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From Technological Innovation to Clinical Adoption: Is Microwave Breast Imaging Ready for Sustainable and Equitable Breast Cancer Detection

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Microwave Breast Imaging; Breast Cancer Detection; Clinical Translation; Artificial Intelligence; Microwave Tomography; Healthcare Sustainability; Health Equity; Medical Imaging; Early Detection; Translational Readiness

Abstract
Microwave Breast Imaging (MBI) is emerging as a non-ionizing imaging modality for breast cancer detection by exploiting dielectric-property differences between healthy and malignant tissues. Although substantial advances in antenna engineering, microwave tomography, computational imaging, and artificial intelligence have significantly improved system performance, routine clinical implementation remains limited. Unlike previous reviews that primarily emphasize technological innovation and diagnostic performance, this review critically examines the translational readiness of MBI by integrating technological maturity, clinical validation, regulatory readiness, implementation feasibility, health-economic considerations, sustainability, and health equity. The study adopts a structured critical comparative review of peer-reviewed literature published between 2020 and 2025 to evaluate the current status of clinical translation and identify the factors governing healthcare adoption. The comparative analysis indicates that MBI has progressed from proof-of-concept research to early clinical translation, supported by multicenter clinical investigations, advances in AI-assisted imaging, and growing clinical validation. However, routine adoption remains constrained by limited prospective clinical validation, the absence of standardized evaluation frameworks, insufficient health-economic assessment, incomplete regulatory pathways, and scarce implementation research. Building on these findings, the review identifies a multidimensional translational evidence gap and introduces the Translational Readiness Framework for Microwave Breast Imaging (TRF-MBI) as a conceptual framework for evaluating clinical adoption and guiding future translational research. The review concludes that successful integration of MBI into breast cancer care depends primarily on strengthening clinical, regulatory, economic, and implementation readiness rather than on further technological innovation, thereby supporting sustainable and equitable healthcare delivery

من الابتكار التكنولوجي إلى التبني السريري :هل التصوير بالميكروويف جاهز للكشف المستدام والعادل عن سرطان الثدي

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الكلمات المفتاحية
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الملخص
تقنية تصوير غير مؤينة واعدة للكشف عن سرطان الثدي، اعتمادًا على (MBI) يُعدُّ التصوير بالميكروويف للثدي ،الاختلافات في الخصائص العازلية بين الأنسجة السليمة والخبيثة .ورغم التقدم الكبير في هندسة الهوائيات والتصوير المقطعي بالميكروويف، والتصوير الحاسوبي، والذكاء الاصطناعي، فإن التطبيق السريري الروتيني لهذه ،التقنية لا يزال محدودًا .وعلى خلاف المراجعات السابقة التي ركزت أساسًا على التطور التقني والأداء التشخيصي من خلال دمج نضجها التكنولوجي، والتحقق MBI تُقيّم هذه المراجعة بصورة نقدية الجاهزية الانتقالية لتقنية .السريري، والجاهزية التنظيمية، وقابلية التطبيق، والاعتبارات الاقتصادية الصحية، والاستدامة، والعدالة الصحية واعتمدت الدراسة مراجعة نقدية مقارنة ومنظمة للأدبيات العلمية المحكمة المنشورة بين عامي 2020 و2025 لتقييم الوضع الحالي للانتقال السريري وتحديد العوامل المؤثرة في تبني التقنية داخل أنظمة الرعاية الصحية .ويُظهر تجاوزت مرحلة إثبات المفهوم ودخلت مرحلة مبكرة من الانتقال السريري، إلا أن تبنيها MBI التحليل المقارن أن لا يزال مقيدًا بمحدودية التحقق السريري واسع النطاق، وغياب أطر التقييم المعيارية، ونقص التقييمات الاقتصادية الصحية، وعدم اكتمال المسارات التنظيمية، وقلة دراسات التطبيق العملي .واستنادًا إلى هذه النتائج، تقترح المراجعة بوصفه إطارًا مفاهيميًا لتقييم الجاهزية الانتقالية للتصوير بالميكروويف للثدي (TRF-MBI) إطار الجاهزية السريرية وتوجيه البحوث المستقبلية .وتخلص الدراسة إلى أن نجاح دمج هذه التقنية في رعاية سرطان الثدي يعتمد .أساسًا على تعزيز الجاهزية السريرية والتنظيمية والاقتصادية والتنفيذية بما يدعم رعاية صحية مستدامة وعادلة

1- INTRODUCTION

Breast cancer remains the most frequently diagnosed cancer among women worldwide and continues to pose a substantial global health problem. According to the latest GLOBOCAN 2022 estimates, approximately 2.3 million new breast cancer cases were diagnosed globally, making it the most common cancer among women and a leading cause of cancer-related mortality. These epidemiological trends underscore the critical importance of effective early detection strategies for reducing disease burden and improving patient survival outcomes (Bray et al., 2024; Freihat et al., 2025; Siegel et al., 2024). Because prognosis is strongly associated with disease stage at diagnosis, timely detection remains one of the most effective approaches for improving treatment success and reducing healthcare costs (Isautier et al., 2024; Monticciolo et al., 2023). Mammography remains the cornerstone of breast cancer screening programs and has contributed significantly to reductions in breast cancer mortality. Nevertheless, important limitations persist. Diagnostic sensitivity decreases in women with dense breast tissue, while infrastructure requirements, trained workforce demands, and unequal access continue to limit screening effectiveness in many healthcare systems, particularly within low-resource settings (Isautier et al., 2024; Monticciolo et al., 2023). Although complementary modalities such as ultrasound and magnetic resonance imaging (MRI) can improve diagnostic assessment in selected populations, their widespread implementation remains constrained by cost, infrastructure requirements, and availability (Isautier et al., 2024; Monticciolo et al., 2023). These challenges have stimulated growing interest in alternative imaging technologies capable of providing safe, affordable, and accessible diagnostic solutions. (AlSawaftah et al., 2022; Aldhaeebi et al., 2020) Among emerging approaches, Microwave Breast Imaging (MBI) has attracted considerable attention because it utilizes low-power, non-ionizing electromagnetic waves to exploit dielectric-property differences between healthy and malignant breast tissues (Aldhaeebi et al., 2020; Wang et al., 2023). Malignant tissues generally exhibit elevated dielectric permittivity and conductivity owing to increased water content, vascularization, and cellular density, thereby creating measurable electromagnetic contrasts that can potentially support tumor detection and localization (Bhargava & Sharma, 2024; Wang et al., 2023). Over the past two decades, MBI has evolved from an experimental concept into a multidisciplinary field integrating antenna engineering, computational electromagnetics, microwave tomography, radar-based sensing, inverse scattering methodologies, and artificial intelligence (AI)-assisted image analysis (Algomly et al., 2025; Sánchez-Bayuela et al., 2024; Wang et al., 2023). Advances in sensing technologies, image reconstruction methods, and machine-learning frameworks have substantially improved imaging capability and accelerated progress toward clinically deployable systems (Purnama et al., 2023; Wang et al., 2023). Simultaneously, emerging clinical platforms such as MammoWave and Wavelia have generated encouraging evidence regarding feasibility, patient acceptability, and lesion detection under real-world conditions (Fasoula et al., 2025; Sánchez-Bayuela et al., 2024). Despite these achievements, widespread clinical adoption has not yet been realized. A fundamental paradox therefore characterizes the field: technological development has advanced rapidly, whereas evidence supporting routine clinical implementation remains comparatively limited. Existing reviews have predominantly emphasized technological innovation, including antenna development, dielectric characterization, image reconstruction methodologies, and AI-assisted diagnostics (Aldhaeebi et al., 2020; Wang et al., 2023). Comparatively less attention has been devoted to the broader translational question of whether MBI possesses sufficient clinical, economic, regulatory, and implementation maturity to become an established component of future breast cancer diagnostic pathways. Consequently, the principal challenge facing the field is no longer technological feasibility but clinical translation. The future success of MBI will depend not only on its ability to detect breast abnormalities but also on its capacity to demonstrate clinical effectiveness, healthcare value, regulatory readiness, implementation feasibility, and equitable accessibility across diverse healthcare environments (Bhargava & Sharma, 2024; Sánchez-Bayuela et al., 2024). Accordingly, this review adopts a translational perspective to critically evaluate the current status of microwave breast imaging. Rather than focusing exclusively on technological progress, the review examines the extent to which existing evidence supports clinical adoption, identifies the principal barriers limiting implementation, evaluates sustainability and health-equity implications, and outlines future research priorities required to bridge the gap between technological innovation and real-world healthcare impact

2- PROBLEM STATEMENT

2.1. Research Questions

1. To what extent is Microwave Breast Imaging ready for clinical adoption?
2. What are the main barriers limiting its implementation in routine clinical practice?
3. How can MBI contribute to healthcare sustainability and diagnostic equity in breast cancer detection?

3- . RESEARCH HYPOTHESIS

This study hypothesizes that Microwave Breast Imaging possesses significant potential to support sustainable and equitable breast cancer detection; however, limitations in clinical, regulatory, and implementation evidence continue to hinder its widespread clinical adoption

4- RESEARCH OBJECTIVES

1. To evaluate the status of Microwave Breast Imaging technology.
2. To analyses the available clinical evidence supporting its use in breast cancer detection.
3. To identify the major barriers affecting its clinical translation and implementation.
4. To explore its potential contribution to healthcare sustainability and diagnostic equity.

5- SIGNIFICANCE OF THE STUDY

This review provides a critical assessment of the clinical readiness of Microwave Breast Imaging and highlights its potential role in improving early breast cancer detection. It also contributes to understanding the opportunities and challenges associated with integrating MBI into sustainable and equitable healthcare systems

6- OPERATIONAL DEFINITIONS

6.1. Microwave Breast Imaging (MBI)

A non-ionizing imaging modality that utilizes low-power electromagnetic waves to detect breast abnormalities based on dielectric-property differences between healthy and malignant tissues.

6.2. Clinical Translation

The process of transforming a medical technology from research and development into routine clinical practice.

6.3. Healthcare Sustainability

The ability of healthcare systems to deliver effective, accessible, and cost-efficient services while maintaining long-term resource availability.

6.4. Health Equity

The principle of ensuring fair and equal access to healthcare services and diagnostic technologies regardless of socioeconomic or geographic differences.

7- PREVIOUS STUDIES

Recent studies on Microwave Breast Imaging (MBI) show a clear transition from laboratory-based innovation toward early clinical evaluation. Sani et al. (2021) examined the MammoWave device as a non-ionizing approach for breast lesion detection and demonstrated that microwave imaging can generate clinically relevant information without breast compression or ionizing radiation. This study provided an important foundation for subsequent clinical work by showing the feasibility of using dielectric-property contrasts for lesion detection in real patients.

Moloney et al. (2021) evaluated the Wavelia Microwave Breast Imaging system in a symptomatic clinical cohort and reported promising tumor-discriminating features, particularly in estimating lesion size and distinguishing benign from malignant breast abnormalities. Although the findings supported the potential clinical usefulness of Wavelia, the study also highlighted the need for larger validation studies before routine clinical adoption.

In a related clinical direction, Janjic et al. (2022) investigated the SAFE microwave breast imaging system using a gradient-boosting machine-learning algorithm for breast lesion classification. The study reported encouraging diagnostic performance, suggesting that artificial intelligence can enhance the interpretability of microwave-based signals. However, its clinical value remains dependent on external validation and broader testing across diverse patient populations.

Sánchez-Bayuela et al. (2023) conducted a multicentric, prospective clinical investigation to evaluate MammoWave's ability to detect breast lesions. This study represented a major step forward because it included both symptomatic and asymptomatic women, moving MBI closer to real-world clinical assessment. Nevertheless, the evidence remained insufficient to establish MBI as a replacement for established screening modalities.

Another MammoWave-related clinical study by Álvarez Sánchez-Bayuela et al. (2024) further confirmed the potential of microwave imaging for breast lesion detection. The study strengthened the clinical evidence base by using a prospective stratified design, yet it also reinforced the need for standardized evaluation frameworks, larger sample sizes, and clearer performance benchmarks before regulatory and healthcare-system integration.

Wang et al. (2023) reviewed microwave imaging and sensing techniques for breast cancer detection and concluded that MBI is promising because it is non-invasive, non-ionizing, and potentially cost-effective. However, the review emphasized that challenges related to image resolution, tissue heterogeneity, inverse scattering, system standardization, and clinical validation continue to limit widespread adoption.

More recently, Sánchez-Bayuela et al. (2024) presented a protocol for an open, multicentric, prospective screening investigation of MammoWave in asymptomatic populations. This protocol is particularly important because it shifts the evidence agenda from feasibility studies toward population-based screening validation, which is essential for determining whether MBI can contribute to sustainable and equitable breast cancer detection.

Fasoula et al. (2025) reported Phase 2 clinical findings for the Wavelia Microwave Breast Imaging system, demonstrating encouraging diagnostic accuracy using

texture-based and intensity-based features. Despite these advances, the study confirms that MBI remains in a translational stage, where future adoption depends on stronger multicentre evidence, health-economic assessment, regulatory readiness, and integration into existing diagnostic pathways.

Taken together, previous studies suggest that MBI has moved beyond proof-of-concept research and has entered an important stage of clinical translation. The literature generally agrees that MBI is safe, patient-friendly, and technologically promising. However, there is also a consistent research gap: most available evidence remains based on pilot studies, early clinical evaluations, or protocol-stage investigations. Therefore, the present review differs from earlier studies by shifting the focus from technological feasibility to clinical maturity, sustainability, health equity, regulatory readiness, and implementation value. Despite the remarkable technological progress achieved in Microwave Breast Imaging (MBI), the existing literature remains predominantly focused on engineering development, antenna design, image reconstruction algorithms, microwave tomography, and artificial intelligence-assisted diagnostic performance (AlSawaftah et al., 2022; Wang et al., 2023) Most studies have concentrated on demonstrating technical feasibility and early-stage clinical effectiveness through pilot investigations and limited clinical cohorts. Furthermore, although recent studies involving platforms such as MammoWave and Wavelia have provided encouraging evidence regarding lesion detection, patient acceptability, and clinical feasibility, substantial gaps remain concerning large-scale clinical validation, long-term effectiveness, regulatory readiness, healthcare-system integration, health-economic evaluation, and real-world implementation. In addition, limited attention has been devoted to assessing MBI from the perspectives of healthcare sustainability and diagnostic equity, particularly regarding its potential contribution to improving access to breast cancer screening in resource-constrained environments. Accordingly, the current review addresses this gap by moving beyond technological performance assessment and critically examining the clinical maturity, implementation readiness, sustainability implications, and health-equity dimensions of Microwave Breast Imaging as a future breast cancer detection modality.

8- METHODOLOGY

This study adopts a critical analytical review approach to evaluate the current translational status of Microwave Breast Imaging (MBI) as a potential modality for sustainable and equitable breast cancer detection. The review is grounded in a systematic examination and critical comparison of contemporary scientific literature addressing technological development, clinical validation, implementation readiness, healthcare sustainability, and diagnostic equity. Relevant peer-reviewed studies published between 2020 and 2025 were identified through major scientific databases and academic search engines, including Google Scholar, Scopus, PubMed, IEEE Xplore, and Web of Science. The selection process focused on studies investigating clinical applications of MBI, microwave tomography, radar-based breast imaging systems, artificial intelligence integration, clinical trials, and translational challenges associated with routine clinical adoption. The collected studies were subjected to comparative and critical analysis to identify areas of agreement and divergence regarding diagnostic performance, clinical effectiveness, implementation barriers, regulatory readiness, health-economic considerations, and equity implications. Particular attention was given to emerging clinical platforms such as MammoWave and Wavelia as representative examples of contemporary translational progress. Rather than providing a purely descriptive summary of previous research, the study employs an interpretive and evaluative perspective aimed at assessing the maturity of existing evidence and determining whether current developments support the transition of MBI from technological innovation to routine clinical practice. Based on this analysis, the review identifies existing knowledge gaps and proposes future research priorities required to facilitate sustainable clinical implementation.

9- RESULTS

9.1. From Dielectric Contrast to Clinical Translation

The scientific foundation of MBI is based on the interaction of electromagnetic waves with biological tissues possessing distinct dielectric properties. Malignant breast tissues typically exhibit higher dielectric permittivity and conductivity than surrounding healthy tissues because of increased water content and microstructural alterations associated with tumor growth (Lazebnik et al., 2020; Wang et al., 2023). These dielectric contrasts provide the fundamental mechanism through which microwave-based systems attempt to detect and localize abnormalities. Contemporary MBI research is generally organized around two principal imaging paradigms. Microwave tomography seeks to reconstruct quantitative dielectric-property distributions through inverse scattering techniques, whereas radar-based imaging aims to identify localized scattering signatures associated with dielectric abnormalities (Sánchez-Bayuela et al., 2024). Although both approaches have demonstrated promising diagnostic potential, each faces trade-offs involving computational complexity, spatial resolution,

imaging robustness, and sensitivity to tissue heterogeneity. The evolution of MBI has been characterized by a gradual transition from proof-of-concept investigations toward clinically oriented research. Early studies primarily focused on validating dielectric contrast mechanisms and demonstrating the feasibility of tumor detection. Subsequent work concentrated on improving sensing technologies, electromagnetic modelling, and imaging performance (Aldhaeebi et al., 2020; Wang et al., 2023). More recently, artificial intelligence has become increasingly integrated into image reconstruction, lesion classification, image interpretation, and decision-support workflows (Bhargava & Sharma, 2024; Sánchez-Bayuela et al., 2024). These developments have significantly strengthened the technological maturity of MBI systems. However, technological progress alone does not guarantee healthcare adoption. Many medical-imaging technologies demonstrate strong laboratory performance yet fail to achieve widespread clinical implementation because they do not generate sufficient evidence of clinical utility, economic value, or implementation feasibility. A critical observation emerging from contemporary literature is that technological maturity has progressed more rapidly than clinical maturity. Recent studies increasingly emphasize improvements in imaging performance, computational efficiency, and algorithmic accuracy, whereas comparatively fewer investigations address questions related to diagnostic effectiveness, healthcare economics, regulatory approval, workflow integration, and long-term clinical impact (Purnama et al., 2023; Sánchez-Bayuela et al., 2024; Wang et al., 2023). Consequently, the central challenge confronting the field has shifted from demonstrating that microwave imaging can detect breast abnormalities to Microwave Breast Imaging has progressed from fundamental electromagnetic research to a clinically relevant technology; however, its future success depends on bridging the persistent gap between technological maturity and healthcare adoption. Achieving this transition requires stronger clinical validation, regulatory readiness, implementation research, and health-economic evidence.

Figure 1 summarizes the developmental pathway of MBI and the major barriers to widespread clinical deployment



9.2. Clinical Evidence: Progress Toward Clinical Maturity

The transition of MBI from laboratory experimentation to patient-centred investigation represents one of the most important developments in the field. While early studies focused predominantly on dielectric characterization, hardware optimization, and image reconstruction, contemporary research increasingly evaluates performance under clinical conditions. This transition is critical because the ultimate value of any diagnostic technology depends on its effectiveness within healthcare environments rather than controlled laboratory settings.

Among recent translational initiatives, the MammoWave project represents a major milestone in clinical microwave imaging. Multicentre investigations demonstrated the feasibility of distinguishing breasts with and without lesions using a non-ionizing and non-compressive imaging platform across multiple clinical sites (Pala et al., 2023). Beyond lesion detection, these studies provided valuable evidence regarding patient comfort, workflow integration, and operational feasibility. Similarly, evaluations of the Wavelia system demonstrated encouraging results in lesion localization and dielectric-property-based tissue characterization, supporting the growing clinical relevance of microwave imaging (Meaney et al., 2025).

Artificial intelligence has further accelerated clinical development. Machine-learning and deep-learning approaches have demonstrated promising performance in lesion classification, image interpretation, and automated decision support (Ghosh et al., 2025; Taghipour-Gorjikolaie et al., 2025). These developments are particularly important because automated analysis may improve reproducibility, reduce operator dependency, and facilitate deployment in healthcare environments with limited specialist expertise.

Nevertheless, the available evidence remains largely focused on feasibility rather than clinical effectiveness. Most published investigations evaluate lesion detectability, image quality, classification performance, reconstruction accuracy, or patient acceptability (Ghosh et al., 2025; Pala et al., 2023). Although these outcomes provide important evidence of technological progress, they do not necessarily demonstrate improvements in diagnostic pathways, patient outcomes, screening effectiveness, or healthcare delivery.

A fundamental distinction therefore exists between clinical feasibility and clinical maturity. Established breast-imaging modalities achieved widespread adoption only after extensive validation through large prospective investigations demonstrating measurable clinical benefit and healthcare impact (Monticciolo et al., 2023). By comparison, the current MBI evidence base remains dominated by pilot studies, early-stage clinical evaluations, and relatively small multicentre investigations. Consequently, important questions remain regarding reproducibility, clinical effectiveness, and large-scale implementation across diverse healthcare systems.

Table 1 illustrates a clear evolution from technology-oriented research toward clinically relevant investigations.

Nevertheless, the predominance of feasibility studies, limited external validation, and the scarcity of large-scale outcome-based trials indicate that MBI remains in a transitional phase between technological maturity and established clinical implementation.

Table 1. Critical Assessment of Recent Clinical Evidence and Translational Progress in Microwave Breast Imaging

Study/Platform	Main Contribution	Key Strength	Main Limitation	Translational Readiness
AlSawaftah et al. (2022)	Review of emerging MBI technologies	Comprehensive technological overview	Limited clinical evidence	Moderate
Fear and Omer (2023)	Assessment of clinical progress	Strong translational perspective	Limited quantitative validation	Moderate
MammoWave (Pala et al., 2023)	Multicentre lesion detection study	Real-patient evaluation and patient comfort	Limited outcome-based evidence	Moderate–High
Bhargava and Sharma (2024)	Review of recent developments	Broad methodological coverage	Limited implementation analysis	Moderate
Wavelia (Meaney et al., 2025)	Clinical lesion localization	Improved dielectric-based imaging	Relatively small clinical scale	Moderate
Taghipour-Gorjikolaie et al. (2025)	AI-assisted lesion classification	Advanced machine-learning framework	Limited external validation	Moderate
Ghosh et al. (2025)	Deep-learning-based diagnosis	Automated image interpretation	Limited clinical deployment evidence	Moderate

9.3. Why Has Microwave Breast Imaging Not Achieved Clinical Adoption Yet?

The evidence reviewed thus far demonstrates that microwave breast imaging has progressed substantially beyond its early experimental phase. Advances in sensing technologies, computational electromagnetics, microwave tomography, radar-based imaging, and artificial intelligence have significantly improved system performance and strengthened the scientific foundations of the field (Fear & Omer, 2023; Sánchez-Bayuela et al., 2024). Nevertheless, despite encouraging technological and clinical developments, MBI has not yet achieved routine integration into breast cancer screening or diagnostic pathways. This apparent contradiction reflects a fundamental translational challenge. In medical imaging, technological innovation alone is insufficient to ensure clinical adoption. Successful implementation requires robust evidence of clinical effectiveness, reproducibility, regulatory readiness, economic value, and compatibility with existing healthcare infrastructures. Consequently, the current position of MBI reflects a gap between technological maturity and healthcare adoption rather than a lack of scientific progress (Fear & Omer, 2023; Purnama et al., 2023; Sánchez-Bayuela et al., 2024).

9.3.1. Technical Challenges

Although considerable advances have been achieved in sensing hardware and image reconstruction methodologies, several technical limitations remain clinically relevant. Breast tissue exhibits substantial heterogeneity in dielectric properties across individuals and tissue compositions, complicating electromagnetic-wave propagation and reducing the consistency of lesion detection (Aldhaeebi et al., 2020; Wang et al., 2023). Furthermore, the inverse scattering problem underlying many MBI approaches remains highly nonlinear and ill-posed, making reconstructed images sensitive to measurement noise, modelling assumptions, and patient-specific variability (Sánchez-Bayuela et al., 2024). These challenges are not merely engineering concerns. Diagnostic technologies must provide reliable and reproducible performance across diverse patient populations and clinical environments. Consequently, technical uncertainty directly influences diagnostic confidence, clinical acceptance, and regulatory evaluation (Fear & Omer, 2023; Sánchez-Bayuela et al., 2024).

9.3.2. The Clinical Validation Gap

The most significant barrier to widespread adoption remains the limited availability of large-scale clinical evidence. Recent investigations have successfully demonstrated feasibility, patient safety, and lesion detectability under clinical conditions (Meaney et al., 2025; Pala et al., 2023). However, relatively few studies have evaluated clinically meaningful outcomes such as diagnostic decision-making, screening effectiveness, reduction of diagnostic delays, or long-term patient benefit. This limitation contrasts sharply with the evidence supporting established breast-imaging modalities. Mammography, ultrasound, and MRI achieved clinical acceptance only after extensive validation through large prospective studies involving diverse patient populations (Isautier et al., 2024; Monticciolo et al., 2023). By comparison, the current MBI evidence base remains dominated by pilot studies, feasibility assessments, and relatively small multicentre investigations. Consequently,

uncertainty persists regarding the precise clinical role of MBI within existing diagnostic pathways (Fear & Omer, 2023; Sánchez-Bayuela et al., 2024).

9.3.3. Standardization and Regulatory Readiness

Another major obstacle is the absence of universally accepted evaluation frameworks. Contemporary MBI systems differ substantially in imaging geometries, operating frequencies, acquisition protocols, reconstruction methodologies, and performance metrics (Fear & Omer, 2023; Sánchez-Bayuela et al., 2024). While this diversity reflects active innovation, it also complicates objective comparison among systems and limits reproducibility across studies. The lack of standardized benchmarking procedures, validation criteria, and performance metrics creates additional challenges for regulatory approval. Unlike mammography and MRI, which operate within well-established clinical standards, microwave imaging currently lacks internationally accepted pathways for performance assessment and clinical certification (Fear & Omer, 2023; Purnama et al., 2023). Without harmonized evaluation frameworks, the translation of promising research findings into regulatory approval and clinical deployment will remain slow.

9.3.4. The Missing Health-Economic Evidence

Affordability is frequently cited as one of the principal advantages of MBI. Compared with advanced imaging modalities such as MRI, microwave systems may eventually require less complex infrastructure and support more decentralized diagnostic services. However, affordability cannot be inferred solely from hardware simplicity (Fear & Omer, 2023; Sánchez-Bayuela et al., 2024). Healthcare adoption depends on a broader range of factors, including equipment maintenance, workforce training, quality assurance, reimbursement policies, workflow integration, and long-term operational costs (World Health Organization, 2025; Tollens,2023). Despite repeated claims regarding potential cost advantages, comprehensive cost-effectiveness analyses remain scarce. Consequently, one of the most frequently cited benefits of MBI remains largely hypothetical rather than evidence-based (Sánchez-Bayuela et al., 2024; Tollens et al., 2023).

9.3.5. The Artificial Intelligence Paradox

Artificial intelligence has emerged as a major driver of innovation within MBI research. Machine-learning and deep-learning algorithms have demonstrated promising performance in image reconstruction, lesion classification, artifact suppression, and automated decision support (Ghosh et al., 2025; Taghipour-Gorjikolaie et al., 2025). Nevertheless, AI introduces an additional layer of translational complexity. Many reported models have been developed using relatively small datasets generated within specialized research environments. External validation across independent populations remains limited, while concerns regarding algorithmic bias, generalizability, explainability, and regulatory compliance continue to restrict clinical deployment. Consequently, AI often improves performance metrics more rapidly than it strengthens clinical evidence (Taghipour-Gorjikolaie et al., 2025). Overall, the principal challenge facing microwave breast imaging is no longer the demonstration of technological feasibility. Rather, the field must generate the clinical, economic, regulatory, and implementation evidence required for healthcare adoption. The transition from technological maturity to measurable healthcare impact therefore represents the defining challenge for the next generation of MBI research (Fear & Omer, 2023; Purnama et al., 2023; Sánchez-Bayuela et al., 2024). As shown in Table 2, the transition of MBI from technological maturity to routine clinical practice remains constrained by unresolved challenges in validation, standardization, regulation, and implementation

Table 2. Challenges Limiting the Clinical Translation of MBI

Barrier Domain	Outstanding Challenge	Clinical Implication
Tissue Heterogeneity	Variable dielectric properties across patients (Aldhaeebi et al., 2020; Sánchez-Bayuela et al., 2024; Wang et al., 2023)	Reduced reproducibility and diagnostic confidence
Image Reconstruction	Sensitivity to noise and modelling assumptions (Sánchez-Bayuela et al., 2024; Wang et al., 2023)	Potential reduction in diagnostic reliability
Clinical Validation	Lack of large prospective trials (Meaney et al., 2025; Monticciolo et al., 2023; Pala et al., 2023)	Insufficient evidence for routine implementation
Standardization	Absence of common protocols and benchmarks (Fear & Omer, 2023; Sánchez-Bayuela et al., 2024	Difficult regulatory evaluation
Health Economics	Limited cost-effectiveness evidence (Purnama et al., 2023; Sánchez-Bayuela et al., 2024)	Uncertain reimbursement and adoption
Regulatory Readiness	Lack of established approval pathways (Fear & Omer,2023; Purnama et al. 2023)	Delayed clinical deployment
AI Integration	Limited external validation and explainability (Ghosh et al., 2025; Taghipour-Gorjikolaie et al., 2025)	Reduced trust in AI-assisted decisions
Healthcare Integration	Limited real-world implementation studies (Fear & Omer, 2023; Purnama et al., 2023; Sánchez-Bayuela et al., 2024)	Uncertain large-scale deployment feasibility

Note: The barriers summarized in this table were synthesized from recent studies addressing clinical validation, electromagnetic imaging challenges, standardization, artificial intelligence integration, regulatory considerations, and healthcare implementation in microwave breast imaging (Aldhaeebi et al., 2020; Fear & Omer, 2023; Ghosh et al., 2025; Purnama et al., 2023; Sánchez-Bayuela et al., 2024; Taghipour-Gorjikolaie et al., 2025; Wang et al., 2023).

9.4. Translational Readiness Framework for Microwave Breast Imaging

A central finding emerging from this review is that the principal obstacle facing microwave breast imaging (MBI) is not a lack of technological innovation, but rather a persistent imbalance between technological maturity and translational readiness. Over the past two decades, research efforts have predominantly focused on antenna development, dielectric characterization, inverse scattering algorithms, image reconstruction techniques, and, more recently, artificial intelligence integration (Aldhaeebi et al., 2020; Taghipour-Gorjikolaie et al., 2025). These advances have substantially improved imaging performance and elevated the technological readiness of MBI systems (Taghipour-Gorjikolaie et al., 2025; Wang et al., 2023). However, progress across the domains required for routine healthcare adoption—including large-scale clinical validation, regulatory qualification, health-economic evaluation, implementation science, and healthcare-system integration—has been considerably slower (Fear & Omer, 2023; Meaney et al., 2025; Pala et al., 2023; Purnama et al., 2023). Consequently, the field has reached a stage in which engineering capabilities have advanced more rapidly than the evidence required to support clinical deployment.

This review therefore proposes a Translational Readiness Framework for Microwave Breast Imaging (TRF-MBI), suggesting that successful clinical adoption depends not only on technological readiness but also on clinical, regulatory, economic, and implementation readiness. From this perspective, the current translational gap in MBI is best understood as a multidimensional evidence deficit rather than a technological limitation. Bridging this gap represents the defining challenge for the next generation of microwave breast

10-DISCUSSION

The findings of the present study indicate that nursing students at the Faculty of Nursing in Surman possess an acceptable level of awareness regarding antibiotic resistance (AR). Nevertheless, several knowledge gaps remain evident. Although most participants recognized AR as an important public health concern, the results revealed a substantial deficiency in formal training, as participation in workshops related to the appropriate use of antibiotics recorded the lowest mean score (1.27). This finding is consistent with the observations reported by Alharbi et al. (2026), who emphasized the importance of structured educational programs in strengthening digital health literacy and promoting evidence-based clinical decision-making.

The findings also demonstrated that nursing students showed a strong sense of professional responsibility. More than two-thirds of the participants (71.66%) reported that they consistently believed in their responsibility to educate patients regarding the risks associated with self-medication. This finding differs from the results reported by Dagameen (2025), in which participants demonstrated less favorable attitudes toward antimicrobial resistance prevention. Furthermore, the positive attitudes observed among students in Surman provide a strong foundation for implementing antimicrobial stewardship programs in educational and clinical settings.

Another important finding concerns the increasing dependence on digital resources for obtaining health-related information. More than half of the participants reported using artificial intelligence tools, such as ChatGPT, to obtain information regarding symptoms and medications. Similar findings have been reported by Mahdi et al. (2026), who observed extensive use of online resources among university students. This reliance on digital platforms may increase the risk of inappropriate self-medication practices, particularly in environments where antibiotics remain easily accessible without prescriptions.

Finally, descriptive differences were observed across demographic characteristics, including age and gender. However, the present study did not employ inferential statistical analyses, such as multiple regression analysis or analysis of variance, to determine whether these variables significantly predicted self-medication behavior. Consequently, further studies are needed to examine these relationships in greater detail.

imaging research (Fear & Omer, 2023; Purnama et al., 2023; Sánchez-Bayuela et al., 2024).

Figure 2. Translational Readiness Framework for Microwave Breast Imaging (TRF-MBI), showing the five readiness domains required for successful clinical adoption and highlighting the multidimensional evidence gap between technological innovation and healthcare implementation.



9.5. Sustainability and Equity Considerations

The long-term value of any diagnostic technology extends beyond technical performance and diagnostic accuracy. Sustainable healthcare innovation requires technologies that are clinically effective, economically viable, accessible to diverse populations, and capable of supporting equitable healthcare delivery. Consequently,

evaluating the future role of MBI requires consideration not only of its engineering capabilities but also of its potential contribution to healthcare sustainability and health equity.

9.5.1. Sustainability Beyond Technological Innovation

Healthcare systems worldwide face increasing pressure from rising cancer incidence, growing demand for diagnostic imaging, workforce shortages, and escalating healthcare expenditures (Bray et al., 2024; Purnama et al., 2023; World Health Organization & International Bank for Reconstruction and Development /The world Bank,2023). Within this context, MBI possesses several characteristics that distinguish it from conventional imaging modalities. Unlike mammography, it employs non-ionizing electromagnetic radiation, eliminating concerns associated with repeated radiation exposure. Furthermore, many proposed MBI systems rely on comparatively simple hardware architectures and may ultimately require less infrastructure than advanced imaging technologies such as MRI (Aldhaeebi et al., 2020; Wang et al., 2023). Another frequently cited advantage is the potential development of portable or semi-portable imaging platforms capable of operating outside highly specialized diagnostic centres. If successfully implemented, such systems could support decentralized diagnostic services and expand access to breast imaging in geographically underserved regions (Fear & Omer, 2023; Sánchez-Bayuela et al., 2024). However, these anticipated benefits should be interpreted cautiously. Although the technical characteristics of MBI suggest potential advantages in cost, accessibility, and scalability, empirical evidence supporting these assumptions remains limited. Most published studies emphasize projected benefits rather than demonstrated healthcare outcomes. Consequently, the sustainability potential of MBI remains promising but not yet validated through comprehensive health-economic and implementation studies (Purnama et al., 2023; Sánchez-Bayuela et al., 2024).

9.5.2. Health Equity: Opportunity or Assumption?

Health equity has become a central objective of contemporary cancer-control strategies because substantial disparities continue to exist in access to breast cancer screening and early diagnosis worldwide (Bray et al., 2024; World Health Organization, 2023). Within the MBI literature, improved accessibility is frequently presented as one of the technology's most important advantages. The underlying premise is that lower-cost, radiation-free, and potentially portable imaging systems could facilitate earlier diagnosis in underserved populations (Fear & Omer, 2023; Sánchez-Bayuela et al., 2024). While this argument is attractive, the relationship between technological accessibility and healthcare equity is more complex than often assumed. A diagnostic device alone cannot eliminate healthcare disparities. Effective cancer screening requires trained personnel, referral pathways, diagnostic confirmation services, treatment availability, quality assurance systems, and healthcare infrastructures capable of supporting patient management following abnormal findings (World Health Organization, 2023). Therefore, the availability of an accessible imaging technology does not automatically translate into equitable healthcare outcomes. Without adequate integration into healthcare systems, new technologies may simply shift existing bottlenecks from image acquisition to diagnosis, referral, or treatment. Current evidence therefore supports the possibility that MBI could contribute to more equitable breast cancer detection, but evidence demonstrating measurable improvements in population-level health equity remains largely absent (Purnama et al., 2023; Sánchez-Bayuela et al., 2024).

9.5.3. From Technological Promise to Healthcare Impact

The evidence reviewed throughout this study suggests that MBI occupies a unique position within the landscape of emerging medical-imaging technologies. Unlike many experimental concepts that remain confined to laboratory environments, MBI has already achieved significant advances in sensing technologies, computational imaging, artificial intelligence integration, and early clinical validation. Nevertheless, the fundamental question is no longer whether microwave imaging can detect breast abnormalities. Rather, the critical issue is whether these technological achievements can be translated into measurable healthcare benefits. Current evidence supports technical feasibility and growing clinical applicability, whereas evidence relating to healthcare sustainability, cost-effectiveness, implementation success, and equity impact remains comparatively limited. Accordingly, MBI should currently be viewed not as a proven solution to global disparities in breast cancer detection but as a promising technology whose broader healthcare impact remains to be established. The future success of the field will depend on the generation of robust translational evidence demonstrating not only diagnostic capability but also clinical value, economic sustainability, and equitable healthcare benefit.

11- DISCUSSION

The findings of the present review indicate that Microwave Breast Imaging (MBI) has reached a relatively advanced stage of technological maturity, but it has not yet achieved sufficient clinical maturity to support routine adoption in breast cancer screening or diagnosis. This conclusion is consistent with the findings of Sani et al. (2021), who demonstrated the feasibility of Mammo Wave as a non-ionizing and non-compressive imaging modality

for breast lesion detection. Their study confirmed that dielectric-property differences between healthy and abnormal breast tissues can produce clinically meaningful microwave images. However, the present review extends this finding by arguing that feasibility alone is insufficient for clinical adoption unless it is supported by large-scale validation, regulatory readiness, and implementation evidence.

Similarly, the results agree with Moloney et al. (2021), who reported that the Wavelia system showed promising clinical usefulness in estimating lesion size and differentiating between benign and malignant breast abnormalities. This supports the current review's conclusion that MBI is no longer limited to laboratory experimentation and has entered the stage of patient-based clinical evaluation. Nevertheless, the current study differs from Moloney et al. (2021) by emphasizing that promising diagnostic features do not necessarily translate into routine clinical integration, especially when evidence remains based on relatively limited clinical cohorts.

The present review also aligns with Janjic et al. (2022) and Dey et al. (2022), who highlighted the growing role of artificial intelligence and machine-learning methods in improving microwave-based lesion classification and localization. These studies support the view that AI can improve image interpretation, reduce operator dependency, and enhance diagnostic decision-making. However, the present review critically differs by identifying what may be called the "AI translation paradox": although AI improves technical performance metrics, its clinical adoption remains constrained by limited external validation, small datasets, algorithmic bias, explainability concerns, and regulatory uncertainty.

The findings further correspond with Sánchez-Bayuela et al. (2023), whose multicentric Mammo Wave investigations represented an important step toward clinical validation. These studies strengthen the evidence that MBI is safe, acceptable to patients, and potentially useful in real clinical settings. However, the present review differs in its interpretation of these findings. While previous studies focused mainly on lesion detection capability and clinical feasibility, the current review argues that multicentric feasibility is not equivalent to population-level effectiveness or healthcare-system readiness. In other words, MBI still needs prospective outcome-based studies capable of demonstrating its added value within existing diagnostic pathways.

The results are also consistent with Wang et al. (2023), who concluded that microwave imaging is promising because it is non-invasive, non-ionizing, and potentially cost-effective. However, the current review adopts a more cautious position. It argues that cost-effectiveness and sustainability should not be assumed from the simplicity of the technology alone. Instead, they require empirical evidence related to equipment costs, maintenance, workforce training, workflow integration, reimbursement, and long-term healthcare outcomes. This represents one of the main points of divergence between the present review and technology-oriented studies that tend to emphasize potential affordability without sufficient health-economic validation.

More recent evidence from Fasoula et al. (2025) supports the view that Wavelia has advanced toward more structured clinical investigation, particularly through multidimensional radiomics and improved diagnostic analysis. This agrees with the current review's finding that MBI is progressing toward clinical translation. Nevertheless, the current study stresses that such progress remains incomplete because successful clinical adoption depends not only on diagnostic accuracy but also on standardization, regulatory approval, clinical workflow integration, and demonstrated benefit across diverse healthcare settings.

Overall, the discussion reveals a clear pattern of agreement and divergence. Previous studies generally agree that MBI is safe, patient-friendly, non-ionizing, and technologically promising. The present review agrees with these conclusions but differs by shifting the analytical focus from technological feasibility to translational readiness. The central contribution of the current study is therefore its argument that the main barrier facing MBI is no longer whether microwave imaging can detect breast abnormalities, but whether it can generate robust clinical, economic, regulatory, and implementation evidence sufficient to justify its use within sustainable and equitable breast cancer detection pathways

12- CONCLUSION

The review demonstrates that MBI has successfully progressed beyond proof-of-concept experimentation and entered an advanced stage of technological maturity characterized by continuous improvements in imaging performance, lesion detection, image reconstruction, and AI-assisted interpretation.

2.Despite these advances, clinical maturity remains significantly lower than technological maturity. The available evidence continues to be dominated by feasibility studies, pilot investigations, and relatively small multicentre trials, limiting confidence in routine clinical implementation.

3.The findings reveal that the primary challenge facing MBI is no longer technological feasibility but translational readiness. The critical issue has shifted from whether microwave imaging can detect breast abnormalities to whether it can generate sufficient clinical, economic,

regulatory, and implementation evidence to justify widespread adoption.

4.The review identifies a persistent translational evidence gap resulting from insufficient large-scale clinical validation, lack of standardized evaluation frameworks, limited health-economic assessment, and incomplete regulatory pathways.

5.Artificial intelligence has emerged as an important driver of innovation in MBI, improving classification performance and image interpretation. However, its contribution remains constrained by limited external validation, concerns regarding generalizability, and regulatory uncertainty.

6.Although MBI is frequently presented as a sustainable and accessible imaging technology, current evidence does not yet conclusively demonstrate its long-term cost-effectiveness, healthcare sustainability, or ability to reduce disparities in breast cancer diagnosis.

7.The study proposes that successful future adoption of MBI depends on achieving balanced progress across five interconnected domains: technological readiness, clinical validation, regulatory approval, health-economic evidence, and healthcare-system integration

13-RECOMMENDATIONS

1. Conduct large-scale multicenter prospective clinical studies involving diverse patient populations to establish robust evidence regarding diagnostic effectiveness and clinical outcomes.
2. Develop internationally standardized protocols and performance benchmarks to improve comparability, reproducibility, and regulatory evaluation of MBI systems.
3. Expand health-economic investigations to assess cost-effectiveness, resource utilization, reimbursement feasibility, and long-term healthcare value.
4. Strengthen implementation-science research to evaluate workflow integration, infrastructure requirements, workforce readiness, and real-world deployment challenges.
5. Promote external validation of artificial intelligence models using independent multicenter datasets to improve reliability, transparency, and clinical trust.
6. .Investigate the potential contribution of MBI to healthcare sustainability and diagnostic equity, particularly in low-resource and underserved healthcare environments.
7. .Support the development of portable and decentralized microwave imaging platforms capable of expanding access to early breast cancer detection services

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