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Liposome-Based Drug Delivery Systems for Targeted Treatment of Breast Cancer

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ABSTRACT: Liposome-based drug delivery systems have emerged as an effective nanotechnological strategy to overcome these limitations by improving drug solubility, stability, pharmacokinetics, and tumor targeting. Liposomes are biocompatible phospholipid vesicles capable of encapsulating both hydrophilic and hydrophobic anticancer agents, enabling controlled drug release and reduced off-target effects. This review provides a comprehensive overview of liposome-based drug delivery systems for targeted treatment of breast cancer. It discusses breast cancer pathophysiology and molecular targets relevant to liposomal design, followed by an in-depth analysis of liposome structure, formulation strategies, and physicochemical properties influencing therapeutic performance. Passive targeting via the enhanced permeability and retention (EPR) effect, active ligand-mediated targeting, and stimuli-responsive liposomal systems are critically examined. The review further highlights therapeutic applications including liposomal chemotherapeutics, combination drug delivery, and gene/siRNA delivery approaches. In vivo pharmacokinetics, biodistribution, clinical progress of approved liposomal formulations, and ongoing clinical developments are also discussed. Additionally, safety, toxicity, and regulatory considerations are addressed, along with key challenges hindering clinical translation. Finally, emerging trends such as multifunctional liposomes, personalized nanomedicine, and scalable manufacturing strategies are explored. Overall, liposome-based drug delivery systems represent a promising and clinically relevant platform for improving the efficacy and safety of breast cancer therapy.

KEYWORDS: Liposomes; Breast cancer; Targeted drug delivery; Nanomedicine; Chemotherapy; Pharmacokinetics; Cancer therapy

I. INTRODUCTION

Breast cancer remains one of the most prevalent malignancies and a leading cause of cancer-related mortality among women worldwide. Despite significant advances in early diagnosis and therapeutic strategies, the effective management of breast cancer continues to be challenged by tumor heterogeneity, drug resistance, and treatment-associated toxicity [1]. Conventional chemotherapy, which relies on systemic administration of cytotoxic agents, often lacks tumor selectivity, resulting in damage to healthy tissues and severe adverse effects such as cardiotoxicity, myelosuppression, and neurotoxicity. These limitations frequently necessitate dose reduction or treatment discontinuation, thereby compromising therapeutic efficacy and patient quality of life [2].

The complexity of breast cancer biology further complicates treatment outcomes. Distinct molecular subtypes including hormone receptor–positive, HER2-positive, and triple-negative breast cancer exhibit variable responses to standard chemotherapeutic regimens. Moreover, physiological barriers such as poor tumor penetration, rapid drug clearance, and multidrug resistance mechanisms significantly reduce the effective concentration of anticancer agents at the tumor site. These challenges underscore the urgent need for advanced drug delivery strategies capable of improving therapeutic precision while minimizing systemic toxicity [3].

Liposome-based drug delivery systems have emerged as a promising nanotechnological approach to overcome the shortcomings of conventional chemotherapy. Liposomes are spherical vesicles composed of phospholipid bilayers capable of encapsulating both hydrophilic and hydrophobic drugs. Their biocompatibility, biodegradability, and structural similarity to biological membranes make them attractive carriers for anticancer agents. Importantly, liposomes can alter the pharmacokinetic profile of encapsulated drugs, prolonging circulation time and enhancing tumor accumulation through the enhanced permeability and retention (EPR) effect [4].

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In addition to passive targeting, liposomal systems can be engineered for active targeting by surface modification with ligands such as antibodies, peptides, or small molecules that recognize tumor-specific receptors overexpressed in breast cancer cells. This targeted approach enhances cellular uptake and intracellular drug delivery, thereby improving therapeutic efficacy while reducing off-target effects. Several liposomal formulations, including liposomal doxorubicin, have already demonstrated clinical success, validating the translational potential of this delivery platform [5, 6].

Overall, liposome-based drug delivery systems represent a versatile and clinically relevant strategy for targeted breast cancer therapy. Their ability to improve drug solubility, stability, biodistribution, and tumor selectivity positions them as a cornerstone in the evolving landscape of precision oncology and nanomedicine-driven cancer treatment.

II. PATHOPHYSIOLOGY AND MOLECULAR TARGETS IN BREAST CANCER

Breast cancer is a heterogeneous disease characterized by complex molecular alterations, diverse cellular phenotypes, and variable clinical outcomes. This heterogeneity poses significant challenges for effective therapy, as tumor behavior and treatment response differ markedly among patients. Understanding the underlying pathophysiology and molecular targets is therefore essential for designing targeted drug delivery systems, such as liposome-based formulations, that can enhance therapeutic efficacy while minimizing systemic toxicity [7].

Breast cancer is broadly classified into distinct molecular subtypes based on hormone receptor status and gene expression profiles, including luminal A, luminal B, human epidermal growth factor receptor 2 (HER2)-positive, and triple-negative breast cancer (TNBC). Luminal subtypes express estrogen and/or progesterone receptors and generally respond well to endocrine therapies; however, resistance to hormonal treatment remains a major limitation. HER2-positive tumors are aggressive but can be targeted using HER2-directed therapies, although cardiotoxicity and acquired resistance are common concerns. TNBC lacks estrogen, progesterone, and HER2 receptors, making it particularly difficult to treat due to the absence of well-defined molecular targets and its high metastatic potential [8]. These subtype-specific challenges highlight the need for advanced drug delivery strategies capable of improving drug accumulation at tumor sites and enabling targeted therapeutic intervention.

The tumor microenvironment (TME) plays a critical role in breast cancer progression and therapeutic resistance. It comprises cancer cells, stromal cells, immune cells, abnormal vasculature, and extracellular matrix components, all of which influence tumor growth and drug response. The disorganized and leaky tumor vasculature contributes to heterogeneous drug distribution, while elevated interstitial fluid pressure and dense extracellular matrix hinder deep penetration of therapeutic agents. Additionally, hypoxia, acidic pH, and immune suppressive conditions within the TME further limit the effectiveness of conventional chemotherapy. Liposomal drug delivery systems can partially overcome these barriers by exploiting the enhanced permeability and retention (EPR) effect and by protecting encapsulated drugs from premature degradation, thereby improving tumor accumulation and retention [8].

Several molecular targets in breast cancer have been explored for liposomal targeting to enhance selectivity and therapeutic outcomes. Overexpressed receptors such as HER2, folate receptor, transferrin receptor, and epidermal growth factor receptor (EGFR) serve as attractive targets for ligand-functionalized liposomes. Additionally, cell surface markers associated with cancer stem cells and angiogenic factors, including vascular endothelial growth factor (VEGF), provide opportunities for targeted intervention. Liposomes can be engineered with antibodies, peptides, or small-molecule ligands to actively bind these targets, facilitating receptor-mediated endocytosis and intracellular drug delivery [9]. By integrating knowledge of breast cancer pathophysiology with targeted liposomal design, it is possible to develop more precise and effective therapeutic strategies tailored to specific tumor subtypes and microenvironmental conditions. Figure 1 shows breast cancer heterogeneity, tumor microenvironment barriers, and the advantages of targeted liposomal drug delivery over conventional chemotherapy

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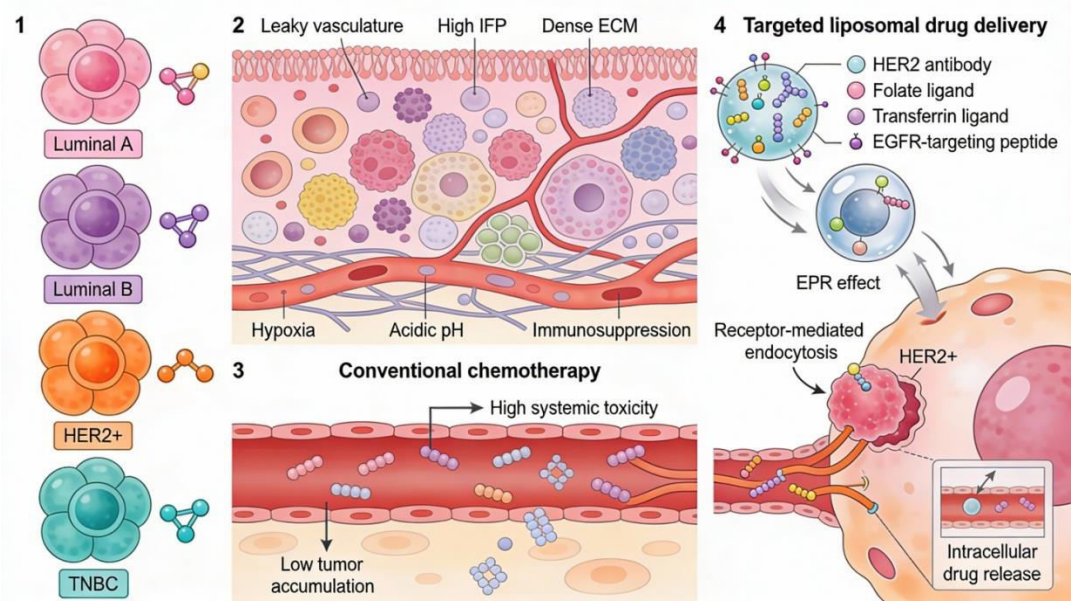

Figure 1: The figure illustrates breast cancer heterogeneity, tumor microenvironment barriers, and the advantages of targeted liposomal drug delivery over conventional chemotherapy. Panel 1 depicts major breast cancer subtypes. Panel 2 highlights tumor microenvironment challenges, including leaky vasculature, hypoxia, acidic pH, dense extracellular matrix, and immunosuppression. Panel 3 shows limitations of conventional chemotherapy, characterized by low tumor accumulation and high systemic toxicity. Panel 4 demonstrates ligand-targeted liposomes exploiting the EPR effect and receptor-mediated endocytosis for efficient intracellular drug delivery.

III. LIPOSOMES AS DRUG DELIVERY SYSTEMS

Liposomes are spherical vesicular drug delivery systems composed of one or more phospholipid bilayers surrounding an aqueous core, closely mimicking biological membranes (Figure 2). Structurally, they are primarily made of natural or synthetic phospholipids, such as phosphatidylcholine, often stabilized with cholesterol to enhance membrane rigidity and reduce permeability [10]. Based on size and lamellarity, liposomes are classified into small unilamellar vesicles (SUVs), large unilamellar vesicles (LUVs), and multilamellar vesicles (MLVs). Functionally, liposomes can also be categorized as conventional liposomes, long-circulating or PEGylated liposomes, ligand-targeted liposomes, and stimuli-responsive liposomes, each designed to improve drug stability, circulation time, or site-specific delivery in breast cancer therapy [10].

The physicochemical properties of liposomes play a crucial role in determining their therapeutic performance. Particle size influences biodistribution, tumor accumulation, and cellular uptake, with nanosized liposomes (typically 80–200 nm) favoring enhanced permeability and retention (EPR)-mediated tumor targeting. Surface charge affects circulation time and interaction with biological membranes; neutral or slightly negative liposomes generally exhibit prolonged systemic circulation, whereas positively charged liposomes enhance cellular uptake but may increase toxicity. Lipid composition, bilayer fluidity, encapsulation efficiency, and drug release kinetics further dictate stability, drug loading capacity, and controlled release behavior, ultimately impacting anticancer efficacy [11].

Liposomal drug delivery offers several advantages, including improved solubility of poorly water-soluble anticancer agents, protection of encapsulated drugs from premature degradation, reduced systemic toxicity, and enhanced tumor targeting (Table 1). Clinically approved liposomal formulations, such as liposomal doxorubicin, demonstrate improved safety profiles compared to free drugs. However, liposomal systems also face limitations, including formulation complexity, high production costs, limited drug loading for certain molecules, and potential immune recognition or accelerated blood clearance upon repeated administration. Despite these challenges, continued advances in liposome engineering are steadily enhancing their clinical potential in targeted breast cancer therapy [12].

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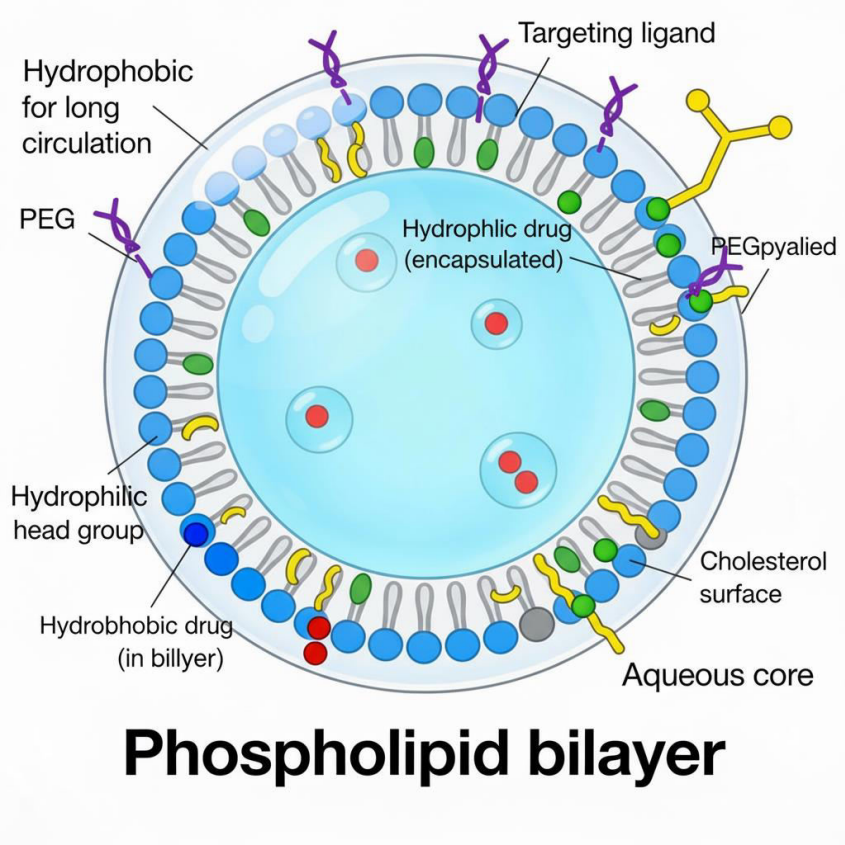

Figure 2: Structure of liposome

Table 1: Advantages and disadvantages of liposomes

Aspect	Advantages	Disadvantages
Biocompatibility and safety	Composed of phospholipids that are **biocompatible**, biodegradable, and generally non-immunogenic.	Risk of complement activation, hypersensitivity reactions, or RES uptake, especially with certain surface charges or compositions.
Drug loading versatility	Can encapsulate both hydrophilic drugs in the aqueous core and hydrophobic/lipophilic drugs in the bilayer.	Encapsulation efficiency can be low for some drugs, with possible drug leakage during storage or circulation.
Pharmacokinetics and targeting	Modify drug distribution, extend circulation time (especially PEGylated forms), and enable passive/active targeting to diseased tissue, improving therapeutic index.	Conventional (non-PEGylated) liposomes can be rapidly cleared by the reticuloendothelial system, limiting exposure at the target site.
Toxicity profile	Reduce systemic toxicity of many agents by shielding normal tissues (e.g., reduced cardiotoxicity with liposomal doxorubicin; reduced toxicity of amphotericin B and taxanes).	Excipient- or surface-related toxicities may occur; cationic formulations can induce cytotoxicity and inflammatory responses.
Stability of drug	Protect encapsulated drugs from enzymatic and chemical degradation, improving stability and sometimes shelf life.	Liposomes themselves may be physically and chemically unstable (aggregation, fusion, phospholipid oxidation and hydrolysis), complicating storage.
Release characteristics	Allow controlled or sustained release by tailoring lipid composition, size, and surface modifications.	Achieving reproducible, predictable release profiles is challenging and may vary with manufacturing and physiological conditions.

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IV. TARGETING STRATEGIES FOR BREAST CANCER THERAPY

Targeted drug delivery is a key advantage of liposome-based systems in breast cancer treatment, as it enhances therapeutic efficacy while minimizing systemic toxicity. Liposomal targeting strategies are broadly classified into passive targeting, active targeting, and stimuli-responsive or multifunctional approaches.

4.1 Passive Targeting via the Enhanced Permeability and Retention (EPR) Effect

Passive targeting exploits the unique pathophysiological characteristics of solid tumors, particularly the enhanced permeability and retention (EPR) effect. Breast tumors possess leaky vasculature with fenestrations ranging from 100 to 800 nm and impaired lymphatic drainage, allowing nanosized liposomes to preferentially accumulate within the tumor interstitium. Long-circulating or "stealth" liposomes, typically surface-modified with polyethylene glycol (PEG), evade rapid clearance by the reticuloendothelial system and achieve prolonged systemic circulation, thereby enhancing tumor accumulation. Several clinically approved liposomal formulations, such as liposomal doxorubicin, rely predominantly on passive targeting through the EPR effect. However, the heterogeneity of tumor vasculature and variability in EPR efficiency among patients can limit the consistency of therapeutic outcomes [13].

4.2 Active Targeting Using Ligands

Active targeting aims to further improve tumor selectivity by functionalizing the liposomal surface with ligands that specifically bind to receptors overexpressed on breast cancer cells. Common targeting ligands include monoclonal antibodies (e.g., anti-HER2), peptides, folic acid, and aptamers. These ligands facilitate receptor-mediated endocytosis, leading to enhanced cellular uptake and intracellular drug delivery. For instance, HER2-targeted immunoliposomes have demonstrated improved cytotoxicity in HER2-positive breast cancer models, while folate-conjugated liposomes exploit the overexpression of folate receptors in certain breast cancer subtypes. Aptamer-based targeting offers additional advantages, including high specificity, low immunogenicity, and ease of synthesis. Active targeting strategies can overcome some limitations of passive targeting; however, challenges such as ligand density optimization, stability, and large-scale manufacturing remain [9, 14].

4.3 Stimuli-Responsive and Multifunctional Liposomes

Stimuli-responsive liposomes are designed to release their payload in response to specific internal or external triggers, such as pH, temperature, enzymes, redox conditions, ultrasound, or magnetic fields. In breast cancer, pH-sensitive liposomes can exploit the acidic tumor microenvironment or endosomal compartments to trigger drug release. Thermosensitive liposomes, combined with localized hyperthermia, enable spatially controlled drug delivery. Multifunctional liposomes integrate targeting ligands, imaging agents, and stimuli-responsive elements into a single platform, enabling theranostic applications. These advanced systems hold significant promise for precision breast cancer therapy, although their clinical translation requires further optimization and regulatory validation [15, 16].

V. THERAPEUTIC APPLICATIONS OF LIPOSOMAL FORMULATIONS IN BREAST CANCER

Liposomal drug delivery systems have emerged as a transformative approach in breast cancer therapy by enhancing drug solubility, improving pharmacokinetics, enabling tumor targeting, and reducing systemic toxicity. By encapsulating diverse therapeutic agents, liposomes offer versatile platforms for chemotherapy, combination therapy, and nucleic acid delivery, addressing key limitations of conventional treatments.

5.1 Liposomal Chemotherapeutic Agents

Liposomal encapsulation of chemotherapeutic drugs is one of the most clinically advanced applications in breast cancer treatment. Anthracyclines such as doxorubicin have been extensively formulated into liposomes to mitigate dose-limiting toxicities, particularly cardiotoxicity. Pegylated liposomal doxorubicin (PLD) exemplifies this strategy, offering prolonged circulation time, enhanced tumor accumulation via the enhanced permeability and retention (EPR) effect, and reduced exposure to healthy tissues. Clinical studies have demonstrated that PLD maintains comparable antitumor efficacy to free doxorubicin while significantly lowering adverse effects [17].

Similarly, liposomal formulations of paclitaxel and docetaxel have been developed to overcome poor aqueous solubility and hypersensitivity reactions associated with conventional solvent-based formulations. Liposomal paclitaxel exhibits improved tolerability, enhanced tumor uptake, and sustained drug release, contributing to better therapeutic outcomes. Other chemotherapeutic agents, including cisplatin, mitoxantrone, and vincristine, have also been successfully

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incorporated into liposomes, showing enhanced efficacy and reduced toxicity profiles in preclinical and clinical evaluations. Collectively, liposomal chemotherapeutic agents represent a clinically validated strategy for improving the therapeutic index of anticancer drugs in breast cancer management [18].

5.2 Co-Delivery Systems and Combination Therapies

Breast cancer is a heterogeneous disease often requiring combination therapies to overcome drug resistance and achieve synergistic anticancer effects. Liposomes provide an ideal platform for the co-delivery of multiple therapeutic agents with distinct physicochemical properties, enabling controlled and synchronized drug release at the tumor site. Co-encapsulation of chemotherapeutic drugs, such as doxorubicin and paclitaxel, within a single liposomal carrier has demonstrated enhanced antitumor efficacy compared to monotherapy by targeting multiple signaling pathways simultaneously [19].

Beyond dual chemotherapy, liposomal systems have been designed to co-deliver chemotherapeutic agents with molecular inhibitors, immunomodulators, or natural bioactives. For instance, liposomes co-loaded with doxorubicin and curcumin or resveratrol have shown the ability to sensitize tumor cells, reduce multidrug resistance, and modulate the tumor microenvironment. Additionally, combination strategies integrating chemotherapy with photothermal or photodynamic agents in multifunctional liposomes have enabled synergistic tumor ablation upon external stimulation [20].

Targeted co-delivery systems further enhance therapeutic precision. Surface-functionalized liposomes bearing ligands such as antibodies (e.g., anti-HER2), peptides, or folate have been employed to selectively deliver combination therapies to breast cancer cells overexpressing specific receptors. These approaches not only improve anticancer efficacy but also minimize off-target toxicity, making liposomal co-delivery systems a promising avenue for personalized breast cancer therapy [6].

5.3 Liposomes for Gene and siRNA Delivery

Gene therapy and RNA interference-based strategies hold immense potential for treating breast cancer by modulating oncogenes, tumor suppressor genes, and drug resistance pathways. However, the clinical translation of nucleic acid therapeutics is hindered by poor stability, rapid degradation, and inefficient cellular uptake. Liposomes have emerged as effective non-viral vectors for delivering genes, plasmid DNA, and small interfering RNA (siRNA) to breast cancer cells [21].

Cationic and ionizable liposomes are particularly effective for complexing negatively charged nucleic acids, protecting them from enzymatic degradation, and facilitating cellular internalization via endocytosis. Liposomal siRNA formulations targeting oncogenes such as HER2, BCL-2, and VEGF have demonstrated significant gene silencing, reduced tumor growth, and enhanced chemosensitivity in breast cancer models. Furthermore, liposomes have been used to co-deliver siRNA with chemotherapeutic drugs, enabling simultaneous gene silencing and cytotoxic effects to overcome multidrug resistance [22].

Advancements in stimuli-responsive and targeted liposomal gene delivery systems have further improved therapeutic outcomes. pH-sensitive, redox-responsive, and ligand-targeted liposomes enable site-specific release of nucleic acids within tumor cells, enhancing transfection efficiency while minimizing systemic toxicity. Overall, liposome-mediated gene and siRNA delivery represents a promising strategy for precision medicine in breast cancer, with ongoing research focused on improving safety, efficiency, and clinical translation [23].

VI. IN VIVO PERFORMANCE AND PHARMACOKINETICS

6.1 Biodistribution and Tumor Accumulation

The in vivo behavior of liposome-based drug delivery systems plays a crucial role in determining their therapeutic success in breast cancer treatment. Following systemic administration, liposomes exhibit altered biodistribution profiles compared to free drugs, largely due to their nanoscale size and surface characteristics. Long-circulating or PEGylated liposomes are designed to evade rapid clearance by the mononuclear phagocyte system, thereby prolonging blood circulation time. This extended circulation enhances passive tumor targeting through the enhanced permeability and retention (EPR) effect, allowing preferential accumulation of liposomes within tumor tissues characterized by leaky vasculature and impaired lymphatic drainage [24].

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In addition to passive targeting, actively targeted liposomes functionalized with ligands such as antibodies, peptides, folate, or aptamers further improve tumor localization by selectively binding to overexpressed receptors on breast cancer cells, including HER2, EGFR, and folate receptors. In vivo imaging and pharmacokinetic studies have consistently demonstrated higher tumor-to-normal tissue ratios for targeted liposomal formulations compared to non-targeted counterparts. Moreover, optimized lipid composition and surface charge contribute to enhanced stability and controlled drug release, minimizing premature drug leakage during systemic circulation [25].

6.2 Improved Efficacy and Reduced Systemic Toxicity

Enhanced tumor accumulation of liposomal formulations directly translates into improved therapeutic efficacy and a favorable safety profile. By delivering higher drug concentrations to tumor sites, liposomes increase antitumor activity while limiting exposure to healthy tissues. Numerous preclinical studies in breast cancer models have reported superior tumor growth inhibition and prolonged survival with liposomal chemotherapeutics compared to free drugs [26].

A major advantage of liposomal drug delivery is the significant reduction in systemic toxicity. Encapsulation of cytotoxic agents within liposomes lowers peak plasma concentrations and reduces off-target drug distribution, thereby minimizing adverse effects such as cardiotoxicity, myelosuppression, and gastrointestinal toxicity. Clinically approved liposomal formulations, such as liposomal doxorubicin, exemplify this benefit by demonstrating comparable or enhanced efficacy with markedly reduced cardiotoxicity. Overall, improved pharmacokinetics, selective tumor targeting, and controlled drug release collectively make liposome-based systems a promising strategy for achieving effective and safer breast cancer therapy [27].

VII. CLINICAL PROGRESS AND APPROVED LIPOSOMAL FORMULATIONS

Liposome-based drug delivery systems have made significant progress in the clinical management of breast cancer by improving therapeutic efficacy while minimizing systemic toxicity. The most prominent clinically approved liposomal formulation is pegylated liposomal doxorubicin (PLD), marketed as Doxil®/Caelyx®. PLD demonstrates prolonged circulation time, enhanced tumor accumulation via the enhanced permeability and retention (EPR) effect, and reduced cardiotoxicity compared with conventional doxorubicin. It is widely used for metastatic and recurrent breast cancer, particularly in patients with prior anthracycline exposure.

Another clinically relevant formulation is non-pegylated liposomal doxorubicin (Myocet®), which shows reduced cardiotoxicity while maintaining antitumor efficacy. Myocet® has been approved in combination with cyclophosphamide for first-line treatment of metastatic breast cancer in several regions. Liposomal formulations of paclitaxel, docetaxel, and vinorelbine are also under advanced clinical evaluation, aiming to overcome solubility issues and reduce hypersensitivity reactions associated with conventional formulations [28].

Recent clinical trials have focused on actively targeted liposomes, functionalized with ligands such as HER2 antibodies, folate, transferrin, and peptides to enhance selective uptake by breast cancer cells. Stimuli-responsive liposomes, including pH-sensitive and thermosensitive systems, are being investigated to achieve controlled drug release within the tumor microenvironment. Additionally, liposomal co-delivery platforms combining chemotherapeutic agents with siRNA or immunomodulators are emerging as promising strategies to address drug resistance and tumor heterogeneity [29].

Overall, clinical evidence supports the safety and efficacy of liposomal formulations in breast cancer therapy, with several products already approved and numerous candidates progressing through clinical trials. Continued advancements in targeting strategies, formulation optimization, and personalized medicine approaches are expected to further expand the clinical impact of liposome-based therapies in breast cancer management [30].

VIII. CHALLENGES, LIMITATIONS, AND FUTURE PERSPECTIVES

Despite significant advances, the clinical translation of liposome-based drug delivery systems for breast cancer remains challenging. Major limitations include formulation instability, batch-to-batch variability, limited drug loading for certain agents, and premature drug leakage during circulation. Biological barriers such as heterogeneous tumor vasculature, variable enhanced permeability and retention (EPR) effects, and rapid clearance by the mononuclear phagocyte system further restrict consistent tumor accumulation. Additionally, large-scale manufacturing under Good

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Manufacturing Practice (GMP) conditions, long-term storage stability, and high production costs pose regulatory and commercial challenges.

From a translational standpoint, discrepancies between preclinical models and clinical outcomes often limit predictive efficacy. Immunogenic reactions, complement activation, and patient-to-patient variability also complicate therapeutic performance. Regulatory approval pathways for complex, multifunctional liposomal systems remain demanding due to the need for comprehensive safety and quality assessments.

Future perspectives focus on the development of next-generation liposomes incorporating active targeting ligands, stimuli-responsive release mechanisms, and multifunctional designs capable of co-delivering drugs and genetic materials. Advances in personalized medicine, supported by molecular profiling of breast cancer subtypes, may enable patient-specific liposomal therapies with improved efficacy and reduced toxicity. Integration of artificial intelligence, quality-by-design approaches, and scalable manufacturing technologies is expected to further accelerate clinical translation and broaden the therapeutic impact of liposomal nanomedicine in breast cancer treatment.

IX. CONCLUSIONS

Liposome-based drug delivery systems have emerged as a transformative strategy for the targeted treatment of breast cancer, addressing many of the limitations associated with conventional chemotherapy. By encapsulating anticancer agents within biocompatible phospholipid vesicles, liposomes improve drug solubility, enhance pharmacokinetic profiles, prolong systemic circulation, and promote preferential tumor accumulation through both passive and active targeting mechanisms. These advantages translate into improved therapeutic efficacy and a significant reduction in systemic toxicity, as evidenced by clinically approved formulations such as pegylated and non-pegylated liposomal doxorubicin.

The versatility of liposomal platforms allows for the delivery of a wide range of therapeutic payloads, including chemotherapeutic agents, combination drug regimens, and nucleic acid–based therapies. Advances in ligand-mediated targeting, stimuli-responsive release systems, and multifunctional liposomes have further expanded their potential to overcome tumor heterogeneity, multidrug resistance, and biological barriers within the tumor microenvironment. Importantly, ongoing clinical trials continue to validate the safety and efficacy of these systems, reinforcing their translational relevance. Despite notable progress, challenges related to manufacturing scalability, regulatory complexity, immunogenicity, and interpatient variability remain barriers to widespread clinical adoption. Addressing these issues through improved formulation design, standardized characterization protocols, and quality-by-design approaches will be critical for future success. Overall, continued innovation in liposomal nanotechnology, coupled with advances in personalized medicine and molecular profiling, positions liposome-based drug delivery systems as a cornerstone of next-generation, precision-oriented breast cancer therapy.

Conflict of interest: No conflict of interest

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