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Advanced nano-drug delivery systems utilizing natural product-based innovations

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***Abstract*---**Background: Natural products have historically played a crucial role in human health, spanning from early uses to modern medicine. Despite their extensive pharmacological potential, clinical applications are often limited by issues such as poor solubility and rapid metabolism. Aim: To explore the use of advanced nano-drug delivery systems to enhance the efficacy of natural products by overcoming their limitations and improving therapeutic outcomes. Methods: This review examines various nano-drug delivery systems that integrate natural products. It discusses advancements in nano-carriers, including liposomes, micelles, and self-assembled structures, focusing on their ability to improve drug solubility, stability, and targeted delivery. Results: Significant progress has been made in developing nano-carriers for natural products, including terpenoids, flavonoids, polyphenols, and alkaloids. Innovations such as targeting warheads and self-assembled systems have shown improved drug delivery and therapeutic efficacy in preclinical studies. Conclusion: Nano-drug delivery systems utilizing natural products offer promising solutions to overcome traditional limitations, enhancing drug bioavailability and targeted delivery. This advancement holds potential for revolutionizing the treatment of complex diseases and improving clinical outcomes.

***Keywords*---**Nano-drug delivery, natural products, targeting warheads, self-assembly, drug solubility, therapeutic efficacy.

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Introduction

Throughout human history, natural products have been fundamental for sustaining life. They have been utilized in various applications, from early practices like paper-making to contemporary uses in fragrance and spice production, and more recently, in disease prevention and treatment (1, 2). With ongoing progress in separation technologies and pharmacological evaluation methods, an increasing array of bioactive compounds from natural sources has been discovered. The extensive structural diversity of these compounds, coupled with their diverse biological activities on various tissues and molecular targets, renders them invaluable in clinical settings, particularly for treating complex conditions such as cancer and cardiovascular diseases (3, 4).

Despite their potential, the clinical efficacy of natural products has often been underwhelming, leading many pharmaceutical companies to hesitate in their development (5–7). Challenges such as poor solubility, limited biological distribution, and rapid metabolic clearance frequently result in suboptimal plasma concentrations of these compounds. Additionally, drugs with high molecular weight and low lipophilicity struggle with permeability and absorption across biological membranes, resulting in inefficient drug transport and short half-lives. Addressing these issues through novel drug delivery methods remains a critical area of research (8, 9). Efforts to enhance the efficacy of natural products are essential for the development of innovative drugs with fewer side effects (10).

Nanotechnology has emerged as a pivotal tool in bridging biological and physical sciences. Nano-drug delivery systems, in particular, have attracted significant interest from the pharmaceutical industry (7, 11, 12). Nano-carriers facilitate drug delivery by encapsulating or attaching therapeutic agents and targeting specific tissues or organs through controlled release (9, 13). Unlike larger materials, nano-sized drugs can move more freely within the human body, enhancing their therapeutic potential (14–19). Despite the broad promise of nanotechnology, the application of nanoparticle-based delivery systems still faces limitations. These systems not only improve the residence time of drugs in the body but also offer advantages such as rapid extravasation and reduced macrophage phagocytosis. Nanostructures can also effectively co-load both hydrophilic and hydrophobic substances. Approved first-generation nano-drug delivery systems, including liposomes and micelles with inorganic nanoparticles (e.g., gold nanoparticles), highlight the advancements in drug delivery, imaging, and therapeutic functions (20, 21). Methods like thin film hydration, high-pressure homogenization, nanoprecipitation, and self-assembly allow for the incorporation of natural products into nano-carriers, representing significant strides in optimizing treatment outcomes through controlled drug release, enhanced solubility, improved targeting, and increased stability (22). Overall, nanotechnology offers substantial support for advancing natural products and modernizing their application.

Nano-Drug Delivery Systems and Natural Products

The integration of nanotechnology with natural products represents a rapidly evolving field with considerable potential. Utilizing nanocarriers for drug delivery

has emerged as a promising method to efficiently transport therapeutic agents to targeted locations within organs, tissues, or cells (6). The synergy between natural products and nanotechnology is particularly advantageous, as nanotechnology enables the encapsulation or attachment of one or more natural products within nano-drug delivery systems. These systems can significantly enhance the bioavailability, targeting precision, and controlled release characteristics of natural products. This advancement addresses many limitations associated with the clinical application of natural products, thereby amplifying their pharmacological benefits and contributing substantially to clinical practice.

Natural Product-Based Nano-Drug Delivery Systems with Targeting Warheads Mechanisms and Advantages

We are witnessing a new era in personalized healthcare where drugs are tailored to individual patient needs and delivered specifically to diseased cells. This area of research is gaining considerable attention (23). Nano-drug delivery systems, developed through advanced nanotechnology, have garnered significant interest for their ability to improve the bioavailability of insoluble drugs. Researchers often enhance these systems by incorporating targeting warheads, which facilitate selective delivery of therapeutic agents to pathological cells via receptor-mediated endocytosis (24, 25). Various reaction mechanisms, such as nucleophilic addition, nucleophilic substitution, and addition-elimination, are employed to attach these warheads, with nucleophilic addition and addition-elimination being the most commonly used (26). These mechanisms enable selective drug delivery, exemplified by aromatic electrophilic substitution targeting specific amino acids like tyrosine and tryptophan (26).

Targeted drug delivery systems offer several advantages over non-targeted ones. They provide the ability to deliver therapeutic drugs specifically to desired organs or tissues, minimizing non-specific uptake and toxicity to healthy cells (27). Furthermore, drugs that exhibit limited efficacy when administered in non-targeted forms at the maximum tolerated dose (MTD) can achieve improved outcomes when coupled with effective targeting warheads (27). For instance, nano-conjugates of polyethylene glycol or methoxy polyethylene glycol, modified with the targeting peptide T7 and linked to podophyllotoxin (PPT) (Pep-SS-NPs), demonstrate a significant increase in MTD (5.3 times) compared to free PPT (28). Additionally, targeting warheads can be linked to diagnostic agents, such as imaging agents, to detect overexpression of target receptors in pathological cells (29). Successful developments include folate-linked radiopharmaceutical imaging agents like 99mTc and 68Ga, which are used to identify tumors with high folate receptor expression necessary for effective drug delivery (30–33). Currently, extensive research is focused on synthesizing and studying warheads that specifically bind to receptors in both in vitro and in vivo settings. Integrins (α2β3, αvβ3, and α5β1) and aminopeptidase N (CD13) are common targets in tumor neovascular systems, recognized by cyclic RGD peptide and linear NGR peptide derivatives, respectively (34). Another prevalent example involves targeting the folate receptor on breast cancer cells, where folate-drug conjugates are synthesized and grafted onto nano-carriers to enhance internalization by cancer cells (35). This section provides a comprehensive overview of advancements in nano-drug delivery systems with targeting warheads.

Natural Products Delivered by Nano-Drug Delivery Systems with Targeting Warheads

Terpenoids

Terpenoids are extensively utilized across various industries, including medicine and food, and are composed of multiple C5H8 units (36). During the late 1990s, substantial research focused on the separation, purification, and structural analysis of terpenoids, leading to a deeper understanding of their medicinal potential. Terpenoids exhibit a range of pharmacological activities, such as anti-tumor, anti-inflammatory, antimicrobial, and antiviral effects, as well as applications in treating cardiovascular diseases (37–41). This section reviews the development of nano-drug delivery systems for notable terpenoid products, specifically triptolide and ginsenoside, to establish a foundation for further research.

Triptolide (TP), predominantly derived from *Tripterygium wilfordii* Hook.f., is a promising candidate for the next generation of anticancer drugs. It is a highly oxidized diterpenoid trioxide with analgesic, anti-inflammatory, and immunomodulatory properties. Several derivatives of triptolide are currently under clinical investigation (22, 42, 43). Advances in drug delivery technologies have been employed to address the clinical challenges associated with TP. For instance, one study (44) developed galactosylated chitosan-triptolide nanoparticles (GC-TP-NPs) to enhance targeted delivery to hepatocellular carcinoma. These nanoparticles demonstrated sustained release and were internalized by cells via the asialoglycoprotein receptor (ASGPR). In vivo studies showed significant accumulation of GC-TP-NPs in liver tumors, reduced systemic toxicity, and minimized male reproductive toxicity compared to free drug administration. The specific attachment of the galactose moiety to liver cancer cell receptors facilitated targeted drug delivery, highlighting the advantages of nano-drug delivery systems with targeting warheads. Another study by Huang et al. (45) developed Pluronic F127/P123 nanoparticles (TP-FPNPs) with folate as a targeting agent and incorporated TP. The TP-FPNPs demonstrated enhanced kidney targeting, prolonged in vivo residence, and improved cellular uptake, offering significantly better therapeutic effects for renal ischemia/reperfusion injury (IRI) compared to TP alone. The folate moiety facilitated cellular uptake via folate receptors on renal tubular cells, leading to controlled drug release and effective treatment of renal IRI, illustrating the potential of folate-functionalized drug-loaded nanoparticles for hydrophobic drug delivery in renal diseases.

Ginsenosides, also referred to as triterpenoid saponins, are primarily found in the dried root of ginseng and possess chemical and biological properties akin to glucocorticoids, indicating substantial therapeutic potential. However, their clinical application is hindered by poor solubility and bioavailability (46, 47). To overcome these limitations, various nano-drug delivery systems have been developed to enhance the pharmacological efficacy of ginsenosides (48). For example, Zhang et al. (49) utilized the A54 peptide to construct micelles loaded with ginsenoside compound K (CK) for liver targeting. The micelles were based on deoxycholic acid-O-carboxymethyl chitosan. Compared to CK alone, the polymer micelles significantly improved the anti-proliferative effect against liver cancer cell lines, demonstrating superior anti-cancer properties. The A54 peptide, specific to

liver cancer cells, enabled the micellar system to target and bind to liver cancer cell receptors, enhancing cellular uptake and extending CK's residence time in the bloodstream, thereby improving its bioavailability.

Flavonoids

Flavonoids possess a C15 backbone structure featuring two phenyl rings (C6-C3-C6). These compounds are recognized for their extensive therapeutic applications, including the ability to mitigate aging processes in various life systems and organs. They are also known for their preventive effects against cardiovascular diseases, Alzheimer's disease, and breast cancer (50–52). Given their therapeutic potential, substantial efforts have been made to enhance their solubility, improve gastrointestinal absorption, and reduce metabolic clearance. Moreover, flavonoids can interact with other dietary components, potentially leading to complexation or precipitation, which can degrade the compounds through microbial action, thereby affecting their stability and bioavailability. To address these challenges, researchers have focused on developing nano-carrier systems to specifically target and deliver flavonoid compounds. This approach has significantly improved the pharmacokinetics and pharmacodynamics of these drugs by altering their free forms (53, 54). Haroon Khan et al. (55) extensively reviewed the enhanced bioavailability and safety implications of flavonoid nano-drugs, while Paola Aiello and colleagues (56) evaluated in vivo studies of dietary flavonoid nanoparticles with anticancer properties. This section highlights recent advancements in nano-drug delivery systems for flavonoid compounds, focusing on gambogic acid and baicalin.

Gambogic Acid (GA) is an emerging flavonoid-based anticancer agent known for its potent tumor activity against various cancers, including colon, pancreatic, and breast cancers (57–60). However, its clinical application is constrained by limited solubility, short action duration, dose-dependent toxicity, and injection site discomfort (61, 62). To enhance bioavailability and clinical efficacy, numerous GA nano-formulations have been developed. One study (63) involved the modification of redox-sensitive chitosan nanoparticles (NPs) with hyaluronic acid (HA) to create HA-coated redox-sensitive chitosan NPs (HA(HECS-ss-OA)/GA) for targeted intracellular delivery of GA. These nanoparticles demonstrated excellent drug loading and, through in vivo and in vitro studies, showed superior anti-tumor efficacy compared to non-sensitive controls and HA-uncoated counterparts. The hyaluronic acid modification facilitated targeted delivery by binding to CD44 receptors on cancer cells, significantly improving drug safety and highlighting the potential of nano-drug delivery systems utilizing natural products as targeting agents.

Baicalin (BAI), extracted from the roots and stems of *Scutellaria baicalensis*, exhibits significant anticancer activity, particularly against breast and ovarian cancer cells (64–66). Researchers (67) developed folate-conjugated bovine serum albumin nanoparticles (FA-BSANPs/BAI) to enhance the delivery and tumor-targeting of BAI using the desolvation-crosslinking method. This folate-modified albumin system prolonged BAI's in vivo residence time and improved its tumor-targeting capability. By leveraging the elevated levels of folate receptors on breast cancer cells, this approach facilitated targeted drug delivery and significantly

enhanced therapeutic efficacy. Additionally, a research team (68) optimized a nano-carrier for neuroprotective agents using RVG29 peptide-modified polyethylene glycol-polylactic acid-co-glycolic acid nanoparticles. This carrier improved drug stability and continuous release, enhancing the effectiveness of neuroprotective agents delivered from the nasal route to the brain. The RVG29 peptide, derived from rabies virus glycoprotein, enabled brain-targeted drug delivery via receptor-mediated endocytosis, thereby enhancing BAI delivery to the brain and improving treatment outcomes for ischemic brain injury.

Polyphenols

Polyphenols are recognized for their potent antioxidant and anti-inflammatory properties, making them valuable for the clinical management of chronic diseases (69). These compounds, found in various vascular plants, are characterized by numerous hydroxyl groups on their aromatic rings (70). Despite their considerable therapeutic potential, polyphenols often suffer from structural instability when exposed to alkaline conditions, light, and heat, primarily due to their multiple hydroxyl groups. Additionally, their low solubility limits gastrointestinal absorption and bioavailability, thereby constraining their pharmaceutical and functional food applications (76). To address these challenges, nano-drug delivery systems have been developed to mitigate issues such as precipitation, rapid degradation, and elimination of polyphenolic compounds. Recent advancements in nano-carrier systems have successfully enhanced the stability and bioavailability of polyphenols (77, 78). This section reviews recent progress in nano-drug delivery systems for two polyphenolic compounds, resveratrol and curcumin, providing a theoretical foundation for future research in this area.

Resveratrol (RES), a natural polyphenol antioxidant with a trans-3,4',5-trihydroxystilbene structure, is found in plants like grapes, mulberries, peanuts, and rhubarb roots. RES is crucial for protecting blood vessels and DNA from oxidative damage, making it important for preventing and treating chronic inflammatory diseases. However, its limited physicochemical properties restrict its application as a standalone medication (79). Strategies such as encapsulation and controlled release using various carriers have emerged to improve RES's bioavailability (80). Jhaveri et al. (81) utilized transferrin-modified polyethylene glycol liposomes (Tf-RES-L) for RES delivery. These functionalized liposomes significantly increased glioblastoma multiforme cell apoptosis by activating the caspase 3/7 pathway, leveraging transferrin receptors upregulated in GBMs for targeted delivery. The functionalized liposomes exhibited uniform size distribution, increased stability, and enhanced cancer cell specificity, demonstrating the efficacy of nano-drug delivery systems with targeting warheads.

Curcumin (Cur), derived from the rhizome of *Curcuma longa*, is known for its antioxidant, wound-healing, and anticancer properties (82, 83). However, its application is limited by low bioavailability, high hydrophobicity, and light-induced degradation. One approach to overcome these issues involves encapsulating curcumin within biodegradable and biocompatible nanoparticles. Feng et al. (84) developed a CD44-targeted drug delivery system by conjugating

hyaluronic acid to propylene glycol-based ethosomes (HA-ES). The HA gel network on the surface of HA-ES reduced curcumin leakage and release, enhancing targeted delivery to inflamed psoriatic skin with high CD44 expression. This localized drug delivery system ensures drug stability and safety in non-target tissues, offering potential for enhanced drug accumulation in inflamed skin areas and other applications.

Alkaloids

Alkaloids are small nitrogenous organic compounds derived from amino acids and isolated from plants. They are categorized into various groups based on their chemical core structures, such as isoquinoline, quinoline, indole, and pyridine alkaloids (85). Numerous studies, both in vivo and clinical, have demonstrated the diverse pharmacological properties of alkaloids, including anticancer, antiviral, and anti-inflammatory effects (86–88). Despite their significant therapeutic potential, alkaloids often face challenges related to poor pharmacokinetics, incompatibility in biological media, and aggregation, which can hinder cellular uptake and limit clinical applications (89, 90). Contemporary research focuses on advancing nano-drug delivery systems with unique physical and chemical properties to protect encapsulated drugs from degradation, enhance permeability, and offer retention benefits (91, 92). This section highlights recent research on nano-drug delivery systems for alkaloids, using paclitaxel as a representative example.

Paclitaxel (PTX), a natural compound extracted from the bark of *Taxus brevifolia*, is renowned for its potent anti-tumor effects, particularly in treating ovarian and uterine cancers (93, 94). However, its clinical use is impeded by poor solubility, instability, tendency to precipitate, and toxicity (95, 96). To address these limitations, researchers (97) developed Tn-Lipo-PTX, a PEGylated paclitaxel nano-liposome with ASGPR targeting capabilities for hepatocellular carcinoma treatment. The use of a configurationally defined N-acetylgalactosamine as a targeting warhead enhanced paclitaxel's cytotoxicity toward liver cancer cells. This study underscores the effectiveness of nano-carriers with warhead modifications for delivering lipophilic drugs. Additionally, human H-chain ferritin (HFtn) has been explored for drug delivery due to its solubility, biodegradability, and uniform size distribution (98–101). Ma et al. (102) demonstrated that functionalizing the N-terminus of HFtn with the C-terminal cyclic peptide tLyP-1 enabled targeted paclitaxel delivery, greatly improving its ability to inhibit cancer cells and highlighting the potential of protein-functionalized targeting peptides for delivering hydrophobic drugs to tumor tissues.

Self-Assembled Nano-Drug Delivery Systems

Self-Assembly Process

- Definition: Self-assembly involves spontaneous formation of stable structures from fundamental units like molecules or nano-materials, driven by non-covalent interactions (e.g., hydrogen bonding, van der Waals forces, π–π stacking, electrostatic interactions).
- Forms: Results in structures such as micelles, liposomes, or helical belts.

- History: Early work by Ghadiri (1993) and Zhang on peptide nanotubes and ionizable peptides [103].

Strategies for Self-Assembly

- Top-Down: Creating nanostructures from larger structures.
- Bottom-Up: Using basic components and molecular recognition to build nanostructures.

Drug Self-Delivery Systems (DSDS)

- Concept: DSDSs use self-assembled drugs as both carriers and medications, enhancing drug encapsulation, loading capacity, and minimizing degradation.
- Advantages: Improved biocompatibility, stability, and safety by avoiding additional nano-catalysts.

Examples of Natural Product-Based Self-Assembled Systems

1. **Ursolic Acid (UA)**
    - Properties: Pentacyclic triterpenoid with anticancer effects.
    - System: Self-assembled carrier-free nano-drug system that improves solubility and tumor targeting.
    - Mechanism: Self-assembly driven by hydrophobic interactions and hydrogen bonding.
2. **Rhein (Rhe)**
    - Properties: Anthraquinone with potential in medical imaging and neurodegenerative disease treatment.
    - System: Controlled-release hydrogel made through self-assembly using π–π stacking and hydrogen bonds.
    - Applications: Alleviates inflammation, wound healing, and improved pharmacological effectiveness.
3. **Paclitaxel (PTX) and Ursolic Acid (UA)**
    - System: Self-assembled into a double-layered vesicle structure with high drug loading capacity.
    - Outcome: Synergistic effect with significant tumor inhibition and excellent therapeutic activity.
4. **Berberine (Ber) and Rhein (Rhe)**
    - System: Self-assembled nano-carrier enhancing antibacterial activity.
    - Result: Increased inhibition of Staphylococcus aureus compared to free drugs.
5. **Tannic Acid and Berberine**
    - System: Supramolecular self-assembly with drug conjugate HA for targeted delivery.
    - Effects: Enhanced drug uptake and anti-inflammatory effects in acute colitis.

Summary

The development of self-assembled nano-drug delivery systems using natural products shows promise in improving drug solubility, targeting, and therapeutic efficacy while addressing issues of stability and bioavailability. These advancements offer potential solutions to clinical challenges and highlight the innovative approaches being explored in drug delivery systems [103].

Self-Assembled Nano-Drug Delivery Systems

Peptide-Based Systems

- Characteristics: Peptides are bioactive compounds with excellent biocompatibility, biodegradability, and chemical versatility. They self-assemble into nanostructures under specific conditions (e.g., pH, ionic strength, light).
- Advantages: Customizable molecular design, effective functional regulation, peptide-specific biomolecular recognition.
- **Applications:**
    - Curcumin Delivery: Amphiphilic peptide R7L10 forms complexes with plasmid DNA to enhance solubility and cellular uptake of curcumin in acute lung injury models.
    - Hydrogels: Peptide-based hydrogels encapsulate drugs and respond to physiological conditions. Examples include FER-8 for PTX delivery and RADA16-I/RVDV16-I hydrogels for emodin delivery, showing improved stability and efficacy [103].
- Studies: Wang et al. reviewed design methodologies for peptide nano-drug delivery systems; Sis and Webber discussed design basics; Hsieh and Liaw proposed size and length control for nanotubes.

Metal-Coordinated Polyphenols

- Concept: Natural polyphenols can coordinate with metals to form metal-polyphenol nanonetworks (MPNs). These structures can improve drug solubility and stability.
- Applications:
    - Shikonin Delivery: Fe(III)-shikonin MPNs (FSSNs) enhance solubility and reduce toxicity. They trigger tumor cell apoptosis and necroptosis.
    - Curcumin and ICG: Curcumin-based MPNs (ICG @Cur-Gd NPs) with Gd3+ improve therapeutic efficacy and reduce biotoxicity through laser treatment.
    - Flavonoids: Flavonoid-based films (e.g., Myricetin, Quercetin) formed by Fe(III) coordination exhibit free radical scavenging activity and reusable surface coatings.
- Studies: Feng et al. developed FSSNs for tumor therapy; Wen et al. created curcumin-based MPNs for enhanced therapeutic efficacy; Bertleff-Zieschang et al. assembled flavonoid films for antioxidant applications [103].

Conclusion

The advancement of nano-drug delivery systems leveraging natural products represents a significant leap in pharmaceutical innovation. This approach addresses critical limitations faced by traditional natural products, such as poor solubility, limited bioavailability, and rapid metabolic clearance. By employing nanotechnology, researchers have successfully enhanced the delivery, targeting, and efficacy of various therapeutic agents derived from natural sources. Key innovations include the use of nano-carriers for improved solubility and targeted delivery, incorporating targeting warheads to enhance specificity, and utilizing

self-assembled nano-systems for controlled release and stability. Notable examples include the development of triptolide and ginsenoside-loaded nanoparticles, flavonoid-based nano-formulations, and self-assembled systems for polyphenols and alkaloids. These advancements demonstrate the potential for natural products to be used more effectively in clinical settings, offering improved therapeutic outcomes and reduced side effects. Overall, the integration of natural products with nano-drug delivery systems promises to revolutionize treatment modalities, particularly for complex diseases such as cancer and cardiovascular conditions. The ongoing research and development in this field are likely to yield further improvements in drug efficacy and patient outcomes, reinforcing the value of combining natural compounds with cutting-edge nanotechnology.

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أنظمة توصيل الأدوية النانوية المتقدمة باستخدام ابتكارات قائمة على المنتجات الطبيعية

الملخص:
الخلفية: لعبت المنتجات الطبيعية تاريخيًا دورًا حاسمًا في صحة الإنسان، بدءًا من الاستخدامات المبكرة إلى الطب الحديث. على الرغم من إمكاناتها الدوائية الواسعة، غالبًا ما تكون التطبيقات السريرية محدودة بسبب مشكلات مثل ضعف الذوبان وسرعة الأيض.
الهدف: استكشاف استخدام أنظمة توصيل الأدوية النانوية المتقدمة لتعزيز فعالية المنتجات الطبيعية من خلال التغلب على محدودياتها وتحسين النتائج العلاجية.
الطرق: تستعرض هذه المراجعة الأنظمة المختلفة لتوصيل الأدوية النانوية التي تدمج المنتجات الطبيعية. وتناقش التقدمات في الناقلات النانوية، بما في ذلك الليبوسومات، والميكيلات، والهياكل ذات التجميع الذاتي، مع التركيز على قدرتها على تحسين ذوبان الأدوية واستقرارها وتوصيلها المستهدف.
النتائج: تم إحراز تقدم كبير في تطوير ناقلات نانوية للمنتجات الطبيعية، بما في ذلك التربينات، والفلافونويد، البوليفينولات، والقلويدات. وقد أظهرت الابتكارات مثل الرؤوس المستهدفة والأنظمة ذات التجميع الذاتي تحسينًا في توصيل الأدوية وفعاليتها العلاجية في الدراسات قبل السريرية.
الاستنتاج: تقدم أنظمة توصيل الأدوية النانوية التي تستخدم المنتجات الطبيعية حلولاً واعدة للتغلب على القيود التقليدية، مما يعزز توافر الأدوية الحيوي والتوصيل المستهدف. هذا التقدم يحمل إمكانات كبيرة في تحويل علاج الأمراض المعقدة وتحسين النتائج السريرية.
الكلمات الرئيسية: توصيل الأدوية النانوية، المنتجات الطبيعية، الرؤوس المستهدفة، التجميع الذاتي، ذوبان الأدوية، الفعالية العلاجية