrics alone.

10.6 Comparative Diagnostic Interpretation: Complementarity without Assumed Superiority

The comparative evidence demonstrates that mammography and microwave imaging are founded on different physical principles and therefore offer potentially complementary information. Mammography provides high-resolution anatomical imaging based on differential X-ray attenuation, whereas microwave imaging seeks to characterize tissue through dielectric-property variations and electromagnetic scattering (Wang, 2023; Reimer & Pistorius, 2023).

Mammography retains advantages in spatial resolution, microcalcification detection, standardized acquisition, and clinical maturity. Microwave imaging provides a non-ionizing, dielectric-based contrast mechanism that may be relevant in dense breasts, where tissue overlap can reduce mammographic sensitivity. However, independence from X-ray attenuation does not establish superior performance in dense tissue; this hypothesis remains plausible but requires direct clinical validation stratified by breast density (Butler et al., 2020; Hussein et al., 2023).

The modalities also differ substantially in radiation physics. Mammography requires dose optimization and established quality assurance because it uses ionizing X-rays. Microwave imaging operates in the non-ionizing radiofrequency/microwave region and does not expose patients to an ionizing-radiation dose. This may support repeated imaging applications, although device-specific safety and exposure standards remain necessary (Yaffe & Mainprize, 2011; O'Loughlin et al., 2018).

From an engineering and translational perspective, mammography is a mature clinical system, whereas microwave imaging remains under active development. Recent studies have focused on improving scan quality, system reliability, calibration, and clinical-stage performance, while platforms such as Wavelia continue to undergo methodological and clinical investigation (Papatrechas et al., 2025; Fasoula et al., 2025).

Overall, the reviewed evidence supports investigating microwave imaging as a complementary rather than substitutive technology. However, even complementarity should not be assumed to improve clinical outcomes. Claims that combining mammography and microwave imaging will increase sensitivity or specificity, reduce unnecessary biopsies, or improve patient outcomes remain hypotheses until tested in direct prospective comparative studies. This distinction is essential for preventing technological plausibility from being presented as established clinical benefit (Aragão et al., 2024; Khan et al., 2025; Álvarez Sánchez-Bayuela et al., 2024).

10.7 Sustainability and SDG 3: Potential Advantages versus Unproven Environmental Superiority

The evidence synthesis indicates that sustainability is becoming increasingly relevant to medical imaging, but environmental sustainability must be distinguished from radiation safety. Mammography requires specialized X-ray equipment, quality assurance, maintenance, and dose optimization. However, these requirements do not by themselves establish that mammography is environmentally less sustainable than microwave imaging.

Environmental life-cycle research in radiology demonstrates that imaging-related impacts arise from multiple sources, including equipment manufacture and use, electricity consumption, consumables, infrastructure, workflow organization, and end-of-life processes (Thiel et al., 2024). The critical implication is that modality sustainability cannot be inferred from radiation type alone.

Microwave imaging has a clear advantage in avoiding ionizing-radiation exposure. Some systems may also permit relatively compact architectures and repeated measurements without cumulative X-ray dose (O'Lou

ghlin et al., 2018; Wang, 2023). These characteristics justify investigation of microwave imaging within sustainable healthcare frameworks.

Nevertheless, the reviewed evidence does not establish that microwave imaging necessarily consumes less electricity, has lower total operating costs, requires fewer lifecycle resources, or generates lower carbon emissions than mammography. Such conclusions require direct comparative energy measurements, health-economic analyses, equipment lifecycle assessment, and evaluation of supporting computational infrastructure.

This distinction becomes particularly important when AI is considered. AI-assisted reconstruction may reduce processing time under specific conditions, but faster computation does not automatically imply lower environmental impact. Training, inference hardware, data storage, and high-performance computing may introduce additional energy burdens. Therefore, computational efficiency and environmental efficiency should not be treated as equivalent.

The most defensible conclusion is that microwave imaging possesses sustainability-relevant characteristics rather than proven environmental superiority. Its contribution to Sustainable Development Goal 3 may currently be framed through non-ionizing operation, patient-centered imaging, potential repeatability, and possible future accessibility. Stronger claims concerning energy efficiency, cost reduction, and environmental advantage remain insufficiently validated.

Future studies should therefore incorporate direct energy metering, prospective cost analysis, equipment life-cycle assessment, infrastructure requirements, device lifespan, maintenance, computational energy use, and end-of-life impacts. Such evidence is necessary before sustainability claims can progress from theoretical

potential to demonstrated comparative advantage (Thiel et al., 2024).

10.8 Integrated Comparative Synthesis

The integrated analysis indicates that no single modality demonstrates superiority across all evaluated domains. Mammography remains dominant in spatial resolution, microcalcification detection, standardization, screening maturity, and clinical validation. Microwave imaging offers a fundamentally different non-ionizing contrast mechanism and potential advantages in repeated measurements, patient tolerability, and electromagnetic tissue characterization, but remains limited by reconstruction complexity, system heterogeneity, lower and system-dependent spatial resolution, and insufficient large-scale clinical validation.

The central comparative finding is therefore not that one modality should replace the other, but that their different physical mechanisms create scientifically plausible complementarity. However, this complementarity remains more strongly established at the level of physical rationale than at the level of demonstrated clinical outcome.

TABLE I. COMPARATIVE ANALYSIS OF THE TECHNICAL AND PHYSICAL CHARACTERISTICS OF MAMMOGRAPHY AND MICROWAVE IMAGING

Analysis Variable	Mammography	Microwave Imaging	Critical Comparative Interpretation
Underlying physical principle	Differential X-ray attenuation	Interaction of microwave fields with tissue dielectric properties	Distinct physical mechanisms provide different information content
Image formation mechanism	Attenuation-based projection imaging	Scattered-field measurement and system-dependent reconstruction	Microwave imaging generally requires more complex inverse modeling
Electromagnetic radiation	Low-dose ionizing X-rays	Non-ionizing microwave electromagnetic fields	Microwave imaging avoids ionizing-radiation dose but still requires device-specific safety compliance
Beer–Lambert attenuation	Central approximation for attenuation physics	Not applicable	Relevant to X-ray imaging, not microwave reconstruction
Electromagnetic propagation and scattering	Not the primary image-contrast mechanism	Fundamental to signal formation	Tissue heterogeneity strongly affects microwave measurements
Dielectric permittivity and conductivity	Not directly measured	Central electromagnetic properties	Potentially useful for tissue characterization, but distributions overlap across tissue classes
Inverse scattering problem	Not central to conventional image formation	Major reconstruction challenge	A key source of computational complexity and instability
Image reconstruction	Mature digital processing and standardized pipelines	Iterative, regularized, tomographic, radar-based, or AI-assisted methods	Microwave methods remain more heterogeneous across systems
AI applications	Detection, classification, triage, workflow support	Reconstruction, signal processing, localization, classification	AI is important in both modalities but may be more tightly coupled to reconstruction in quantitative microwave imaging
Diagnostic information	High-resolution anatomical information	Dielectric-property-sensitive electromagnetic information	Potential complementarity is plausible but requires direct clinical validation
Spatial resolution	High	Lower and system-dependent	Mammography remains superior for fine structural detail and microcalcifications
Dense-breast relevance	Sensitivity may be reduced by masking	Alternative contrast mechanism is scientifically attractive	Superiority in dense breasts should not be assumed without direct stratified evidence
Radiation safety	Low-dose ionizing exposure	No ionizing-radiation dose	Clear physical distinction; clinical benefit depends on intended use
Patient comfort	Compression generally required	Several systems avoid conventional compression	Potential tolerability advantage, but system-specific
Clinical maturity	Established screening modality	Emerging and under validation	Major asymmetry in evidence maturity
Sustainability	Environmental burden requires lifecycle assessment	Sustainability-relevant characteristics but limited direct comparative evidence	Environmental superiority of microwave imaging is not yet established
Potential role	Primary established screening modality	Emerging complementary modality	Replacement is not supported by current evidence

The comparative synthesis reinforces the principal conclusion that mammography has substantially stronger established clinical evidence, whereas microwave imaging has promising physical and technological characteristics but a less mature evidence base. Importantly, descriptors such as "non-ionizing," "portable," or "AI-enabled" should not be used as proxies for diagnostic superiority or environmental sustainability.

11. CONCLUSIONS

- Mammography remains the established screening modality because of its high spatial resolution, standardized clinical use, and ability to detect microcalcifications and subtle structural abnormalities, although its performance may be reduced in dense breasts.
- Microwave imaging provides a non-ionizing contrast mechanism based on tissue dielectric properties and electromagnetic scattering, but its clinical performance remains limited by tissue heterogeneity, inverse-scattering complexity, system variability, and insufficient large-scale validation.
- Advances in computational electromagnetics, regularized reconstruction, and AI-assisted methods have improved the technical feasibility of microwave imaging; however, current evidence supports its role as a potential complement to mammography rather than a replacement.

Future clinical adoption requires standardized systems, robust patient-specific reconstruction, prospective multicenter validation, and direct evidence of added diagnostic value. Its relevance to patient safety and SDG 3 is promising, while environmental and economic benefits require direct lifecycle, energy, cost, and accessibility assessments.

12. RECOMMENDATIONS

- Conduct large-scale prospective multicenter studies to validate the diagnostic performance, reproducibility, and clinical utility of microwave breast imaging across diverse populations.
- Develop standardized acquisition and quality-assurance protocols covering system calibration, patient positioning, signal assessment, reconstruction reporting, and performance evaluation.
- Advance physics-informed image reconstruction by integrating electromagnetic modeling, regularized inverse methods, patient-specific approaches, and artificial intelligence, with emphasis on robustness and external validation.
- Evaluate multimodal imaging prospectively to determine whether combining microwave imaging with mammography provides measurable clinical benefits, particularly in women with dense breasts.
- Perform direct sustainability and health-economic assessments using life-cycle analysis, energy measurements, infrastructure requirements, cost-effectiveness, and accessibility outcomes to establish evidence-based contributions to sustainable healthcare and SDG 3.

REFERENCES

Adachi, M., Nakagawa, T., Fujioka, T., Mori, M., Kubota, K., Oda, G., & Kikkawa, T. (2022). Feasibility of portable microwave imaging device for breast cancer detection. Diagnostics, 12(1), 27. https://doi.org/10.3390/diagnostics12010027

Aldhaeebi, M. A., Alzoubi, K., Almoneef, T. S., Bamatraf, S. M., Attia, H., & Ramahi, O. M. (2020). Review of microwaves techniques for breast cancer detection. Sensors, 20(8), 2390. https://doi.org/10.3390/s20082390

Álvarez Sánchez-Bayuela, D., Ghavami, N., Romero Castellano, C., Bigotti, A., Badia, M., Papini, L., Raspa, G., Palomba, G., Ghavami, M., Loretoni, R., Calabrese, M., Tagliafico, A., & Tiberi, G. (2023). A multicentric, single arm, prospective, stratified clinical investigation to confirm MammoWave's ability in breast lesions detection. Diagnostics, 13(12), 2100. https://doi.org/10.3390/diagnostics13122100

Álvarez Sánchez-Bayuela, D., López-Brea Alarza, T., Giovanetti González, R., Romero Castellano, C., Fracassini, A., Papini, L., Taghipour-Gorjikolaie, M., Ghavami, N., & Tiberi, G. (2024). Microwave imaging for breast cancer screening: Protocol for an open, multicentric, interventional, prospective, non-randomised clinical investigation to evaluate cancer detection capabilities of MammoWave system on an asymptomatic population across multiple European countries. BMJ Open, 14(11), e088431. https://doi.org/10.1136/bmjopen-2024-088431

Ambrosanio, M., Franceschini, S., Pascazio, V., & Baselice, F. (2022). An end-to-end deep learning approach for quantitative microwave breast imaging in real-time applications. Bioengineering, 9(11), 651. https://doi.org/10.3390/bioengineering9110651

Aragão, A. de J., Carvalho, D., Sanches, B. C. de S., & Van Noije, W. A. M. (2024). A review on microwave imaging systems for breast cancer detection. IEEE Access, 12, 190611–190628. https://doi.org/10.1109/ACCESS.2024.3516762

Butler, R. S., Hooley, R. J., & Philpotts, L. E. (2020). Breast density notification legislation: An update after 10 years. AJR American Journal of Roentgenology, 214(6), 1424–1435. https://doi.org/10.2214/AJR.19.22275

Costanzo, S., & Flores, A. (2022). Enhanced machine learning approach for accurate and fast resolution of inverse scattering problem in breast cancer detection. Electronics, 11(15), 2308. https://doi.org/10.3390/electronics11152308

Destounis, S. V., Santacroce, A., & Arieno, A. (2020). Update on breast density, risk estimation, and supplemental screening. AJR American Journal of Roentgenology, 214(2), 296–305. https://doi.org/10.2214/AJR.19.21994

Elhatw, A., Chung, H. L., Kamal, R. M., De Jesus, C., Jean, S., Vishwanath, V., Ferreira Dalla Pria, H. R., Patel, M. M., Guirguis, M. S., & Moseley, T. W. (2023). Advanced breast imaging modalities—DBT, CEM, MBI, PEM, MRI, AI. Current Breast Cancer Reports, 15(2), 108–113. https://doi.org/10.1007/s12609-023-00483-5

Fasoula, A., Papatrechas, G., Arvanitis, P., Duchesne, L., Gil Cano, J. D., O'Donnell, J., Abd Elwahab, S. M., & Kerin, M. (2025). Wavelia microwave breast imaging Phase#2 clinical investigation: Methodological evolutions and multidimensional radiomics analysis towards controlled specificity. Cancers, 17(18), 2973. https://doi.org/10.3390/cancers17182973

Fico, N., Di Grezia, G., Cuccurullo, V., Salvia, A. A. H., Iacomino, A., Sciarra, A., & Gatta, G. (2023). Breast imaging physics in mammography (Part I). Diagnostics, 13(20), 3227. https://doi.org/10.3390/diagnostics13203227

Giaquinto, A. N., Sung, H., Miller, K. D., Kramer, J. L., Newman, L. A., Minihan, A., Jemal, A., & Siegel, R. L. (2024). Breast cancer statistics 2024. CA: A Cancer Journal for Clinicians, 74(6), 477–495. https://doi.org/10.3322/caac.21863

Hussein, H., Abbas, E., Keshavarzi, S., Fazelzad, R., Bukhanov, K., Kulkarni, S., Au, F., Ghai, S., & Alabousi, A. (2023). Supplemental breast cancer screening in women with dense breasts and negative mammography: A systematic review and meta-analysis. Radiology, 306(3), e221785. https://doi.org/10.1148/radiol.221785

Janjic, A., Cayoren, M., Akduman, I., Yilmaz, T., Onemli, E., Bugdayci, O., & Aribal, M. E. (2021). SAFE: A novel microwave imaging system design for breast cancer screening and early detection—Clinical evaluation. Diagnostics, 11(3), 533. https://doi.org/10.3390/diagnostics11030533

Joines, W. T., Zhang, Y., Li, C., & Jirtle, R. L. (1994). The measured electrical properties of normal and malignant human tissues from 50 to 900 MHz. Medical Physics, 21(4), 547–550. https://doi.org/10.1118/1.597312

Khan, A. Q. A. Q., Touseeq, M. T., Rehman, S., Tahir, M., Ashfaq, M., Jaffar, E., & Abbasi, S. F. (2025). Advances in breast cancer diagnosis: A comprehensive review of imaging, biosensors, and emerging wearable technologies. Frontiers in Oncology, 15, 1587517. https://doi.org/10.3389/fonc.2025.1587517

Lazebnik, M., Popovic, D., McCartney, L., Watkins, C. B., Lindstrom, M. J., Harter, J., Sewall, S., Ogilvie, T., Magliocco, A., Breslin, T. M., Temple, W., Mew, D., Booske, J. H., Okoniewski, M., & Hagness, S. C. (2007). A large-scale study of the ultrawideband microwave dielectric properties of normal, benign and malignant breast tissues obtained from cancer surgeries. Physics in Medicine & Biology, 52(20), 6093–6115. https://doi.org/10.1088/0031-9155/52/20/002

Marcon, M., Fuchsjäger, M. H., Clauser, P., & Mann, R. M. (2024). ESR Essentials: Screening for breast cancer—General recommendations by EUSOBI. European Radiology, 34, 6348–6357. https://doi.org/10.1007/s00330-024-10740-5

O'Loughlin, D., Elahi, M. A., Lavoie, B. R., Fear, E. C., & O'Halloran, M. (2021). Assessing patient-specific microwave breast imaging in clinical case studies. Sensors, 21(23), 8048. https://doi.org/10.3390/s21238048

O'Loughlin, D., O'Halloran, M., Moloney, B. M., Glavin, M., Jones, E., & Elahi, M. A. (2018). Microwave breast imaging: Clinical advances and remaining challenges. IEEE Transactions on Biomedical Engineering, 65(11), 2580–2590. https://doi.org/10.1109/TBME.2018.2809541

Papatrechas, G., Fasoula, A., Arvanitis, P., Duchesne, L., Raveneau, A., Gil Cano, J. D., O'Donnell, J., Abd Elwahab, S., & Kerin, M. (2025). Microwave breast imaging system modules, enhancing scan quality and reliability of diagnostic outputs during clinical testing. Bioengineering, 12(10), 1079. https://doi.org/10.3390/bioengineering12101079

Reimer, T., & Pistorius, S. (2023). Review and analysis of tumour detection and image quality analysis in experimental breast microwave sensing. Sensors, 23(11), 5123. https://doi.org/10.3390/s23115123

Safdar, A., Sohani, B., Iqbal, F., Barzamini, R., Rahmani, A., & Aliyu, A. (2026). Advanced microwave imaging techniques for early detection of breast cancer: A review and future perspectives. BioMed, 6(1), 6. https://doi.org/10.3390/biomed6010006

Smith, K., Bourqui, J., Wang, Z., Besler, B., Lesiuk, M., Roumeliotis, M., Quirk, S., Grendarova, P., Pinilla, J., Price, S., Docktor, B., & Fear, E. C. (2023). Microwave imaging for monitoring breast cancer treatment: A pilot study. Medical Physics, 50(11), 7118–7129. https://doi.org/10.1002/mp.16756

Sung, H., Ferlay, J., Siegel, R. L., Laversanne, M., Soerjomataram, I., Jemal, A., & Bray, F. (2021). Global cancer statistics 2020: GLOBOCAN estimates of incidence and mortality worldwide for 36 cancers in 185 countries. CA: A Cancer Journal for Clinicians, 71(3), 209–249. https://doi.org/10.3322/caac.21660

Thiel, C. L., Vigil-Garcia, M., Nande, S., Meijer, C., Gehrels, J., Struk, O., Thornander, S., Pullella, D., Omary, R. A., Carver, D. E., & Scheel, J. R. (2024). Environmental life cycle assessment of a U.S. hospital-based radiology practice. Radiology, 313(2), e240398. https://doi.org/10.1148/radiol.240398

Wang, L. (2023). Microwave imaging and sensing techniques for breast cancer detection. Micromachines, 14(7), 1462. https://doi.org/10.3390/mi14071462

Yaffe, M. J., & Mainprize, J. G. (2011). Risk of radiation-induced breast cancer from mammographic screening. Radiology, 258(1), 98–105. https://doi.org/10.1148/radiol.10100655

Yurtseven, A., Janjic, A., Cayoren, M., Bugdayci, O., Aribal, M. E., & Akduman, I. (2025). XGBoost enhances the performance of SAFE: A novel microwave imaging system for early detection of malignant breast cancer. Cancers, 17(2), 214. https://doi.org/10.3390/cancers17020214

AUTHOR BIOGRAPHY

Dalal Ammar Alakhdhar Ali is a faculty member at the Libyan Authority for Scientific Research, Libya. She holds a Master's degree in Physics from the Libyan Academy for Graduate Studies. Her research interests include medical physics, medical imaging, artificial intelligence in medical diagnosis, radiation physics, and the sustainability of healthcare technologies. Her research focuses on the development and evaluation of modern

Dalal Ammar Alakhdhar Ali is a faculty member at the Libyan Authority for Scientific Research, Libya. She holds a Master's degree in Physics from the Libyan Academy for Graduate Studies. Her research interests include medical physics, medical imaging, artificial intelligence in medical diagnosis, radiation physics, and the sustainability of healthcare technologies. Her research focuses on the development and evaluation of modern medical imaging techniques, particularly non-ionizing imaging modalities, to improve diagnostic accuracy, enhance patient safety, and promote sustainable healthcare systems in alignment with the Sustainable Development Goals (SDGs).