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Tissue-equivalent materials in three-dimensional-printed anthropomorphic breast phantoms for mammography

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ABSTRACT

Introduction: Anthropomorphic breast phantoms are essential tools in mammographic imaging, allowing repeated and safe evaluation for training, quality assurance, and protocol optimization without patient radiation exposure. With the increasing use of three-dimensional (3D) printing, these phantoms can be tailored to replicate complex breast anatomy, but their effectiveness is largely determined by the selection of appropriate tissue-mimicking materials. This study reviews the literature on materials used in the fabrication of 3D-printed breast phantoms, focusing on their physical and radiological properties and their ability to simulate relevant mammographic structures.

Methods: A literature search was performed in PubMed and Scopus databases during the summer of 2025. Studies published in English between 2015 and June 2025 were included. The review focused on research involving 3D-printed breast phantoms for mammography that utilized tissue-equivalent materials, following predefined inclusion and exclusion criteria.

Results: Nine studies met the inclusion criteria and were grouped according to the main material categories used in phantom fabrication: thermoplastic polymers, photopolymer resins, and composite materials. Thermoplastics were frequently selected because of their accessibility and reasonable radiological similarity to adipose and glandular tissues. Photopolymer resins provided high spatial resolution and improved anatomical detail. Composite materials, including radiopaque fillers and contrast agents, were used to reproduce pathological features, such as lesions and microcalcifications.

Conclusion: Material selection plays a key role in the development of realistic 3D-printed anthropomorphic breast phantoms for mammography. Future research should focus on standardizing material selection and phantom design to better align with diagnostic requirements and improve their value in clinical training, quality control, and imaging research.

Keywords: Breast phantom; mammography; three-dimensional printing; materials

INTRODUCTION

Anthropomorphic breast phantoms are important tools in diagnostic radiology, especially for tasks that require repeated imaging without exposing patients to radiation. They are commonly used in training, image quality assessment, dose optimization, and evaluation of clinical systems. In breast imaging, these phantoms also support the evaluation and refinement of emerging new imaging techniques, screening protocols, and reconstruction algorithms. In breast imaging, these phantoms enable the validation and optimization of novel imaging techniques, screening protocols, and reconstruction algorithms. Over the past decade, they have increasingly become central to virtual clinical trials, offering a practical and cost-effective alternative to large-scale randomized studies (1). While these models serve diverse imaging tasks, their clinical utility heavily depends on their anatomical and radiological realism. Anthropomorphic breast phantoms may be realized as either physical constructs or computational models that replicate the anatomy and X-ray attenuation properties of the human breast. To be clinically relevant, they must accurately represent the outer contour of the breast and its internal components, including adipose tissue, fibroglandular tissue structures, as well as different types of lesions. The effectiveness of a phantom is largely influenced by the selection

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of materials, which need to closely resemble human tissue with respect to physical density, elemental composition, and effective atomic number (2). In clinical mammography, the application of anthropomorphic breast phantoms plays a critical role in optimizing diagnostic protocols, ensuring equipment consistency, and enhancing radiologic technologist and radiologist training. However, commercial phantoms are often limited by high costs, limited anatomical variability, and a lack of transparency regarding the materials used in their fabrication. These drawbacks have led to growing interest in more flexible, laboratory-based alternatives. Among them, three-dimensional (3D) printing has emerged as a particularly promising solution. It allows accurate anatomical reproduction and fine control of material properties, enabling it to produce patient-specific or task-specific breast models that replicate the complex structure of breast tissue, including various types of lesions (3).

This study aims to review literature on tissue-equivalent materials applied in the fabrication of 3D-printed anthropomorphic breast phantoms for mammography, focusing on the types of materials used, along with their physical and radiological properties, and their suitability for replicating breast anatomy, in both clinical and research settings.

METHODS

This review article synthesizes scientific literature focused on the application of tissue-mimicking materials in the fabrication of 3D-printed anthropomorphic breast phantoms for mammography, and whose title and keywords included the terms: "breast phantom," "3D printing," "tissue equivalent materials," and "mammography." The search included studies published from January 2015 to June 2025. Only articles in English were included in the study. A search of the PubMed and Scopus databases was conducted during the summer of 2025. The inclusion criteria were limited to studies primarily focusing on breast phantoms designed for mammography, specifically those constructed using tissue equivalent materials. Studies were excluded if they involved non-human or non-breast phantoms or if they described commercially available phantoms without disclosure of material composition. In addition, studies were excluded if they were based solely on numerical simulations or phantoms developed for imaging modalities other than mammography. Reports, abstracts, study protocols, conference proceedings, and case reports were also excluded, as were reviews and studies employing a qualitative design. The review process followed a three-stage approach. In the first stage, a total of 2066 titles were screened based on relevance to the inclusion and exclusion criteria, resulting in the exclusion of 1950 records. In the second screening phase, the abstracts of the remaining 116 studies were evaluated, after which 44 articles were selected for full-text assessment in the final stage. The final inclusion was based on studies that clearly reported details regarding phantom development and material characteristics, and imaging evaluation protocols. Ultimately, nine studies satisfied all inclusion criteria and were included in the final review (Figure 1).

RESULTS

The main characteristics of the nine studies included in this review are presented in Table 1. All selected studies met the predefined inclusion criteria and reflect different approaches to the use of tissue-mimicking materials in the fabrication of 3D-printed breast phantoms for mammography.

All of the included studies concentrated on developing breast phantoms designed to realistically replicate the anatomical and radiological properties of human breast tissue for use in applications in medical imaging, quality assurance, and training. To facilitate clarity and comparison, the studies were grouped according to the material types used in phantom fabrication: thermoplastic polymers, photopolymer resins, and composite materials.

Thermoplastic polymers

Thermoplastic polymers used in breast phantom fabrication are primarily processed using extrusion-based 3D printing methods, such as fused deposition modeling (FDM). In this process, material is built up layer by layer through a heated nozzle, which shapes the internal structure of the printed object. This process directly influences parameters such as layer adhesion, porosity, and infill distribution. These structural features considerably affect the mechanical properties and the X-ray attenuation behavior of the final phantom (4).

Thermoplastic polymers are among the most commonly used materials for producing breast phantoms, particularly in FDM 3D printing. Commonly used materials include polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polyethylene terephthalate glycol (PET-G), and Nylon that have been widely studied for their capacity to mimic components of breast tissue, especially adipose and glandular structures. PLA is commonly preferred due to its ease of printing and low tendency to warp. It is also biodegradable, which makes it suitable for prototypes and users with less experience. ABS offers higher mechanical strength and better heat resistance, although it requires more controlled printing conditions. PET-G provides a balanced combination of toughness, chemical resistance, and good printability (4-7).

The reviewed studies identified the thermoplastics most frequently used, each associated with a specific function in the phantom, such as replicating adipose or glandular tissue, and linked them to relevant references (Table 2).

From a physical perspective, commonly used thermoplastics exhibit distinct density ranges that directly influence their radiological behavior. PLA typically ranges from 1.20 to 1.25 g/cm^3, whereas ABS has a density of about 1.04-1.07 g/cm^3. PET-G generally falls between 1.23 and 1.27 g/cm^3, while nylon exhibits intermediate values of approximately 1.13-1.15 g/cm^3, positioning it between adipose- and glandular-equivalent materials (4-6).

Among the materials considered, ABS is frequently selected to mimic adipose tissue due to its relatively low X-ray attenuation, which closely matches the radiological characteristics of fat. In contrast, PLA and PET-G have higher attenuation values, which makes them more suitable for simulating glandular tissue. These materials are popular choices

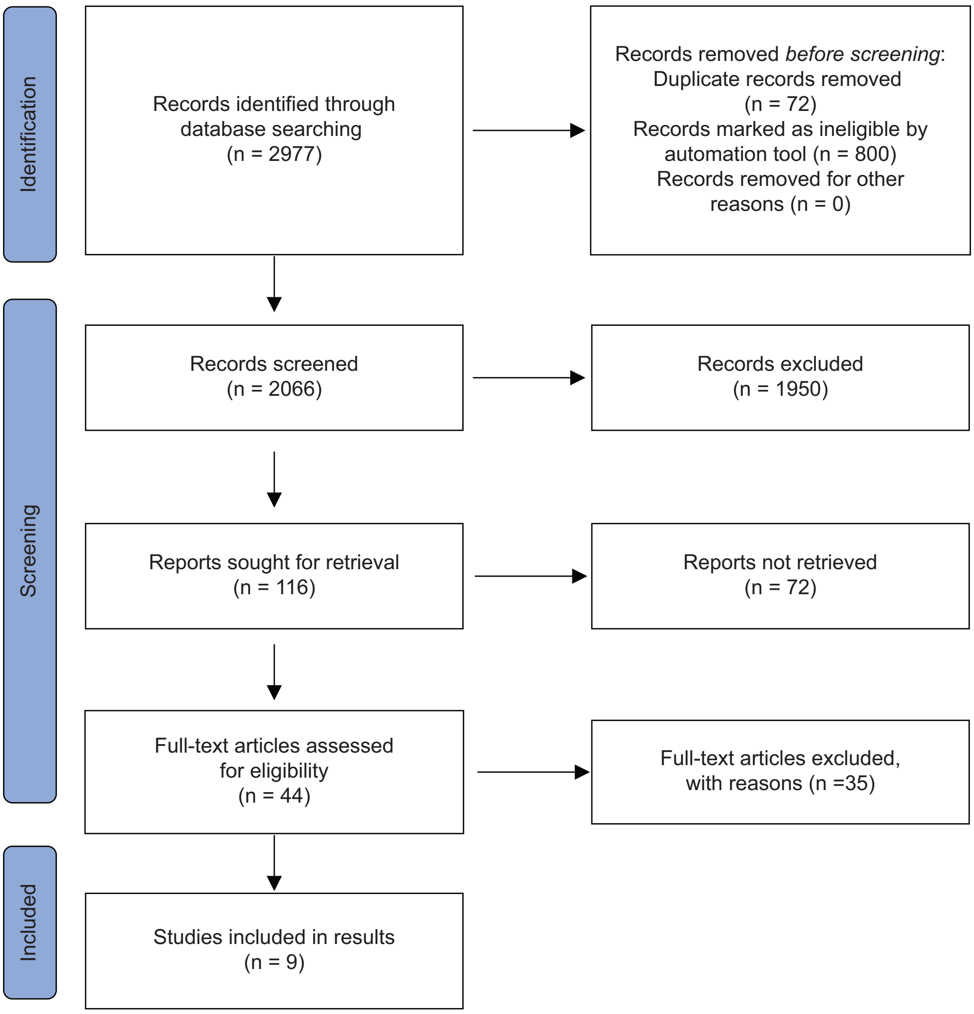

FIGURE 1. Flowchart of a selection of studies for the review.

because they are easily accessible, cost-efficient, and compatible with commonly used FDM printers, making them practical options for routine research and phantom fabrication. However, thermoplastics such as PLA and PET-G are hygroscopic and tend to absorb moisture, which can lead to printing defects such as air voids and a reduction in overall structural integrity of the phantom (4-6). This may increase porosity, cause inconsistent filament flow, and weaken interlayer adhesion, ultimately affecting both the mechanical stability and radiological uniformity of the printed phantom. Despite these limitations, their ease of printing, good mechanical strength, and low cost make them well-suited for producing large or modular breast phantoms.

Photopolymer resins

Photopolymer resins are used in advanced manufacturing processes such as vat photopolymerization, which includes stereolithography (SLA) and material jetting (PolyJet). In these methods, liquid resin is selectively cured, using light to produce highly detailed and precise 3D structures. These technologies are characterized by high spatial resolution and their capability to produce more uniform internal structures (6).

Photopolymer resins were employed in several studies to fabricate high-resolution components of anthropomorphic breast phantoms. These materials are particularly well-suited for replicating anatomical detail, skin surface contours, and internal lesion structures due to their fine print resolution, tunable mechanical stiffness, and X-ray attenuation characteristics.

Resins such as Gray V4, White V4, Flexible 80A v1, TangoBlackPlus™, VeroClear™, VeroPureWhite, and JF Flexible were applied in the included studies to simulate different types of breast tissue and structural layers. Their high spatial resolution, typically around 200 micrometers or better, allowed for accurate representation of complex glandular and adipose structures. In several cases, researchers combined multiple resins within a single phantom to replicate variations in tissue density and mechanical behavior. For example, flexible resins such as TangoBlackPlus™ were selected to mimic the elasticity of soft tissue, while stiffer resins such as VeroClear™ were used for structural or skin-mimicking components (6,8,9). These resins also demonstrated strong X-ray attenuation capabilities, with some studies specifically optimizing material formulations to simulate the radiological behavior of glandular and adipose tissues. The ability to customize and mix resin types allows for improved anatomical and radiological realism. However, limitations such as higher cost, the requirement for specialized equipment, and post-processing requirements, along with the brittleness of certain resins like Wax40, can restrict broader implementation.

The photopolymer materials used across the included studies, as well as their roles in phantom fabrication, are summarized in Table 3.

TABLE 1. Characteristics of eligible studies

Author, year, reference number, title	Main objectives	Materials and methods	Results	Conclusion
Bliznakova, 2024, (6) Assessment of a method for manufacturing realistic breast lesions for experimental investigations	To evaluate seven materials suitable for 3D printing based on their ability to replicate imaging characteristics of breast lesions.	Seven irregularly shaped lesions were created using FDM materials (PLA, ABS, PET-G) and various resins. The lesions were embedded into physical phantoms filled with either water or paraffin, and then imaged using mammography. In parallel, computational phantoms were developed to represent varying attenuation characteristics of breast tissues. The resulting images from both approaches were evaluated in terms of contrast-to-noise ratio and overall contrast to evaluate the performance of the materials employed.	All the resins and filament materials tested were effective for simulating breast lesions. Among them, PLA and White v4 resin showed the highest density and closely resembled lesions, showing slightly lower attenuation than glandular tissue. In contrast, ABS and Flexible 80A v1 resin, being less dense, were better suited for representing lesions that contain fat. The other materials also effectively mimicked the characteristics of malignant lesions.	These materials are well-suited for producing realistic breast phantoms, making them useful for experimental studies, improving mammography protocols, supporting equipment quality control, and supporting the diagnosis and evaluation of breast cancer.
Bustos Flores et al., 2022, (11) Breast phantom made of acrylic slabs for tests in mammography DR	To create a cost-effective and realistic breast phantom that accurately simulates average breast density and common lesions for use in mammography and tomosynthesis applications.	A breast phantom was created using five semicircular slabs, with four made from PMMA and one from self-curing acrylic resin, selected for its density that mimics human tissue. The acrylic slab contained embedded features that simulate microcalcifications (small calcium carbonate particles) and masses (a mixture of acrylic resin and calcium bicarbonate).	After constructing the breast phantom using PMMA and acrylic resin, 2D imaging was conducted with a mammography or tomosynthesis unit. Structures that mimic lesions were visually identified and marked on high-resolution images, which were then further analyzed through magnified views. The raw data underwent ImageJ analysis, revealing pixel value distributions and providing both top and 3D visualizations of the internal structures of the phantom.	This study presents a breast phantom made from PMMA and acrylic resin that simulates average breast density and includes lesion-like structures for use in digital mammography and tomosynthesis. It offers a practical, but detailed approach to producing realistic, heterogeneous phantoms with potential future applications in dosimetry and quality assurance.
Esposito et al., 2019, (7) Investigation of the refractive index decrement of 3D printing materials for manufacturing breast phantoms for phase contrast imaging	To evaluate the suitability of different 3D printing materials as substitutes for breast tissue in physical phantoms used in both 2D and 3D X-ray imaging applications.	Twelve different 3D printing materials were examined at different photon energies. The evaluation utilized propagation-based phase-contrast imaging and phase-shift maps were reconstructed using Paganin's algorithm, with breast glandular, adipose, and skin tissues as reference standards. The refractive index decrement (δ) and absorption index (β) were measured, and the percentage difference ($\Delta\delta$) was calculated to evaluate how suitable the materials were.	The method showed an accuracy of around 4%, validated against the properties of PMMA and Nylon. It was determined that ABS effectively simulate adipose tissue, Hybrid is suitable for glandular tissue, while PET-G is appropriate for representing skin.	The evaluated materials have shown strong potential for use in 3D-printed breast phantoms that closely replicate both anatomical structure and radiological properties.
Ikejimba et al., 2017, (10) A novel physical anthropomorphic breast phantom for 2D and 3D X-ray imaging	To develop a fast and cost-effective method for producing realistic breast phantoms compatible with both 2D and 3D imaging systems.	The phantom was produced through digital modeling using analytical equations, which segmented it into adipose and glandular regions via Voronoi segmentation. The model was printed layer by layer using inkjet technology with parchment paper and radiopaque ink that contained either 25% or 33% iohexol. Three types of parchment (P1, P2, P3) were evaluated. Materials' attenuation properties were measured using FFDM and a spectroscopic detector. The entire process was validated for precision, consistency, and ink reliability.	Parchment paper types P1 and P2 showed attenuation values similar to those of adipose tissue, while the ink-infused parchment closely resembled glandular tissue. Specifically, the effective linear attenuation coefficients (μ_eff) for P1+I25% and P1+I33% were measured at 0.89 and 0.94 cm^{-1}, respectively, which are nearly equivalent to the glandular tissue's value of 0.90 cm^{-1}. The phantom exhibited a strong correlation between printed and simulated images, with a deviation of less than 3% variation in ink signal across different prints and under 1% variability in ink batches. Imaging conducted with FFDM and DBT confirmed the phantom's effectiveness for realistic breast imaging.	This study presents a cost-effective and practical method for creating anatomically precise breast phantoms utilizing inkjet printing and readily available materials.

(Contd...)

TABLE 1. *(Continued)*

Author, year, reference number, title	Main objectives	Materials and methods	Results	Conclusion
Ivanov et al., 2018, (4) Suitability of low-density materials for 3D printing of physical breast phantoms	To evaluate various 3D printing materials by analyzing their X-ray attenuation and refractive properties to determine which most closely replicate the characteristics of breast tissues.	The step-wedge phantoms were designed using computational modeling and fabricated with SLA and FDM techniques. X-ray imaging was carried out using monochromatic beams at different energies. The experimental data were analyzed to determine the materials' linear attenuation coefficients, which were subsequently compared to theoretical values for breast tissue attenuation and refractive indices.	Most resin-based materials, along with Nylon, Hybrid, and PET-G, showed attenuation properties that closely resemble those of glandular tissue, while ABS exhibited attenuation characteristics similar to adipose tissue. For applications in phase-contrast imaging, combining ABS with resin materials appears to be a promising candidate for representing both adipose and glandular tissues.	These findings support the creation of a new anthropomorphic breast phantom with improved anatomical and radiological realism, specifically designed for use in advanced mammography techniques that operate at higher photon energies.
Rossman et al., 2019, (8) Three-dimensionally-printed anthropomorphic physical phantom for mammography and digital breast tomosynthesis with custom materials, lesions, and uniform quality control region	To develop a modular breast phantom that enhances the visualization of lesions and calcifications while providing a standardized region for routine quality control testing in mammography and DBT.	The study enhances earlier phantom designs by utilizing modified 3D printers to produce voxelized phantoms that feature smooth transitions between glandular and adipose tissues. Adipose tissue is represented with Jf Flexible material, while glandular tissue is represented either by Jf Flexible doped with salts or nanoparticles, or by using the resin VeroPureWhite. Additionally, the phantom includes modular inserts for masses, calcifications, iodinated objects, and a uniform chest wall area designated for standard QC tools.	The modular design allows for the representation of a wider range of breast tissue densities, improving anatomical realism compared to earlier models. The use of interchangeable inserts improves the evaluation of lesion and calcification visibility, while the uniform region supports standard quality control measurements.	Enhanced modular breast phantom serves as a flexible and anatomically accurate instrument for improving the evaluation of clinical mammography and tomosynthesis systems in both diagnostic and QC settings.
Santos et al., 2019, (9) Characterization and applicability of low-density materials for making 3D physical anthropomorphic breast phantoms	To assess the suitability of low-density materials as tissue-equivalent components for 3D-printed breast phantoms.	Mammographic X-ray spectra were recorded both before and after they passed through different material thicknesses using a CdTe detector. This process generated attenuation curves, and linear attenuation coefficients, $\mu(E)$, were calculated for each material within the 10-20 keV range. PMMA served as a reference to validate the methodology, comparisons were performed against values reported in the literature for glandular, adipose, skin, and blood tissues.	The experimental $\mu(E)$ values for PMMA showed close agreement with published literature data, supporting the validity of the method's accuracy. TangoBlackPlus™ and VeroClear™ exhibited the best compatibility with glandular tissue, showing average differences of−0.36% and+1.85%, respectively. Meanwhile, a urethane-based polymer was identified to be the closest match to adipose tissue, with a+3.39% difference. However, none of the materials tested provided sufficient equivalency for skin or blood.	TangoBlackPlus™ and VeroClear™ are effective options for mimicking glandular tissue, while the urethane-based polymer is appropriate for simulating adipose tissue in 3D-printed breast phantoms.
Schopphoven et al., 2019, (12) Breast phantoms for 2D digital mammography with realistic anatomical structures and attenuation characteristics based on clinical images using 3D printing	To create a method for fabricating breast phantoms suitable for 2D DM, focusing on realistic anatomical features and X-ray attenuation properties derived from clinical images through 3D printing techniques.	The phantom was fabricated using PolyJet 3D printing technology along with a material similar to polypropylene. A calibration function was designed to link the thickness of the material to its X-ray attenuation properties, and the printer's lateral resolution was found to be approximately 200 μm. The pixel intensities from unprocessed clinical images were transformed into corresponding heights for the phantom, resulting in a 3D model that was printed and validated using the same FFDM system. Additionally, the phantom underwent evaluation on five different FFDM systems to assess its compatibility.	Anthropomorphic breast phantoms showed a strong correlation with the corresponding human breast image regarding both anatomical features and attenuation properties on the calibration system. The AEC, exposure settings and image post-processing were consistent between the clinical images and the corresponding phantom images. In addition, the phantom proved to be compatible with various other FFDM systems.	A 3D printing-based approach was developed to produce realistic breast phantoms for DM, accurately capturing both anatomical structure and radiological properties.
Varallo et al., 2022, (5) Fabrication of 3D printed patient-derived anthropomorphic breast phantoms	To develop anatomically accurate, compressed breast phantoms, this project involves	Using FDM with a layer resolution of 0.1 mm and full infill, three breast phantoms were created from digital models based on segmented clinical breast CT scans. A dual-extruder 3D printer was used to produce the phantoms using ABS, PLA,	The images of the phantoms produced using DM and DBT exhibited realistic internal textures, accurately reflecting the glandular structures found in clinical images. The β values recorded in DM images	3D-printed breast phantoms produced using ABS, PLA and PET were able to realistically replicate both anatomical

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TABLE 1. *(Continued)*

Author, year, reference number, title	Main objectives	Materials and methods	Results	Conclusion
for mammography and digital breast tomosynthesis: Imaging assessment with clinical X-ray spectra	the design, fabrication, and characterization of 3D-printed models intended for use in DM and DBT.	and PET materials, where ABS simulated adipose tissue and PLA or PET represented glandular and skin tissues. The phantoms were imaged at three clinical locations with DM and DBT systems, employing standard X-ray spectra. Anatomical noise was evaluated by estimating the β parameter in both DM and CT images.	varied from 2.84 to 3.79, while lower values were shown in CT scans, indicating differences in how textures are represented across these imaging modalities.	structures and radiographic texture, highlighting their strong potential for use in clinical quality assurance, image quality assessment, and dosimetry studies.

FDM: Fused deposition modeling, PLA: Polylactic acid, ABS: Acrylonitrile butadiene styrene, PET-G: Polyethylene terephthalate glycol, PMMA: Polymethyl methacrylate, FFDM: Full-field digital mammography, DM: Digital mammography, DBT: Digital breast tomosynthesis, SLA: Stereolithography, FDM: Fused deposition modeling QC: Quality control, CdTe: Cadmium telluride, CT: Computed tomography, AEC: Automatic exposure control, 3D: three-dimensional

TABLE 2. Thermoplastic materials used in breast phantom fabrication

Phantom region	Material	Notes	References
Adipose tissue	ABS	Low X-ray attenuation, fat simulation	(4,6)
Glandular tissue	PLA	Tunable attenuation with infill density	(4-6)
Glandular tissue	PET/PET-G	Higher attenuation, good structural stability	(4,7)
Glandular tissue	Nylon	Radiological similarity, strength	(7)
Lesion simulation	ABS	Used to mimic masses/calcifications	(4,6)
Structural support	PET/PET-G	Durable, compatible with modular designs	(4,7)

PLA: Polylactic acid, ABS: Acrylonitrile butadiene styrene, PET: Polyethylene terephthalate, PET-G: Polyethylene terephthalate glycol

TABLE 3. Photopolymer resins used in breast phantom fabrication

Phantom region	Material(s)	Notes	References
Glandular tissue, skin, structure	VeroPureWhite, VeroClear, TangoBlackPlus	High-resolution resins for detailed anatomical replication	(8,9)
Outer contour	Polypropylene-like resin	Provides dimensional stability and smooth external surfaces	(12)
Lesions and inserts	Wa×40, Flex, Tough resins	Used for radiopaque lesion simulation	(6)

Composite materials

Several studies have used composite materials to improve both the realism and functionality of 3D-printed breast phantoms. These materials were often selected for their radiological characteristics, structural properties, or ability to simulate specific anatomical features that are not easily reproduced using conventional thermoplastics or photopolymers. Innovative low-cost materials, such as parchment paper and iodinated radiopaque inks, were used by Ikejimba et al. to mimic glandular and adipose tissue attenuation profiles across diagnostic X-ray spectra (10). These materials allowed for precise attenuation tuning, providing effective simulation of heterogeneous tissue compositions. To simulate calcifications and lesion structures, materials like calcium hydroxyapatite (HA) and aluminum oxide (AO) were employed due to their radiopacity and particle size control, ranging from 200 to 600 micrometers, supporting visibility studies and image quality analysis (11). These additives were incorporated into modular phantom inserts for targeted assessment of radiological performance. Other studies utilized composite resins enhanced with salts, metal oxides, or nanoparticles to tailor both the mechanical and imaging properties of the printed structures (7,8). These materials enabled the simulation of pathological features such as tumors or microcalcifications, as well as compatibility with advanced imaging methods, like phase contrast imaging. While composite materials offer significant radiological fidelity and targeted anatomical simulation, they are commonly used for inserts or localized components rather than for full phantom construction.

DISCUSSION

Polymers emerged as the dominant material category across the included studies, mainly due to their compatibility with various 3D printing technologies, cost-effectiveness, and adaptability to different tissue types. Four studies employed FDM using thermoplastics such as PLA, ABS, PET-G, and Nylon, materials that are preferred due to their low melting points, reliable extrusion behavior, and tunable radiological properties. Among them, PLA was the most frequently used, appearing in three studies, and was used to simulate both adipose and glandular tissues depending on infill parameters (4-6). ABS was selected in two studies to mimic adipose tissue because of its radiological similarity, while Nylon and PET-G were employed for simulating glandular tissue, given their higher attenuation coefficients and consistent structural behavior (4,7). The attenuation characteristics of these materials were energy-dependent, as highlighted by Ivanov et al., reinforcing their suitability for mammographic simulations (4). Bliznakova also reported that PLA and wax-based materials achieved favorable contrast-to-noise ratios, enhancing lesion visibility. Furthermore, incorporating flexible polymers such as Flex and Tough resins improved mechanical realism, offering better tactile feedback and structural response under compression (6).

Photopolymer resins, used in SLA and PolyJet technologies, were featured in four of the included studies (6,8,9,12). Their high resolution, fine surface replication, and ability to model anatomical detail make them valuable for fabricating components such as ductal networks, skin contours, and lesion inserts. These ultrasound-curable resins, often epoxy- or acrylate-based, exhibit distinct mechanical behavior depending on viscosity. Low-viscosity formulations cure rapidly but are brittle, whereas higher-viscosity variants provide better structural integrity but may require dilution, potentially compromising performance. Rossman et al. and Santos et al. utilized Vero resins (VeroPureWhite, VeroClear, TangoBlackPlus) to model layered breast anatomy with high spatial fidelity (8,9). Schopphoven et al. applied a polypropylene-like resin for the phantom shell to achieve dimensional stability and a realistic outer shape (12). Bliznakova et al. explored Wax40, Flex, and Tough resins, which were particularly effective in simulating lesions, due to their radiological contrast and mechanical distinction from surrounding materials (6). Despite their advantages in resolution and anatomical realism, the limitations of photopolymers, particularly brittleness, cost, and specialized post-processing, restrict their use in larger or compressible phantom components.

Composite materials were also examined, primarily for replicating features such as microcalcifications, lesion structures, and contrast-enhanced regions. HA and AO were used to simulate microcalcifications ranging from 200 to 600 μm, essential for image quality assessments (11). Ikejimba et al. proposed an innovative approach based on the use of parchment paper and iodinated ink to mimic glandular and adipose tissue attenuation at a reduced cost, validated across a range of X-ray energies. The incorporation of nanoparticles, radiopaque inks, and ceramic additives further enhanced the radiological and mechanical fidelity of phantom components (10). These hybrid formulations, such as composites infused with salts, carbon nanotubes, or metal oxides, enable precise tuning of attenuation and support applications in phase contrast imaging (7,8). However, such specialty materials are often typically limited to small inserts or localized features due to their brittleness, fabrication complexity, or cost constraints.

All included studies underscored the utility of 3D-printed anthropomorphic breast phantoms in improving diagnostic accuracy, image quality assurance, and clinical training. Ivanov et al. and Rossman et al. demonstrated how thermoplastics and photopolymers could simulate heterogeneous tissue distributions, thereby enabling radiologists to practice interpreting complex cases in a controlled setting. They also introduced a modular phantom design with interchangeable inserts for different pathologies, promoting repeated, standardized testing scenarios for both learners and experienced clinicians (4,8). Santos et al. and Schopphoven et al. developed patient-specific phantoms derived from real imaging data, enabling precise simulation of individual anatomical variability for both training purposes and equipment calibration (9,12). Bliznakova et al. focused on lesion detectability and contrast modulation, producing inserts with known radiographic profiles to test image quality metrics under various acquisition protocols. The anatomical precision achieved using photopolymers allowed for faithful replication of glandular networks and ductal structures, crucial for evaluating early-stage cancer detection (6). In contrast-enhanced protocols, the incorporation of radiopaque and doped materials enabled testing of phantoms under conditions that closely reflect clinical imaging. In addition, Ikejimba et al. introduced a low-cost, resource-efficient approach using readily available materials such as parchment paper and iodine-based ink, demonstrating that diagnostic relevance can still be maintained even in low-resource settings, which may support broader implementation in such environments (10).

Limitations

This review has several limitations that should be considered when interpreting the findings. The number of included studies was limited (n = 9), indicating that research on 3D-printed anthropomorphic breast phantoms is still at an early stage. Furthermore, there was marked variability across studies in fabrication methods, material choices, and approaches used to assess physical and radiological properties. Future research should focus on standardizing material selection and phantom design to better align with diagnostic requirements and improve their value in clinical training, quality control, and imaging research.

CONCLUSION

This review highlights how important material selection is in the development of 3D-printed anthropomorphic breast phantoms for mammography. Thermoplastics and photopolymers are still the most frequently used materials, each offering distinct advantages in printability, structural stability, and radiological performance. The incorporation of composite materials and radiopaque additives can further improve realism, especially when simulating lesions and microcalcifications. However, the absence of standardized fabrication methods and validated material benchmarks remains a key limitation, reducing consistency and comparability between studies. To support better clinical training, quality control, and research in breast imaging, future work should aim to establish clear guidelines for material selection and phantom design that are aligned with specific imaging and diagnostic requirements.

DECLARATION OF INTERESTS

Authors declare no conflict of interest.

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