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Review Article

Role of Microencapsulation in Cancer Therapy: Current Advances and Therapeutic Applications

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Abstract

Cancer remains one of the leading causes of morbidity and mortality worldwide and continues to pose a major challenge to healthcare systems despite substantial progress in diagnosis and treatment strategies. Conventional cancer therapies, particularly chemotherapy, often suffer from several limitations including poor drug selectivity, systemic toxicity, multidrug resistance, rapid drug degradation, and undesirable adverse effects on healthy tissues. These challenges significantly reduce therapeutic effectiveness and negatively affect patient quality of life. In recent years, microencapsulation technology has emerged as a promising pharmaceutical approach for improving the delivery and therapeutic performance of anticancer agents. Microencapsulation involves the incorporation of active therapeutic substances within protective polymeric or lipid-based matrices to achieve controlled, sustained, and targeted drug release.The application of microencapsulation in cancer therapy has demonstrated considerable advantages, including enhanced drug stability, improved bioavailability, reduced systemic toxicity, prolonged circulation time, and site-specific drug targeting. Various microencapsulation techniques such as spray drying, solvent evaporation, ionic gelation, coacervation, fluidized bed coating, and microfluidic encapsulation have been extensively explored for anticancer drug delivery. Moreover, advanced microencapsulation systems using biodegradable polymers have shown significant potential for improving therapeutic outcomes and reducing adverse drug reactions.Several anticancer agents including doxorubicin, paclitaxel, cisplatin, tamoxifen, and natural bioactive compounds have been successfully incorporated into microencapsulation systems for enhanced efficacy and tumor targeting. Although promising progress has been achieved, challenges associated with large-scale manufacturing, reproducibility, formulation stability, and regulatory approval continue to affect clinical translation. This review highlights the role of microencapsulation in cancer therapy, recent technological advancements, pharmaceutical applications, therapeutic benefits, and future perspectives for improving cancer treatment outcomes.

Keywords: Microencapsulation, Cancer Therapy, Controlled Drug Delivery, Anticancer Drugs, Targeted Drug Delivery.

1. Introduction

Cancer is a complex and multifactorial disease characterized by uncontrolled cellular proliferation, abnormal cell growth, invasion of surrounding tissues, and metastatic spread to distant organs. It remains one of the most serious global public health concerns, accounting for millions of deaths annually and creating substantial socioeconomic burden worldwide. Different forms of cancer including breast cancer, lung cancer, colorectal cancer, prostate cancer, leukemia, liver cancer, and cervical cancer continue to increase in prevalence because of aging populations, environmental exposure, unhealthy lifestyles, genetic predisposition, and delayed diagnosis. Despite considerable advancements in medical science, cancer treatment remains challenging due to disease heterogeneity, tumor resistance, recurrence, and treatment-associated toxicity [1].

Conventional therapeutic approaches used in cancer management primarily include surgery, radiotherapy, chemotherapy, immunotherapy, hormone therapy, and targeted biological treatments. Among these, chemotherapy remains one of the most widely employed strategies because of its ability to destroy rapidly dividing cancer cells. However, traditional chemotherapeutic drugs frequently exhibit several disadvantages including poor specificity toward tumor tissues, rapid systemic distribution, low bioavailability, instability, short circulation time, and severe toxic effects on healthy organs [2]. Common adverse effects such as nausea, vomiting, immunosuppression, hair loss, organ toxicity, and multidrug resistance often compromise treatment effectiveness and reduce patient adherence.

The major challenge associated with conventional anticancer therapy is the inability to selectively deliver drugs to tumor tissues while minimizing toxicity to normal cells. Many anticancer agents possess poor aqueous solubility and are rapidly metabolized or degraded before reaching therapeutic concentrations at the target site. Furthermore, repeated administration of high drug doses may increase systemic toxicity and promote drug resistance, thereby reducing overall therapeutic success [3]. These limitations have encouraged pharmaceutical researchers to develop advanced drug delivery systems capable of improving therapeutic precision and enhancing treatment outcomes.

Microencapsulation has emerged as a highly promising pharmaceutical technology for overcoming several challenges associated with conventional cancer therapy. The technique involves surrounding active therapeutic molecules with polymeric coating materials to form microsized particles capable of protecting drugs from degradation while controlling release kinetics [4]. Through microencapsulation, anticancer drugs can be delivered in a sustained and targeted manner, thereby improving drug concentration at tumor sites while minimizing adverse effects on healthy tissues. Encapsulated drug systems may also improve stability, prolong circulation time, enhance bioavailability, and reduce dosing frequency.

Recent advances in pharmaceutical sciences have significantly expanded the role of microencapsulation in cancer treatment. Various advanced encapsulation techniques including ionic gelation, spray drying, electrospraying, fluidized bed coating, coacervation, and microfluidic technologies have shown promising outcomes in improving the efficacy of anticancer drugs [5]. Additionally, the incorporation of biodegradable polymers such as poly(lactic-co-glycolic acid) (PLGA), chitosan, alginate, gelatin, and polycaprolactone has further enhanced controlled release and targeted delivery potential. Considering these developments, microencapsulation is increasingly recognized as a valuable approach for modern cancer therapeutics and personalized medicine.

Therefore, this review aims to discuss the role of microencapsulation in cancer therapy, highlighting its pharmaceutical importance, encapsulation techniques, therapeutic advantages, recent advancements, anticancer applications, and future prospects for improving cancer treatment outcomes.

2. Overview of Cancer and Challenges in Conventional Chemotherapy

Cancer develops as a result of genetic mutations and abnormal cellular signaling pathways that disrupt normal cell growth and division. Under normal physiological conditions, cell proliferation and apoptosis remain tightly regulated to maintain tissue homeostasis. However, mutations affecting oncogenes, tumor suppressor genes, and DNA repair mechanisms can lead to uncontrolled proliferation, resulting in tumor formation. Malignant tumors possess the ability to invade surrounding tissues and metastasize to distant organs through blood circulation and lymphatic systems, making treatment considerably more difficult [6]. Depending on tissue origin and pathological characteristics, cancer may be classified into carcinoma, sarcoma, leukemia, lymphoma, and melanoma, each requiring different therapeutic strategies.

Among the available treatment modalities, chemotherapy remains one of the most frequently utilized approaches because of its broad-spectrum anticancer activity and ability to destroy rapidly proliferating cells. Chemotherapeutic agents such as doxorubicin, cisplatin, paclitaxel, methotrexate,

tamoxifen, and cyclophosphamide have demonstrated significant clinical benefits in reducing tumor burden and prolonging patient survival [7]. However, conventional chemotherapy is often associated with several limitations that considerably reduce therapeutic effectiveness and compromise patient safety.

One of the major drawbacks of conventional chemotherapy is poor selectivity toward cancer cells. Most anticancer drugs circulate systemically and affect both malignant and healthy rapidly dividing cells, including those present in bone marrow, hair follicles, gastrointestinal tissues, and reproductive organs [8]. This non-specific distribution frequently leads to severe adverse effects such as nausea, vomiting, anemia, immunosuppression, alopecia, fatigue, mucositis, nephrotoxicity, hepatotoxicity, and cardiotoxicity. Such toxic manifestations often necessitate dose reduction or discontinuation of therapy, thereby affecting treatment outcomes.

Drug resistance represents another important challenge in conventional cancer therapy. Tumor cells may develop resistance through multiple mechanisms including drug efflux transporters, altered cellular metabolism, reduced intracellular drug accumulation, DNA repair enhancement, and mutation of therapeutic targets [9]. Multidrug resistance significantly reduces the effectiveness of chemotherapy and contributes to cancer recurrence and poor prognosis. Furthermore, repeated exposure to high-dose chemotherapeutic agents may aggravate toxicity and accelerate resistance development.

Poor aqueous solubility and limited bioavailability of many anticancer agents further complicate treatment. Drugs such as paclitaxel and curcumin often exhibit poor dissolution characteristics, restricting their absorption and therapeutic concentration at tumor sites [10]. Additionally, rapid systemic clearance and short plasma half-life reduce drug retention in the body, necessitating frequent administration and increasing patient burden. Premature degradation of drugs before reaching target tissues also limits treatment success and may contribute to suboptimal therapeutic outcomes. Another major concern in cancer therapy involves the inability to maintain sustained therapeutic drug concentrations at tumor sites. Conventional formulations often release drugs rapidly, leading to fluctuations in plasma drug levels and inadequate therapeutic exposure [11]. Such irregular drug distribution may reduce anticancer efficacy and simultaneously increase systemic toxicity. Therefore, maintaining controlled and prolonged drug release has become a major objective in pharmaceutical oncology research.

Because of these limitations, modern pharmaceutical research increasingly focuses on developing advanced drug delivery systems capable of improving drug targeting, reducing toxicity, enhancing bioavailability, and prolonging therapeutic action. Microencapsulation technology has gained substantial importance in this context because of its potential to protect therapeutic agents, regulate release kinetics, and improve selective delivery toward tumor tissues [12]. Encapsulation-based systems can minimize systemic exposure while increasing drug accumulation at the target site, thereby significantly improving therapeutic effectiveness and reducing adverse reactions.

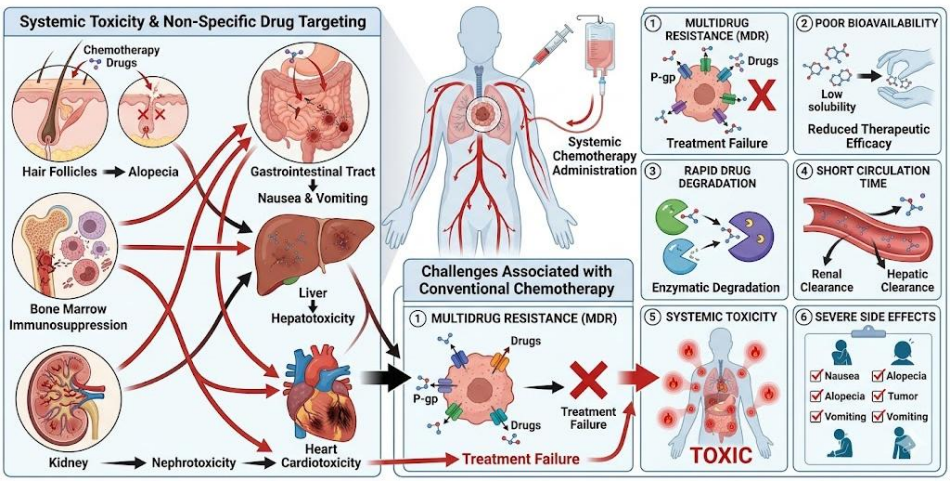

Fig 1: Major Challenges of Conventional Chemotherapy in Cancer

3. Fundamentals of Microencapsulation in Cancer Therapy

Microencapsulation is an advanced pharmaceutical formulation strategy in which active therapeutic substances are enclosed within protective coating materials to form microsized delivery systems capable of modifying drug release and improving therapeutic performance. In cancer therapy, microencapsulation plays an important role in enhancing the efficacy of anticancer agents while minimizing their undesirable

toxic effects. The encapsulation process involves incorporation of drugs into biodegradable polymeric matrices or membrane-based systems that protect therapeutic compounds from degradation and facilitate sustained or targeted release [13]. These systems generally range from one to several hundred micrometers in size and may exist as microcapsules or microspheres depending on their structural organization.

The principle of microencapsulation in cancer therapy is primarily based on controlled and site-specific drug delivery. Encapsulated drug systems are designed to release therapeutic agents gradually over a prolonged period, thereby maintaining consistent plasma drug concentrations and reducing frequent dosing requirements [14]. Unlike conventional chemotherapy, where drugs distribute non-selectively throughout the body, microencapsulation allows preferential localization of anticancer agents at tumor sites, reducing damage to healthy tissues. Controlled release characteristics significantly improve treatment effectiveness by maintaining optimal drug concentrations within the tumor microenvironment.

Microencapsulation offers several therapeutic advantages in oncology. One of the most important benefits is protection of anticancer drugs from premature degradation caused by enzymatic activity, pH variations, oxidation, and physiological instability [15]. Several anticancer compounds exhibit poor chemical stability and may lose therapeutic activity before reaching target tissues. Encapsulation within protective polymeric matrices helps preserve drug integrity and improves shelf-life as well as in vivo performance.

Improvement in bioavailability represents another important advantage of microencapsulation systems. Many anticancer drugs demonstrate poor aqueous solubility and limited absorption, thereby restricting therapeutic efficacy. Encapsulation improves dissolution behavior and facilitates better drug absorption, leading to increased therapeutic concentration at target tissues [16]. Furthermore, encapsulated formulations may prolong circulation time in blood, allowing greater accumulation of therapeutic agents within tumor tissues through passive and active targeting mechanisms.

Reduction of systemic toxicity is a major reason for the increasing use of microencapsulation in cancer therapy. Conventional chemotherapeutic drugs frequently affect rapidly dividing healthy cells and cause severe adverse effects. Encapsulation reduces direct exposure of healthy tissues to toxic drugs by controlling release behavior and restricting drug accumulation mainly to diseased regions [17]. Consequently, patient tolerance, treatment adherence, and overall therapeutic outcomes may improve significantly.

Various natural and synthetic polymers are utilized for microencapsulation in cancer treatment. Natural polymers such as chitosan, alginate, gelatin, dextran, and albumin are preferred because of their biodegradability and biocompatibility [18]. Synthetic polymers including poly(lactic-co-glycolic acid) (PLGA), polycaprolactone (PCL), polyethylene glycol, and Eudragit are extensively used due to their controlled degradation properties and sustained drug release capabilities. Selection of suitable polymer depends on drug characteristics, route of administration, desired release profile, and therapeutic requirements.

The growing importance of microencapsulation in oncology has significantly transformed modern pharmaceutical research. Continuous advancements in polymer engineering, particle design, and encapsulation technologies have improved precision drug delivery and enabled the development of innovative anticancer formulations with enhanced therapeutic performance [19]. Consequently, microencapsulation is increasingly recognized as a promising strategy for overcoming limitations associated with traditional chemotherapy and improving patient outcomes in cancer management.

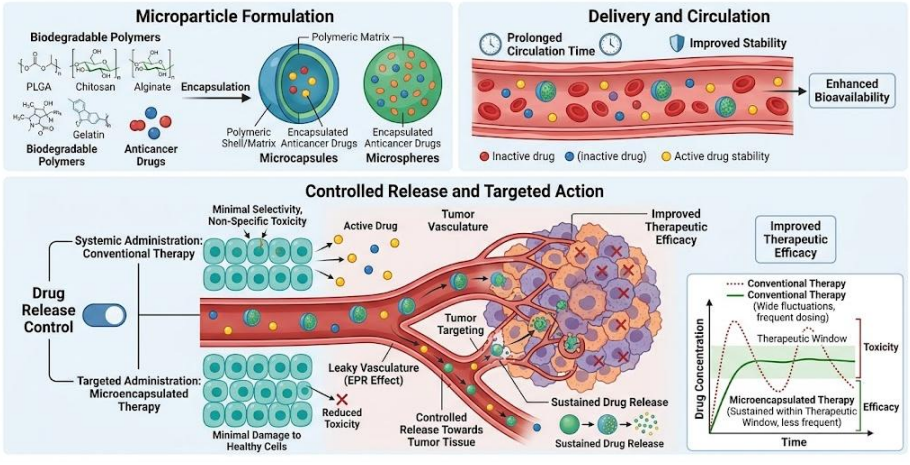

Fig 2: Fundamental of Microencapsulation for Targeted Cancer Therapy

4. Microencapsulation Methods Used in Cancer Drug Delivery

The effectiveness of microencapsulation in cancer therapy largely depends on the encapsulation technique employed during formulation development. Different microencapsulation methods have been explored for improving the stability, targeting ability, and controlled release behavior of anticancer drugs. Selection of an appropriate method depends on several factors including drug solubility, polymer compatibility, desired release kinetics, encapsulation efficiency, particle size, and route of administration. Over the years, both conventional and advanced microencapsulation techniques have gained considerable attention for delivering anticancer agents with improved therapeutic outcomes.

Spray drying is one of the most commonly used pharmaceutical microencapsulation techniques for cancer drug delivery because of its simplicity, rapid processing, and industrial scalability. The method involves atomization of a drug–polymer solution into a heated chamber where solvent evaporation results in formation of dry microparticles [20]. Spray drying has been widely investigated for encapsulating anticancer drugs such as paclitaxel, doxorubicin, and curcumin to improve stability and sustained release behavior. The technique allows production of particles with relatively uniform morphology and suitable drug loading efficiency. However, thermal degradation of heat-sensitive compounds may sometimes limit its application.

Solvent evaporation is another extensively used method in cancer drug delivery systems. In this approach, anticancer drugs and polymers are dissolved in volatile organic solvents and emulsified into aqueous media to form microparticles. Gradual evaporation of solvent results in polymer precipitation and encapsulation of therapeutic agents [21]. Biodegradable polymers such as poly(lactic-co-glycolic acid) (PLGA) and polycaprolactone are commonly utilized for preparing sustained-release anticancer formulations using this method. Solvent evaporation has shown promising results for prolonged release of chemotherapeutic drugs and reduction of systemic toxicity.

Ionic gelation has emerged as an important microencapsulation technique for cancer therapy due to its mild preparation conditions and excellent biocompatibility. The process relies on ionic interactions between oppositely charged polymers to form hydrogel-like particles capable of entrapping anticancer agents [22]. Natural polymers such as sodium alginate and chitosan are commonly used because of their biodegradability and minimal toxicity. Ionic gelation is particularly useful for encapsulating sensitive bioactive compounds and natural anticancer agents that may degrade under harsh processing conditions.

Coacervation or phase separation remains another useful encapsulation method for cancer drug delivery. This technique involves separation of polymer-rich phases that surround drug particles and form protective coatings [23]. Coacervation provides relatively high encapsulation efficiency and controlled release characteristics, making it suitable for delivering poorly soluble anticancer compounds. The method has also shown potential in protecting unstable therapeutic agents from environmental degradation and improving formulation stability.Fluidized bed coating technology has gained industrial importance for preparing sustained-release cancer formulations. In this method, particles are suspended in an upward stream of air while polymer coatings are sprayed continuously to form encapsulated systems [24]. The technique provides uniform coating thickness and improved reproducibility, which are essential for achieving predictable release behavior. Fluidized bed coating is commonly applied for modifying drug release profiles and improving oral delivery of anticancer agents.

Electrospraying technology has emerged as a promising modern encapsulation method because of its ability to generate highly uniform micro- and nanosized particles. Electrical forces are used to produce charged droplets that solidify into encapsulated particles with narrow size distribution [25]. This method offers improved encapsulation efficiency, enhanced control over particle morphology, and reduced solvent requirements. Electrosprayed systems have shown encouraging outcomes for pulmonary cancer therapy and targeted delivery applications.

Microfluidic encapsulation represents one of the newest approaches in cancer drug delivery and has attracted substantial research interest. This technology utilizes microscale channels to control droplet formation with high precision, resulting in highly uniform particles and reproducible release characteristics [26]. Microfluidic systems provide excellent control over particle engineering and are increasingly investigated for personalized medicine and tumor-targeted therapies.

Because cancer therapy requires highly selective and controlled delivery systems, modern pharmaceutical research increasingly emphasizes advanced encapsulation methods capable of reducing systemic toxicity while improving therapeutic precision. Consequently, continuous innovations in microencapsulation technologies are expected to further strengthen the role of encapsulated drug delivery systems in oncology.

5. Role of Microencapsulation in Cancer Therapy

Microencapsulation has transformed cancer treatment by offering a pharmaceutical platform capable of improving the therapeutic performance of anticancer drugs while minimizing treatment-associated complications. One of the major advantages of microencapsulation is its ability to achieve targeted drug delivery. Conventional chemotherapy distributes drugs non-selectively throughout the body, affecting healthy tissues alongside cancer cells and resulting in severe adverse effects. Encapsulated drug systems improve localization of therapeutic agents within tumor tissues, thereby reducing systemic toxicity and increasing treatment precision [27]. Improved targeting also allows lower therapeutic doses, minimizing patient discomfort and treatment-related complications.

Controlled and sustained drug release represents another important role of microencapsulation in cancer therapy. Many conventional chemotherapeutic agents exhibit rapid elimination and short biological half-life, making repeated administration necessary. Frequent dosing may increase toxicity and negatively affect patient adherence [28]. Encapsulation enables gradual release of drugs over extended durations, maintaining stable therapeutic concentrations and improving anticancer efficacy. Sustained-release systems may also reduce fluctuations in plasma drug levels and prevent sudden toxic peaks.

Microencapsulation significantly contributes to reduction of systemic toxicity associated with chemotherapy. Many anticancer agents damage rapidly dividing healthy cells, leading to adverse effects including hair loss, gastrointestinal toxicity, bone marrow suppression, and organ damage [29]. Encapsulation protects healthy tissues by restricting uncontrolled drug release and promoting selective accumulation near tumor tissues. Consequently, patients may experience improved tolerability and better quality of life during treatment. Improvement of drug stability and bioavailability also represents a major contribution of microencapsulation in oncology. Several anticancer agents demonstrate poor aqueous solubility, instability, and susceptibility to premature degradation within physiological environments [30]. Encapsulation within polymeric carriers protects these therapeutic agents and improves dissolution characteristics, enabling greater absorption and prolonged systemic circulation. Such improvements contribute to increased therapeutic concentration at tumor sites and enhanced treatment effectiveness.

Another significant role of microencapsulation involves overcoming multidrug resistance in cancer therapy. Tumor cells frequently develop resistance mechanisms that reduce intracellular drug concentration and limit therapeutic effectiveness [31]. Controlled release systems may improve sustained intracellular exposure of therapeutic agents, thereby increasing the likelihood of successful tumor destruction. Moreover, combination therapy involving multiple encapsulated agents has shown potential for reducing resistance and improving treatment outcomes. Microencapsulation has also gained importance in the delivery of natural bioactive compounds with anticancer potential. Therapeutic molecules such as curcumin, resveratrol, quercetin, and epigallocatechin gallate frequently exhibit poor stability and limited bioavailability [32]. Encapsulation improves their stability and enables more effective delivery, thereby increasing therapeutic usefulness in cancer management.

The integration of biodegradable polymers and advanced engineering technologies has further expanded the role of microencapsulation in personalized cancer treatment. Modern systems now enable controlled targeting, improved precision, and reduced adverse effects, making encapsulated drug delivery increasingly valuable in contemporary oncology research [33].

6. Microencapsulated Anticancer Drugs

The successful application of microencapsulation technology in cancer therapy has enabled improved delivery of several anticancer agents that otherwise suffer from poor stability, limited bioavailability, rapid degradation, and severe systemic toxicity. Encapsulation of anticancer drugs within polymeric carriers has significantly enhanced therapeutic effectiveness by improving controlled release behavior and reducing adverse effects. Various conventional chemotherapeutic agents and natural bioactive compounds have been successfully incorporated into microencapsulation systems for better therapeutic performance. Doxorubicin is one of the most widely used chemotherapeutic drugs for treating breast cancer, leukemia, lymphoma, and several solid tumors. Despite its effectiveness, the drug is associated with serious cardiotoxicity and systemic adverse effects when administered conventionally [34]. Microencapsulation of doxorubicin using biodegradable polymers such as poly(lactic-co-glycolic acid) (PLGA), chitosan, and alginate has demonstrated improved tumor targeting and sustained release behavior. Encapsulated doxorubicin systems reduce exposure to healthy tissues while maintaining effective drug concentration at tumor sites, thereby improving safety and therapeutic outcomes.

Paclitaxel is another important anticancer agent commonly used in the treatment of breast, ovarian, and lung cancers. The drug possesses poor aqueous solubility and exhibits formulation-related

limitations that affect clinical effectiveness [35]. Microencapsulation techniques have been widely investigated to improve paclitaxel solubility, controlled release, and stability. Polymeric microspheres containing paclitaxel have shown prolonged drug retention and enhanced antitumor activity while reducing toxic side effects associated with conventional administration.

Cisplatin remains a highly effective chemotherapeutic agent for treating various malignancies including lung, ovarian, bladder, and testicular cancers. However, nephrotoxicity, neurotoxicity, and rapid systemic elimination significantly limit its therapeutic utility [36]. Encapsulation of cisplatin into biodegradable microspheres has demonstrated improved drug localization, reduced toxicity, and prolonged therapeutic action. Controlled release formulations of cisplatin have also shown potential for minimizing organ damage while improving anticancer efficiency.

Tamoxifen, a selective estrogen receptor modulator commonly used in hormone-responsive breast cancer, has also benefited from microencapsulation approaches. Sustained-release encapsulated formulations of tamoxifen improve therapeutic consistency and reduce fluctuations in plasma drug concentration [37]. Such systems may also reduce dosing frequency and improve patient compliance during long-term cancer treatment.

Methotrexate, an important anticancer and immunosuppressive agent, is frequently associated with severe toxicity and poor selectivity. Encapsulation techniques have been explored to improve methotrexate delivery through sustained release and improved tumor localization [38]. Polymeric microspheres have shown encouraging results in reducing systemic toxicity while maintaining therapeutic effectiveness.

Natural bioactive compounds with anticancer properties have increasingly gained research interest due to their favorable safety profile and therapeutic potential. Curcumin, a polyphenolic compound derived from turmeric, demonstrates strong antioxidant, anti-inflammatory, and anticancer properties. However, poor water solubility and rapid metabolism considerably limit its clinical effectiveness [39]. Microencapsulation improves curcumin stability, absorption, and tumor targeting, making it more suitable for cancer therapy. Similarly, resveratrol and quercetin have demonstrated enhanced therapeutic performance following encapsulation due to improved bioavailability and sustained release behavior [40].

The incorporation of anticancer agents into microencapsulation systems has significantly improved treatment efficiency while minimizing adverse effects commonly associated with conventional chemotherapy. As pharmaceutical technologies continue to evolve, advanced encapsulation systems are expected to further improve precision drug delivery and personalized cancer therapeutics.

7. Recent Advances and Industrial Applications

Recent technological advancements have significantly improved the pharmaceutical applications of microencapsulation in cancer therapy. Modern encapsulation systems increasingly utilize biodegradable polymers, smart materials, and targeted drug delivery mechanisms to improve treatment precision and reduce systemic toxicity. These advancements have enabled greater control over drug release kinetics, improved particle uniformity, and enhanced encapsulation efficiency, making microencapsulation an important strategy in pharmaceutical oncology [41].

One of the major developments in recent years is the emergence of stimuli-responsive or smart microencapsulation systems. These systems are capable of releasing anticancer agents in response to specific physiological conditions such as pH variation, enzymatic activity, temperature, or oxidative stress present within tumor microenvironments [42]. Because tumor tissues often exhibit acidic conditions compared with healthy tissues, pH-responsive microcapsules can selectively release therapeutic agents at the tumor site while minimizing exposure to normal organs. Such approaches considerably improve treatment selectivity and reduce systemic adverse effects.

Targeted delivery systems represent another important advancement in cancer microencapsulation research. Surface modification of microcapsules with ligands, antibodies, peptides, and receptor-specific molecules improves recognition and accumulation of therapeutic agents within cancer tissues [43]. This targeted approach reduces drug wastage and improves therapeutic concentration at disease sites, enhancing overall treatment effectiveness.

Industrial pharmaceutical sectors increasingly utilize microencapsulation for developing modified-release formulations and improving the commercial performance of anticancer drugs. Microencapsulation technologies are now widely employed to improve stability of heat-sensitive compounds, enhance shelf-life, and facilitate controlled release dosage forms [44]. Pharmaceutical industries also adopt encapsulation techniques for taste masking, moisture protection, and improving compatibility of combination formulations.

Biodegradable polymers including poly(lactic-co-glycolic acid) (PLGA), chitosan, alginate, gelatin, and polycaprolactone continue to play major roles in industrial encapsulation systems because of their favorable biocompatibility, biodegradability, and controlled release properties [45]. Continuous improvements in polymer engineering have enabled more efficient drug loading and predictable release profiles suitable for cancer therapeutics.

The integration of nanotechnology with microencapsulation has further expanded industrial applications in oncology. Nano–micro hybrid systems offer improved penetration, prolonged circulation time, and enhanced tumor targeting capabilities [46]. These systems are increasingly explored for personalized medicine, combination therapy, and advanced targeted delivery applications.

Although considerable progress has been achieved, challenges related to manufacturing cost, scale-up difficulties, reproducibility, regulatory approval, and formulation complexity continue to limit broader industrial implementation. Nevertheless, continued research and technological innovation are expected to accelerate commercialization and improve clinical applications of microencapsulation-based cancer therapy [47].

8. Challenges and Future Perspectives

Despite remarkable progress in the application of microencapsulation for cancer therapy, several scientific, technological, and regulatory challenges continue to limit widespread clinical implementation. One of the major concerns involves achieving consistent reproducibility during large-scale manufacturing. Variations in particle size, drug loading efficiency, encapsulation stability, and release characteristics may significantly influence therapeutic outcomes and product quality [48]. Ensuring manufacturing precision therefore remains an important requirement for industrial acceptance.

High production costs associated with advanced encapsulation technologies also represent an important limitation. Techniques such as microfluidic encapsulation, electrospraying, and smart polymer engineering require sophisticated instruments and specialized expertise, increasing overall formulation expenses [49]. Such economic challenges may restrict accessibility and delay commercialization, particularly in developing healthcare systems.

Another major challenge relates to regulatory approval and quality control. Encapsulation systems intended for clinical use must undergo extensive safety evaluation, toxicity assessment, stability studies, and therapeutic validation before receiving regulatory acceptance [50]. Long-term toxicity associated with polymer degradation products and excipient interactions must also be carefully investigated to ensure patient safety.

Future research in cancer microencapsulation is expected to focus on development of personalized medicine approaches capable of delivering patient-specific therapies with improved precision. Stimuli-responsive systems, smart polymers, artificial intelligence-assisted formulation design, and hybrid nano–micro delivery platforms are likely to become increasingly important in next-generation oncology treatment [51]. Furthermore, integration of targeted molecular therapy with encapsulation systems may significantly improve therapeutic success and reduce recurrence.

As pharmaceutical sciences continue to evolve, microencapsulation technology is expected to play an increasingly important role in improving cancer treatment outcomes through safer, more efficient, and more selective drug delivery systems [52].

9. Conclusion

Microencapsulation has emerged as a highly promising pharmaceutical strategy for improving the therapeutic effectiveness of cancer treatment. Conventional chemotherapy often suffers from poor selectivity, rapid degradation, low bioavailability, severe systemic toxicity, and multidrug resistance, which considerably reduce treatment success. Microencapsulation effectively addresses many of these limitations by providing controlled, sustained, and targeted delivery of anticancer agents. Various encapsulation techniques including spray drying, solvent evaporation, ionic gelation, coacervation, fluidized bed coating, electrospraying, and microfluidic systems have demonstrated considerable potential for improving cancer drug delivery. Encapsulation of drugs such as doxorubicin, paclitaxel, cisplatin, methotrexate, tamoxifen, and natural bioactive compounds has shown improved therapeutic efficacy, enhanced stability, prolonged circulation time, and reduced adverse effects. Furthermore, recent advances involving smart stimuli-responsive carriers and targeted delivery systems have substantially expanded the pharmaceutical importance of microencapsulation in oncology.

Although challenges related to scale-up, regulatory approval, formulation complexity, and manufacturing cost remain important concerns, ongoing research continues to improve industrial feasibility

and clinical translation. Future developments in personalized medicine, smart polymers, and hybrid nano–micro technologies are expected to further enhance cancer treatment precision and patient outcomes. Therefore, microencapsulation represents an important and evolving approach in modern pharmaceutical cancer therapy with strong potential to improve both therapeutic efficiency and patient quality of life.

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