Journal of Pharmaceutical Research and Integrated Medical Sciences (JPRIMS)
ISSN: 3049-1681 | Vol. 03, Issue-05, May-2026 | pp.-72-90

ORIGINALARTICLE https://aktpublication.com/index.php/jprims/index

Advances in Nano-Immunotherapy: Pharmaceutical Formulation Strategies for Enhanced Immune Targeting

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Abstract:

Nano-immunotherapy leverages advanced nanocarrier systems to overcome limitations of conventional immunotherapies, providing precise immune modulation through targeted delivery of antigens, immunomodulators, and genetic material. Lipid-based, polymeric, inorganic, and hybrid nanocarriers enable controlled release, enhanced bioavailability, and site-specific immune activation, optimizing therapeutic efficacy while minimizing systemic toxicity. Pharmaceutical formulation strategies, including particle engineering, surface functionalization, and payload optimization, are critical to enhancing immune targeting and pharmacokinetics. Clinically, nano-immunotherapeutics have demonstrated remarkable success in vaccines, cancer immunotherapy, and genetic disease treatment, exemplified by mRNA-LNP COVID-19 vaccines and liposomal chemotherapies. Despite challenges in manufacturing, stability, and regulatory approval, emerging trends such as AI-driven design, personalized formulations, and integration with gene-editing technologies forecast a future of precision nano-immunotherapy with broad clinical impact.

Keywords: Nano-immunotherapy, COVID-19, AI-driven design

Received: Feb. 17, 2026 **Revised: March 26, 2026** **Accepted: April. 28, 2026** **Published: May 04, 2026**

DOI: https://doi.org/10.64063/3049-1681.vol.3.issue5.5

https://aktpublication.com/index.php/jprims/issue/archive

1. Introduction

Immunotherapy has revolutionized the landscape of modern medicine, offering a powerful approach to combat cancer, infectious diseases, and autoimmune disorders by harnessing the body's own immune system. Unlike traditional chemotherapeutics that directly target diseased cells, immunotherapies work by reprogramming immune mechanisms to recognize and eliminate pathological cells [1-2]. Breakthroughs such as immune checkpoint inhibitors, CAR-T cell therapies, monoclonal antibodies, and cancer vaccines have dramatically improved patient survival and treatment outcomes in previously untreatable diseases. However, despite these achievements, conventional immunotherapies often suffer from significant drawbacks, including poor bioavailability, rapid systemic clearance, immune-related adverse effects, and the development of immune escape mechanisms by tumor or viral cells. These challenges limit therapeutic precision and reduce overall clinical efficacy [3-4].

To address these limitations, nanotechnology has emerged as a transformative tool in immunomodulation and targeted immune activation. Nanocarriers provide precise control over drug release, protect delicate biomolecules such as proteins or nucleic acids from enzymatic degradation, and enable site-specific delivery to immune cells or lymphoid tissues [5]. By modulating particle size, surface charge, and ligand functionalization, nanotechnology-based systems can direct immune responses toward desired pathways—either stimulating immunity for cancer and infection therapy or suppressing it in autoimmune and inflammatory diseases. Furthermore, nanoscale delivery platforms can co-encapsulate multiple agents, such as antigens, adjuvants, and cytokines, creating synergistic effects that amplify therapeutic potency.

Pharmaceutical formulation science plays a central role in the success of nano-immunotherapy by designing and optimizing nanocarriers that integrate immunological and pharmacological principles. Through rational formulation strategies, researchers can fine-tune pharmacokinetics, biodistribution, and immune cell uptake, leading to improved therapeutic efficacy and reduced systemic toxicity. Advances in lipid-based, polymeric, inorganic, and biomimetic nanocarriers have expanded the possibilities for precise immune modulation and durable immune memory generation [6-7].

The objective of this review is to explore the advances in nano-immunotherapy, focusing on pharmaceutical formulation strategies that enhance immune targeting, pharmacokinetic performance, and clinical translation. It discusses the underlying mechanisms of immune activation by nanocarriers, the impact of formulation design on therapeutic outcomes, and current clinical trends shaping the future of precision immunotherapy.

2. Fundamentals of Nano-Immunotherapy

Nano-immunotherapy represents a cutting-edge intersection of nanomedicine and immunology, designed to enhance or regulate immune responses through the strategic use of nanoscale drug

delivery systems. The central concept involves merging nanotechnology with immunomodulation, enabling precise manipulation of immune pathways for therapeutic benefit. Unlike conventional immunotherapies that rely solely on biological molecules such as antibodies or cytokines, nano-immunotherapy leverages the unique physicochemical and biological properties of nanoparticles to achieve controlled delivery, targeted immune activation, and improved pharmacokinetic performance. This integrated approach allows for more efficient antigen presentation, sustained immune stimulation, and reduced systemic toxicity, paving the way for personalized and precision immunotherapies [8-9].

Nanocarriers play a pivotal role in immune activation mechanisms, primarily through the enhancement of antigen presentation and cytokine release. When engineered to carry antigens or adjuvants, nanoparticles can efficiently deliver these payloads to antigen-presenting cells (APCs) such as dendritic cells and macrophages. Upon internalization, the nanoparticles promote antigen processing and presentation via major histocompatibility complex (MHC) pathways, leading to robust T-cell activation and proliferation. Additionally, certain nanocarriers stimulate the release of proinflammatory cytokines and chemokines, which recruit effector immune cells like cytotoxic T lymphocytes (CTLs) and natural killer (NK) cells to the site of infection or tumor tissue. This cascade of events amplifies immune surveillance and improves therapeutic efficacy against otherwise resistant disease targets [11-12].

In the context of immune targeting, two primary strategies are employed: passive and active targeting. Passive targeting exploits the natural biodistribution of nanoparticles and the enhanced permeability and retention (EPR) effect, which allows nanocarriers to accumulate preferentially in tumor or inflamed tissues due to leaky vasculature. While this approach is effective for certain cancer therapies, it often lacks precision in cell-specific immune modulation. Conversely, active targeting involves functionalizing nanoparticle surfaces with ligands—such as antibodies, peptides, aptamers, or carbohydrates—that specifically bind to receptors on immune cells or tumor-associated antigens. This targeted recognition enhances selective uptake by immune cells, promoting localized immune activation and minimizing off-target effects [13].

The physicochemical properties of nanoparticles—particularly their size, surface charge, and surface chemistry—play a critical role in determining the magnitude and nature of immune responses. Nanoparticles within the size range of 20–200 nm are typically optimal for lymphatic transport and efficient uptake by APCs. Surface charge influences cellular interactions; for instance, cationic particles tend to enhance membrane binding and endocytosis, whereas neutral or anionic particles exhibit prolonged circulation and reduced clearance [14-15]. Surface chemistry, including hydrophilicity, PEGylation, and functional group modification, further dictates biocompatibility, immune evasion, and receptor binding specificity. Fine-tuning these parameters allows for precise modulation of immune responses—either stimulating immunity for cancer and infectious disease therapy or inducing tolerance in autoimmune disorders.

3. Nanocarrier Platforms for Immunotherapy

The success of nano-immunotherapy largely depends on the selection and engineering of nanocarrier systems that can efficiently deliver immunomodulatory agents, antigens, or nucleic acids to the desired immune cells or tissues. Different classes of nanocarriers — lipid-based, polymeric, inorganic, and hybrid — have demonstrated unique advantages in tailoring immune responses, enhancing antigen presentation, and improving therapeutic outcomes [16].

3.1. Lipid-Based Nanocarriers

Lipid-based systems such as liposomes, solid lipid nanoparticles (SLNs), and lipid nanoparticles (LNPs) have emerged as versatile vehicles for immune modulation. Liposomes provide a biomimetic environment for encapsulating both hydrophilic and hydrophobic agents, making them suitable for co-delivering antigens and adjuvants. SLNs, on the other hand, offer enhanced physical stability and controlled release, while LNPs have revolutionized mRNA-based vaccines (e.g., COVID-19 vaccines by Pfizer-BioNTech and Moderna), establishing their clinical relevance in both infectious disease prevention and cancer immunotherapy [18]. Lipid nanocarriers can promote antigen uptake by dendritic cells, stimulate cytokine secretion, and enhance both humoral and cellular immune responses. Their biocompatibility and tunable surface modifications make them ideal for immune cell-specific targeting and reduced systemic toxicity.

3.2. Polymeric Nanoparticles

Polymeric nanoparticles provide structural integrity and controlled drug release profiles, crucial for sustained immune activation. Commonly used biodegradable polymers such as poly(lactic-co-glycolic acid) (PLGA), chitosan, and PEG-PLA are FDA-approved, making them attractive for translational applications [19]. Through surface modification with ligands or antibodies, these nanoparticles can target specific immune cell receptors such as CD11c or CD80/86 on dendritic cells. Moreover, the polymeric shell protects the encapsulated immunotherapeutic cargo from premature degradation, ensuring prolonged antigen presentation and enhanced immune memory formation.

3.3. Inorganic Nanoparticles

Gold, silica, and iron oxide nanoparticles have drawn attention for their multifunctional capabilities in immune modulation, imaging, and therapy. Gold nanoparticles can serve as carriers for antigens or immunostimulants and simultaneously facilitate photothermal therapy to induce tumor cell apoptosis and antigen release [21-22]. Silica nanoparticles, due to their porous nature, offer high loading efficiency for peptides and nucleic acids, while iron oxide nanoparticles are exploited for magnetic targeting and MRI-based immune tracking. These inorganic systems can act as immune adjuvants themselves, enhancing antigen-specific immune responses and promoting T-cell activation [23].

3.4. Biomimetic and Hybrid Nanocarriers

Next-generation nano-immunotherapeutic strategies focus on biomimicry and hybridization to achieve precise immune modulation. Cell membrane-coated nanoparticles—for example, red blood cell, macrophage, or cancer cell membranes—can cloak the nanocarriers, allowing them to evade immune clearance and deliver antigens or drugs directly to the target site. Lipid–polymer hybrid nanoparticles combine the biocompatibility of lipids with the mechanical stability of polymers, ensuring improved payload protection, sustained release, and efficient lymphatic trafficking. Such hybrid systems are being explored for cancer vaccines, autoimmune disorders, and infectious disease immunotherapies [24].

Table 1: Summary of Nanocarrier Systems Used in Immune-Targeted Drug Delivery

Nanocarrier Type	Composition	Advantages	Applications in Immunotherapy	Reference
Liposomes / SLNs / LNPs	Phospholipids, cholesterol, triglycerides	Biocompatible, high antigen encapsulation, clinical validation	mRNA vaccines, cancer immunotherapy	25
Polymeric NPs	PLGA, PEG-PLA, chitosan	Controlled release, surface modifiability, biodegradability	Cancer vaccines, antigen delivery, immune cell targeting	26
Inorganic NPs	Gold, silica, iron oxide	Multifunctional (imaging + therapy), immune activation	Photothermal therapy, vaccine adjuvants, immune tracking	27
Biomimetic / Hybrid NPs	Cell membranes, lipid-polymer hybrids	Immune evasion, dual functionality, stability	Personalized immunotherapy, autoimmune regulation	28

4. 4. Pharmaceutical Formulation Strategies for Enhanced Immune Targeting

The formulation design of nano-immunotherapeutics is pivotal in determining their biodistribution, immune activation potential, and overall therapeutic success. Pharmaceutical scientists employ a combination of particle engineering, surface modification, and cargo optimization techniques to precisely deliver immunomodulators to desired immune compartments such as lymph nodes, macrophages, or dendritic cells (DCs). These strategies aim to overcome traditional barriers like immune suppression, enzymatic degradation, and poor circulation stability while amplifying antigen-specific immune responses [29].

4.1. Particle Engineering for Site-Specific Immune Delivery

The physicochemical characteristics of nanoparticles — including size, shape, charge, and rigidity — dictate their interaction with immune cells and their trafficking routes within the

body. Nanoparticles in the 10–200 nm range efficiently drain into lymph nodes, where antigen-presenting cells (APCs) such as dendritic cells reside.Smaller particles (<100 nm) tend to favor lymphatic transport and antigen presentation, whereas larger particles are more readily taken up by macrophages in the spleen or liver. Engineering nanoparticle surfaces with hydrophilic coatings (e.g., PEGylation) enhances systemic circulation, while cationic modifications facilitate endosomal escape and cytosolic delivery of nucleic acids or proteins [30].

4.2. Surface Functionalization for Immune Cell Targeting

Surface modification plays a key role in guiding nanocarriers toward specific immune cell populations. Conjugation with antibodies, peptides, or carbohydrate ligands allows selective binding to immune receptors such as CD11c (dendritic cells), CD206 (macrophages), or DEC-205.

- Antibody-functionalized nanoparticles improve targeted antigen delivery and reduce systemic off-target effects.
- Peptide ligands (e.g., RGD, mannose) enhance receptor-mediated endocytosis, particularly by macrophages and dendritic cells.
- Glycan-decorated nanoparticles mimic pathogen-associated molecular patterns (PAMPs), triggering toll-like receptor (TLR) pathways for stronger immune activation.

These functionalized nanocarriers can be further tailored to display multivalent ligand architectures, maximizing cell-specific binding and internalization efficiency [31-32].

4.3. Encapsulation of Immune Modulators and Genetic Cargo

Nano-immunotherapeutic formulations can encapsulate a broad spectrum of immune-active agents — from small-molecule modulators and cytokines to complex biomacromolecules such as DNA, mRNA, and siRNA.

- Cytokine-loaded nanoparticles (e.g., IL-2, IFN-γ) promote T-cell proliferation and enhance cytotoxic immune responses.
- mRNA-loaded lipid nanoparticles (LNPs) have already shown immense success in vaccine technology by facilitating efficient cytoplasmic translation and antigen expression.
- siRNA or DNA nanocarriers are being developed to reprogram tumor-associated macrophages (TAMs) or silence immune checkpoint pathways, restoring effective anti-tumor immunity.Encapsulation protects these biomolecules from enzymatic degradation, improves bioavailability, and enables co-delivery of adjuvants or antigens for synergistic immune activation [33].

4.4. Optimization of Release Kinetics for Sustained Immune Activation

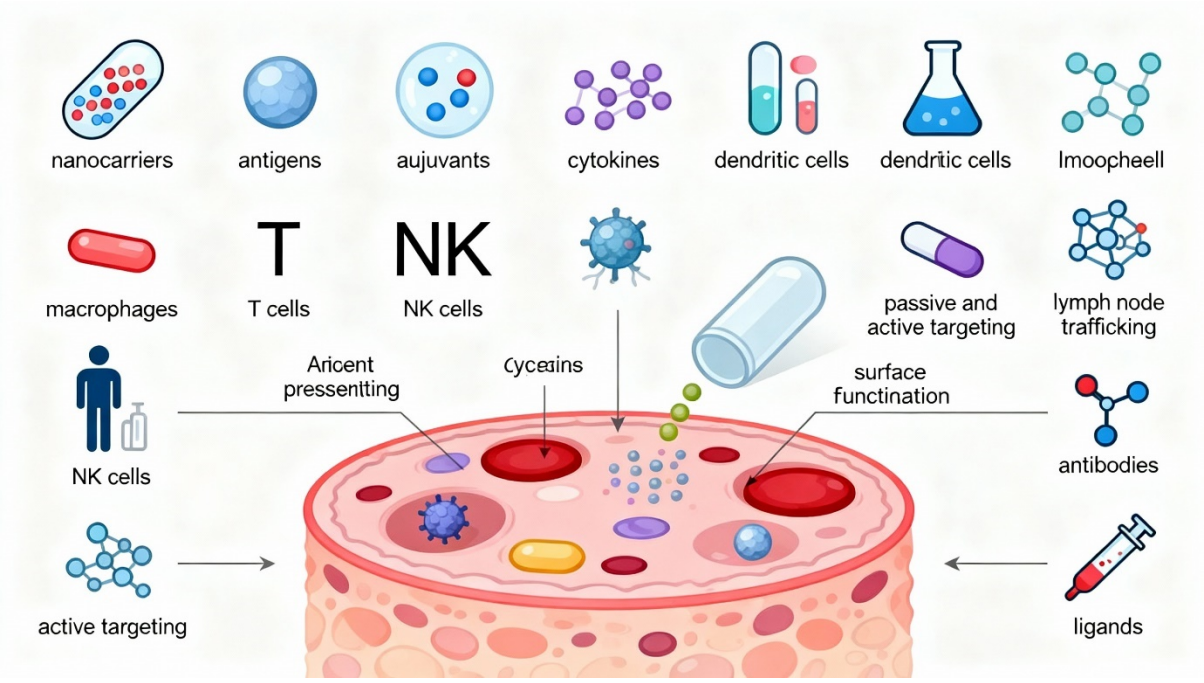
Controlled and sustained release of immunotherapeutic agents is crucial to maintaining a prolonged and effective immune response. By adjusting polymer degradation rates, lipid composition, or crosslinking density, formulators can fine-tune the release kinetics to achieve either a burst release for rapid immune priming or a sustained release for long-term immune memory formation.For example, PLGA-based nanoparticles degrade gradually to provide continuous antigen presentation to dendritic cells, ensuring persistent stimulation of cytotoxic T lymphocytes (CTLs). Similarly, lipid-based systems can be engineered with phase-transition lipids that respond to physiological stimuli such as pH or temperature for on-demand cargo release [34-35].

4.5. Overcoming Immune Tolerance and Enhancing Antigen Presentation

One of the most formidable challenges in immunotherapy is immune tolerance, where the immune system fails to recognize or attack malignant or infected cells. Nanoformulations are being designed to overcome this by promoting antigen cross-presentation and danger signal activation.

Incorporation of TLR agonists (like CpG oligonucleotides or poly(I:C)) or STING activators within nanoparticles can trigger robust type I interferon responses, enhancing dendritic cell maturation and antigen presentation. Additionally, co-delivery of immune checkpoint inhibitors (e.g., anti-PD-1 or anti-CTLA-4 antibodies) with antigenic payloads amplifies T-cell activation and reverses local immunosuppression in the tumor microenvironment [36].

***Figure** 1: Schematic representation of nano-immunotherapy targeting mechanisms.*



5. Pharmacokinetic and Pharmacodynamic Considerations

The therapeutic success of nano-immunotherapy hinges not only on immune activation but also on a clear understanding of how nanocarriers behave within biological systems—how they are absorbed, distributed, metabolized, and excreted (ADME). Pharmacokinetic (PK) and pharmacodynamic (PD) profiling is essential to optimize dosing regimens, minimize toxicity, and ensure that the immune-targeted formulations achieve sustained and localized immune stimulation. Nanocarrier design directly influences these parameters, dictating how long the therapeutic agent remains active and where it exerts its effect [37].

5.1. Impact of Nanocarrier Properties on ADME

The physicochemical characteristics of nanocarriers—particle size, surface charge, lipid or polymer composition, and hydrophobicity—determine their in vivo journey from administration to elimination.

- Absorption: Nanosystems with hydrophilic coatings (e.g., PEGylation) can evade opsonization and prolong circulation, whereas cationic nanoparticles exhibit stronger interaction with negatively charged cellular membranes, enhancing uptake by antigen-presenting cells (APCs). Oral and mucosal routes benefit from lipid-based or polymeric nanocarriers that promote trans-epithelial transport and lymphatic absorption.
- Distribution: Biodistribution is governed by the enhanced permeability and retention (EPR) effect, where nanoparticles accumulate preferentially in tumor and inflamed tissues due to leaky vasculature. Surface-functionalized nanoparticles can further localize to lymph nodes or specific immune cell subsets.
- Metabolism and Excretion: Biodegradable polymers (PLGA, chitosan) and lipids are metabolized via natural enzymatic pathways, reducing long-term toxicity. Non-biodegradable inorganic particles (e.g., gold, silica) are generally cleared through the reticuloendothelial system (RES), particularly by liver and spleen macrophages. Adjusting the degradation rate can balance drug release duration with systemic clearance.

Overall, nanocarrier engineering enables precise control over ADME parameters, optimizing both the exposure time and site-specific delivery of immunotherapeutics [38-39].

5.2. Biodistribution Studies in Lymphoid and Tumor Tissues

Understanding where and how nanocarriers localize post-administration is crucial for designing efficient immune-targeted systems. Lymphoid tissues—including lymph nodes, spleen, and Peyer's patches—are primary hubs for immune activation. Nanocarriers sized between 10–100 nm can effectively enter the lymphatic system and accumulate in these tissues, facilitating antigen presentation by dendritic cells.

In tumor microenvironments (TMEs), nanoparticles leverage the EPR effect for passive targeting. However, active targeting through ligand conjugation (e.g., mannose, folate, or

antibody-based) significantly improves localization to tumor-associated immune cells like macrophages and T cells. Studies using fluorescence and PET imaging have demonstrated prolonged nanoparticle retention in both lymphoid organs and tumor tissues, correlating with enhanced immune priming and tumor regression [40-41].

5.3. PK–PD Modeling for Predicting Immune Response and Therapeutic Outcomes

Pharmacokinetic–pharmacodynamic (PK–PD) modeling has emerged as a powerful tool in the rational design of nano-immunotherapeutics. By integrating drug concentration–time data (PK) with biological response metrics (PD), these models help predict optimal dosing strategies and immune activation profiles.

For instance, mRNA-LNP vaccines demonstrate a rapid initial burst in antigen expression (high Cmax, short Tmax) followed by a sustained immune response, which can be quantitatively linked to antibody titers and T-cell activation curves. Computational PK–PD simulations are also being used to evaluate immune checkpoint inhibitor-loaded nanoparticles, optimizing release kinetics and tumor exposure.

Advanced models now incorporate AI-driven algorithms and machine learning frameworks to predict inter-individual variability, immune response magnitude, and potential toxicity, making it possible to personalize nano-immunotherapy regimens [42].

5.4. Case Studies: Nanoformulations Enhancing Immunotherapeutic Index

Several nanoformulations have demonstrated remarkable pharmacokinetic and pharmacodynamic improvements over conventional immunotherapies:

Table 2: Pharmacokinetic and pharmacodynamic features of representative nano-immunotherapy formulations.

Nanoformulation	Therapeutic Agent	PK/PD Improvements	Clinical or Preclinical Outcome	Reference
Lipid Nanoparticles (LNPs)	mRNA (COVID-19 vaccine)	Enhanced lymphatic delivery, rapid antigen expression	Robust humoral and cellular immunity; successful human trials	43
PLGA Nanoparticles	IL-2 cytokine	Sustained release, prolonged circulation half-life	Increased T-cell proliferation and tumor suppression	44
Gold Nanoparticles	Peptide antigen	Controlled biodistribution, immune activation	Potent antigen-specific CTL response in murine	45

			cancer models	
Liposome–Antibody Conjugates	Anti-PD-1 mAb	Targeted delivery to tumor-infiltrating lymphocytes	Improved therapeutic index and reduced immune-related toxicity	46
Biomimetic Hybrid Nanocarriers	Tumor antigen + CpG adjuvant	Enhanced APC activation, long-term immune memory	Significant tumor regression and immune memory formation	47

These examples underscore how pharmaceutical design at the nanoscale can drastically influence both the pharmacokinetics (drug exposure and biodistribution) and pharmacodynamics (immune response and therapeutic effect) of immunotherapies.

6. Clinical Translation and Approved Nano-Immunotherapeutics

The clinical landscape for nano-immunotherapy has evolved rapidly from proof-of-concept studies to several high-impact, regulatory-approved products and a robust clinical pipeline. Nanocarrier technologies have been instrumental in translating immunomodulatory strategies into real-world therapies by improving delivery of antigens, nucleic acids, cytokines, and adjuvants; protecting labile payloads; and tuning biodistribution to lymphoid and tumor tissues [48]. The most visible success has been the lipid nanoparticle (LNP)–based mRNA vaccines for COVID-19, which validated LNPs as scalable, clinically acceptable vectors for nucleic acid immunotherapies. Beyond vaccines, nanoparticle formulations have achieved approvals or strong clinical evidence in oncology and genetic disease, demonstrating improved pharmacokinetics, targeted exposure, and in many cases better safety profiles versus conventional formulations.

Major success stories illustrate different ways nanotechnology enabled clinical impact. mRNA–LNP vaccines (Pfizer–BioNTech BNT162b2 and Moderna mRNA-1273) rapidly advanced through clinical trials and regulatory approvals by combining potent antigen expression with established LNP chemistry that protects mRNA and promotes efficient uptake by antigen-presenting cells [49-50]. In oncology, Abraxane® (albumin-bound paclitaxel) improved drug delivery and tolerability relative to solvent-based paclitaxel, allowing higher dosing and better response rates in several solid tumors. Liposomal drugs such as Doxil® showed how encapsulation reduces off-target toxicity (e.g., cardiotoxicity) while altering PK to enhance tumor exposure. In the nucleic-acid therapeutics space, Onpattro® (patisiran)—an LNP-formulated siRNA—demonstrated that LNPs can safely and effectively deliver RNA drugs systemically to the liver, producing clinically meaningful improvements in hereditary ATTR amyloidosis. Vaccines using nanoparticle adjuvants (e.g., AS01 in licensed vaccines) and protein-based nanoparticle vaccines (e.g., Novavax's NVX-CoV2373) further highlight the diversity of clinically successful nano-enabled immunotherapies.

Despite these achievements, clinical translation faces real challenges. Scalability and manufacturing remain nontrivial: producing uniform nanoparticles under GMP with consistent batch-to-batch characteristics (size, encapsulation efficiency, impurity profile) requires specialized facilities and robust process controls. Safety evaluation is complex because nanoparticles can interact with the immune system in unexpected ways—immunogenicity of carrier components, complement activation, and off-target accumulation (e.g., liver and spleen) must be carefully profiled across species [51-52]. Regulatory pathways for nanomedicines are still maturing: agencies expect thorough characterization of the nanomaterial, reproducible manufacturing, and detailed nonclinical safety packages, and guidance sometimes differs across jurisdictions, slowing global development. Finally, clinical endpoints for immunotherapies (durable immune memory, biomarkers of response) often require longer follow-up and multi-dimensional readouts (cellular + humoral immunity), adding complexity to trials.

Clinical data from approved products provide encouraging evidence: mRNA–LNP COVID-19 vaccines produced high neutralizing antibody titers and robust T-cell responses with acceptable safety profiles across large populations; Onpattro improved neuropathy scores and quality-of-life measures in ATTR patients; liposomal chemotherapies reduced acute toxicities and in some settings improved response rates or progression-free survival. These outcomes underscore that careful nanoparticle design—tuned for stability, biodistribution, and immune engagement—can translate into measurable clinical benefit [53-54].

Table 3. Clinically Approved or Investigational Nano-Immunotherapy Products

Product	Payload / Modality	Indication	Nanoplatform	Regulatory Status	Clinical Highlights	Reference
BNT162b2 (Pfizer–BioNTech)	mRNA encoding SARS-CoV-2 spike	COVID-19 prevention	Lipid nanoparticle (LNP)	Approved / EUA globally	High efficacy against symptomatic COVID; robust humoral & cellular responses	55
mRNA-1273 (Moderna)	mRNA encoding SARS-CoV-2 spike	COVID-19 prevention	Lipid nanoparticle (LNP)	Approved / EUA globally	High efficacy; scalable LNP platform for further vaccines	56
Onpattro® (patisiran)	siRNA	Hereditary ATTR amyloidosis	Lipid nanoparticle (LNP)	FDA approved	Improved neuropathy & quality-of-life;	57

					demonstrated systemic RNA delivery	
NVX-CoV2373 (Novavax)	Recombinant spike protein + adjuvant	COVID-19 prevention	Protein nanoparticle + Matrix-M adjuvant	Approved/EUA in multiple regions	Strong neutralizing antibody titers; good safety profile	58
Shingrix®	Recombinant glycoprotein E + AS01 adjuvant	Herpes zoster prevention	Liposomal adjuvant system (AS01)	Approved	High efficacy across age groups; durable immunity	59
Abraxane®	Paclitaxel (albumin-bound NP)	Solid tumors (breast, lung, pancreas)	Albumin-bound nanoparticle	Approved	Improved tolerability; enabled solvent-free higher dosing	60
Doxil®	Doxorubicin (PEGylated liposome)	Ovarian cancer, Kaposi sarcoma	PEGylated liposome	Approved	Prolonged circulation, reduced cardiotoxicity	61
(Selected investigationals)	e.g., nanoparticle-delivered checkpoint inhibitors, cytokines, vaccine candidates	Cancer, infectious diseases	Various (LNPs, polymeric, biomimetic)	Phase I–III trials	Early data show targeted immune modulation, improved PK/PD in some cohorts	62

7. Challenges and Limitations

Despite impressive progress, nano-immunotherapy faces persistent technical and translational hurdles that temper enthusiasm. Stability and reproducibility remain front-line problems: many nanoparticle formulations are sensitive to minor changes in raw-material lots, solvent traces, or processing conditions, which can shift size distributions, zeta potential, and payload retention. Those small shifts cascade into big differences in biological behavior, making reliable batch-to-batch manufacturing—and therefore clinical development—difficult. Closely related is the issue of immunotoxicity and unintended immune activation. Nanocarriers designed to stimulate immune responses can sometimes trigger off-target inflammation, complement activation, or anti-carrier antibodies, producing adverse events or accelerating clearance on repeat dosing.

Predicting these reactions across species is hard, so preclinical safety packages must be deep and multi-modal [63].

On the production side, manufacturing scale-up and cost barriers are nontrivial. Microfluidic or high-pressure homogenization methods that yield narrow, well-controlled nanoparticle populations at lab scale often require expensive, sterile, and highly controlled facilities to scale up under GMP[64]. Consumables, ionizable or specialty lipids, and rigorous in-process analytics add to cost, which can limit access and commercial viability—especially for combination therapies or personalized formulations[65]. Finally, regulatory uncertainties and standardization gaps complicate global development: regulatory authorities are converging on principles but differ in expectations for characterization, release criteria, and nonclinical testing for nanomaterials. The lack of universally accepted reference methods for critical quality attributes (CQAs) such as particle identity, morphological heterogeneity, or nanomaterial-specific impurities slows review timelines and makes cross-study comparisons difficult. Overcoming these challenges will require standardized analytical toolsets, predictive immunotoxicology, and closer industry-regulator collaboration [66-67].

8. Future Perspectives

The next decade will likely see nano-immunotherapy shift from platform validation to precision deployment. Personalized nano-immunotherapy—where formulations are tailored to a patient's tumor neoantigen profile, HLA type, or immune status—is emerging as a realistic goal, enabled by rapid sequencing, computational antigen prediction, and modular nanoparticle platforms. AI-driven nanocarrier design will accelerate optimization: machine learning models trained on formulation, biophysical, and in vivo datasets can predict how specific lipid or polymer choices, sizes, and surface chemistries affect ADME and immunogenicity, drastically reducing experimental cycles. Multi-antigen delivery systems and combinatorial payloads (antigen + adjuvant + immune-modulator) will allow tuned immune landscapes—priming, expanding, and sustaining responses while minimizing exhaustion [68].

Integration with CRISPR/Cas9 and gene-editing platforms opens transformative avenues for immune modulation: nanoparticles that deliver editing machinery to T cells or tumor stromal cells could reprogram the tumor microenvironment, knock out immune checkpoints locally, or produce durable in-situ expression of therapeutic cytokines[69]. Nanovaccines will move beyond infectious diseases into cancer prevention and early-stage therapeutic vaccination, with particulate platforms engineered for durable memory and lymph node targeting. Lastly, hybrid nanocarriers—blending lipids, polymers, inorganic components, and biomimetic coatings—will enable sophisticated combination therapies (immunotherapy + chemotherapy, phototherapy, or metabolic modulators) with synchronized pharmacokinetics and spatiotemporal control. Realizing these futures depends on parallel advances in scalable manufacturing, regulatory science, and translational clinical trial designs that capture immunological endpoints [70-71].

9. Conclusion

Nano-immunotherapy represents a powerful convergence of materials science, immunology, and pharmaceutical formulation—one that has already delivered high-impact products and validated core concepts such as targeted antigen delivery and nanoparticle-enabled nucleic acid vaccines. By precisely engineering particle properties, surface biology, and payload kinetics, nanoparticle platforms can overcome major limitations of conventional immunotherapies—improving bioavailability, directing immune activation, and widening therapeutic windows. Yet, persistent barriers in stability, immunotoxicology, manufacturing, and regulation mean that progress must be both scientific and systemic. The way forward is inherently interdisciplinary: chemists, formulation scientists, immunologists, clinicians, process engineers, and regulators must co-design solutions. When they do, the result will be a new generation of precision immune modulators—smarter, safer, and tailored to the patient—turning the promise of nano-immunotherapy into broad, durable clinical reality.

Reference

1. Cutaneous melanoma. (2025). *Nature Reviews Disease Primers, 11*, 23. https://doi.org/10.1038/s41572-025-00603-8
2. Hanrahan, G. B., Giobbie-Hurder, A., Allais, B., Vogelzang, J., Fay, C., & Tsibris, H. C. (2025). Melanoma tumor mutational burden and indoor tanning exposure. *JAMA Dermatology, 161*, 198–202. https://doi.org/10.1001/jamadermatol.2024.4819
3. Castejón-Griñán, M., Cerdido, S., Sánchez-Beltrán, J., Lambertos, A., Abrisqueta, M., Herraiz, C., et al. (2024). Melanoma-associated melanocortin 1 receptor variants confer redox signaling-dependent protection against oxidative DNA damage. *Redox Biology, 72*, 103135. https://doi.org/10.1016/j.redox.2024.103135
4. Huang, R. Y., Youssef, G., Nelson, T, Wen, P. Y., Forsyth, P., Hodi, F. S., et al. (2025). Comparative analysis of intracranial response assessment criteria in patients with melanoma brain metastases treated with combination nivolumab + ipilimumab in CheckMate 204. *Journal of Clinical Oncology, 43*, 1210–1218. https://doi.org/10.1200/JCO.24.00953
5. Nease, L. A., Church, K. P., Delclaux, I., Murakami, S., Astorkia, M., Zerhouni, M., et al. (2024). Selenocysteine tRNA methylation promotes oxidative stress resistance in melanoma metastasis. *Nature Cancer, 5*, 1868–1884. https://doi.org/10.1038/s43018-024-00844-8
6. Delcoigne, B., Lysell, J., & Askling, J. (2025). Incidence, stage and outcome of melanoma, keratinocyte and other cancers in individuals with vitiligo or alopecia: Intraindividual or familial risks? *British Journal of Dermatology.* https://doi.org/10.1093/bjd/ljaf074
7. Smith, M. J., Peach, H., Keohane, S., Lear, J., Jamieson, L. A., & Mohamed, H. S. (2025). Melanoma: Assessment and management summary of 2022 update of the NICE guidelines. *British Journal of Dermatology.* https://doi.org/10.1093/bjd/ljaf016
8. Molgora, M., & Colonna, M. (2025). Targeting brain macrophages: NF-κB as a therapeutic gateway in melanoma brain metastasis. *Cancer Cell, 43*, 328–329. https://doi.org/10.1016/j.ccell.2025.02.020

9. Lim, S. Y., Boyd, S. C., Diefenbach, R. J., & Rizos, H. (2025). Circulating microRNAs: Functional biomarkers for melanoma prognosis and treatment. *Molecular Cancer, 24*, 99. https://doi.org/10.1186/s12943-025-02298-7
10. Wawrzyniak, P., & Hartman, M. L. (2025). Dual role of interferon-gamma in the response of melanoma patients to immunotherapy with immune checkpoint inhibitors. *Molecular Cancer, 24*, 89. https://doi.org/10.1186/s12943-025-02294-x
11. Schiantarelli, J., Benamar, M., Park, J., Sax, H. E., Oliveira, G., Bosma-Moody, A., et al. (2025). Genomic mediators of acquired resistance to immunotherapy in metastatic melanoma. *Cancer Cell, 43*, 308–316.e6. https://doi.org/10.1016/j.ccell.2025.01.009
12. Patel, S. P., Sheth, R. A., Davis, C., & Medina, T. (2025). Combination immunotherapy with nivolumab plus ipilimumab in melanoma of unknown primary. *Journal of Clinical Oncology, 43*, 907–911. https://doi.org/10.1200/JCO-24-01802
13. Liang, L., Kuang, X., He, Y., Zhu, L., Lau, P., Li, X., et al. (2025). Alterations in PD-L1 succinylation shape anti-tumor immune responses in melanoma. *Nature Genetics, 57*, 680–693. https://doi.org/10.1038/s41588-025-02077-6
14. Lin, Y., Hou, J., Li, B., Shu, W., & Wan, J. (2025). Advancements in nanomaterials and molecular probes for spatial omics. *ACS Nano, 19*, 11604–11624. https://doi.org/10.1021/acsnano.4c18470
15. Balwe, S. G., Moon, D., Hong, M., & Song, J. M. (2024). Manganese oxide nanomaterials: Bridging synthesis and therapeutic innovations for cancer treatment. *Nano Convergence, 11*, 48. https://doi.org/10.1186/s40580-024-00456-z
16. Wu, B., Yao, C., Wang, H., Dai, H., Tian, B., Li, D., et al. (2025). Ellagic acid–protein nanocomplex inhibits tumor growth by reducing intratumor bacteria and inhibiting histamine production. *Biomaterials, 317*, 123078. https://doi.org/10.1016/j.biomaterials.2024.123078
17. Chen, L., Ming, H., Li, B., Yang, C., Liu, S., Gao, Y., et al. (2024). Tumor-specific nano-herb delivery system with high L-arginine loading for synergistic chemo and gas therapy against cervical cancer. *Small*, e2403869. https://doi.org/10.1002/smll.202403869
18. Wang, M., Yu, F., & Zhang, Y. (2025). Present and future of cancer nano-immunotherapy: Opportunities, obstacles and challenges. *Molecular Cancer, 24*, 26. https://doi.org/10.1186/s12943-024-02214-5
19. Liu, Q., Chen, G., Liu, X., Tao, L., Fan, Y., & Xia, T. (2024). Tolerogenic nano-/microparticle vaccines for immunotherapy. *ACS Nano.* https://doi.org/10.1021/acsnano.3c11647
20. Chen, Z., Guo, Z., Hu, T., Huang, B., Zheng, Q., Du, X., et al. (2024). Double-layered microneedle patch loaded with bioinspired nano-vaccine for melanoma treatment and wound healing. *International Journal of Biological Macromolecules, 262*, 129961. https://doi.org/10.1016/j.ijbiomac.2024.129961
21. Lin, Q., Zhang, Y., Zeng, Y., Zha, Y, Xue, W., & Yu, S. (2025). Hybrid membrane–based biomimetic nanodrug with melanoma-homing and NIR-II laser–amplified peroxynitrite boost for enhanced antitumor therapy. *Biomaterials, 317*, 123045. https://doi.org/10.1016/j.biomaterials.2024.123045

22. Zhang, W., Yuan, S., Zhang, Z., Fu, S., Liu, S., Liu, J., et al. (2025). Regulating tumor cells to awaken T cell antitumor function and enhance melanoma immunotherapy. *Biomaterials, 316*, 123034. https://doi.org/10.1016/j.biomaterials.2024.123034
23. Zhu, W., Zhou, Z., Yang, M., Chen, X., Zhu, S., Yu, M., et al. (2024). Injectable nanocomposite immune hydrogel dressings: Prevention of tumor recurrence and anti-infection after melanoma resection. *Small*, e2309476. https://doi.org/10.1002/smll.202309476
24. Linderman, S. W., DeRidder, L., Sanjurjo, L., Foote, M. B., Alonso, M. J., Kirtane, A. R., et al. (2025). Enhancing immunotherapy with tumour-responsive nanomaterials. *Nature Reviews Clinical Oncology, 22*, 262–282. https://doi.org/10.1038/s41571-025-01000-6
25. Li, Z., Xi, Z., Fan, C., Xi, X., Zhou, Y., Zhao, M., et al. (2025). Nanomaterials evoke pyroptosis boosting cancer immunotherapy. *Acta Pharmaceutica Sinica B, 15*, 852–875. https://doi.org/10.1016/j.apsb.2024.11.011
26. Peng, S., Hou, X., Liu, J., & Huang, F. (2025). Advances in polymer nanomaterials targeting cGAS-STING pathway for enhanced cancer immunotherapy. *Journal of Controlled Release, 381*, 113560. https://doi.org/10.1016/j.jconrel.2025.02.056
27. Desaunay, M., & Poulikakos, P. I. (2025). Overcoming melanoma therapy resistance with RAF–MEK and FAK inhibition. *Cancer Cell, 43*, 330–332. https://doi.org/10.1016/j.ccell.2025.02.012
28. Lubrano, S., Cervantes-Villagrana, R. D., Faraji, F., Ramirez, S., Sato, K., Adame-Garcia, S. R., et al. (2025). FAK inhibition combined with the RAF–MEK clamp avutometinib overcomes resistance to targeted and immune therapies in BRAF V600E melanoma. *Cancer Cell, 43*, 428–445.e26. https://doi.org/10.1016/j.ccell.2025.02.001
29. Lipchick, B., Guterres, A. N., Chen, H. Y., Zundell, D. M., Del Aguila, S., Reyes-Uribe, P. I., et al. (2025). Selective abrogation of S6K2 identifies lipid homeostasis as a survival vulnerability in MAPK inhibitor-resistant NRAS-mutant melanoma. *Science Translational Medicine, 17*, eadp8913. https://doi.org/10.1126/scitranslmed.adp8913
30. Ran, R., Li, L., Cheng, P., Li, H., He, H., Chen, Y., et al. (2024). High frequency of melanoma in cdkn2b−/−/tp53−/− *Xenopus tropicalis*. *Theranostics, 14*, 7470–7487. https://doi.org/10.7150/thno.97475
31. Li, Y., Liu, H., Li, J., Fu, C., Jiang, B., Chen, B., et al. (2025). MLLT3 regulates melanoma stemness and progression by inhibiting HMGB1 nuclear entry and MAGEA1 m5C modification. *Advanced Science, 12*, e2408529. https://doi.org/10.1002/advs.202408529
32. Zheng, D. X., Bozym, D. J., Tarantino, G., Sullivan, R. J., Liu, D., & Jenkins, R. W. (2025). Overcoming resistance mechanisms to melanoma immunotherapy. *American Journal of Clinical Dermatology, 26*, 77–96. https://doi.org/10.1007/s40257-024-00907-7
33. Rafiq, Z., Kang, M., Barsoumian, H. B., Manzar, G. S., Hu, Y., Leuschner, C., et al. (2025). Enhancing immunotherapy efficacy with synergistic low-dose radiation in metastatic melanoma: Current insights and prospects. *Journal of Experimental & Clinical Cancer Research, 44*, 31. https://doi.org/10.1186/s13046-025-03281-2

34. Martin-Liberal, J., Márquez-Rodas, I., Cerezuela-Fuentes, P., Soria, A., Garicano, F., Medina, J., et al. (2025). Challenges and perspectives in the management of BRAF-mutated metastatic melanoma: Systemic treatment sequencing and brain metastases. *Cancer Treatment Reviews, 133*, 102886. https://doi.org/10.1016/j.ctrv.2025.102886
35. O'Brien, M. T., Iwamoto, S., Haq, R., & Johnson, D. B. (2025). "Re-re-treatment?" Third and fourth courses of BRAF/MEK inhibition in advanced melanoma. *European Journal of Cancer*. https://doi.org/10.1016/j.ejca.2025.115378
36. Kim, J., Brunetti, B., Kumar, A., Mangla, A., Honda, K., & Yoshida, A. (2024). Inhibition of glutaminase elicits senolysis in therapy-induced senescent melanoma cells. *Cell Death & Disease, 15*, 902. https://doi.org/10.1038/s41419-024-07284-3
37. Alhusaini, S., Naya, L., Reddy, S. A., & Patel, C. B. (2024). MEK pathway inhibitor-mediated response in BRAF V600-mutant melanoma with brain parenchymal and leptomeningeal metastases. *Annals of Neurology, 96*, 1227–1229. https://doi.org/10.1002/ana.27062
38. Wen, Y., Wang, H., Yang, X., Zhu, Y., Li, M., Ma, X., et al. (2024). Pharmacological targeting of casein kinase 1δ suppresses oncogenic NRAS-driven melanoma. *Nature Communications, 15*, 10088. https://doi.org/10.1038/s41467-024-54140-1
39. Wei, X., Zou, Z., Zhang, W., Fang, M., Zhang, X., Luo, Z., et al. (2024). Phase II study of the MEK inhibitor tunlametinib in advanced NRAS-mutant melanoma. *European Journal of Cancer, 202*, 114008. https://doi.org/10.1016/j.ejca.2024.114008
40. Marasco M, Kumar D, Seale T, Borrego SG, Kaplun E, Aricescu I, et al. Concurrent SOS1 and MEK suppression inhibits signaling and growth of NF1-null melanoma. Cell Rep Med. 2024;5:101818. doi:10.1016/j.xcrm.2024.101818
41. Berry D, Moldoveanu D, Rajkumar S, Lajoie M, Lin T, Tchelougou D, et al. The NF1 tumor suppressor regulates PD-L1 and immune evasion in melanoma. Cell Rep. 2025;44:115365. doi:10.1016/j.celrep.2025.115365
42. Zhan Y, Guo J, Yang W, Goncalves C, Rzymski T, Dreas A, et al. MNK1/2 inhibition limits oncogenicity and metastasis of KIT-mutant melanoma. J Clin Invest. 2024;134. doi:10.1172/JCI181338
43. Zhou Z, Farhan M, Xing X, Zhou W, Lin R, Zeng S, et al. Artemisinin suppressed melanoma recurrence and metastasis after radical surgery through the KIT/PI3K/AKT pathway. Int J Biol Sci. 2025;21:75–94. doi:10.7150/ijbs.97341
44. Haugh A, Daud AI. Therapeutic strategies in BRAF V600 wild-type cutaneous melanoma. Am J Clin Dermatol. 2024;25:407–19. doi:10.1007/s40257-023-00841-0
45. Long GV, Carlino MS, Au-Yeung G, Spillane AJ, Shannon KF, Gyorki DE, et al. Neoadjuvant pembrolizumab, dabrafenib and trametinib in BRAF(V600)-mutant resectable melanoma: the randomized phase 2 NeoTrio trial. Nat Med. 2024;30:2540–8. doi:10.1038/s41591-024-03077-5
46. Dudnichenko O, Penkov K, McKean M, Mandalà M, Kukushkina M, Panella T, et al. First-line encorafenib plus binimetinib and pembrolizumab for advanced BRAF V600-mutant melanoma: Safety lead-in results from the randomized phase III STARBOARD study. Eur J Cancer. 2024;213:115070. doi:10.1016/j.ejca.2024.115070

47. Long GV, Hauschild A, Santinami M, Kirkwood JM, Atkinson V, Mandala M, et al. Final results for adjuvant dabrafenib plus trametinib in stage III melanoma. N Engl J Med. 2024;391:1709–20. doi:10.1056/NEJMoa2404139
48. Misiag P, Molik K, Kisielewska M, Typek P, Skowron I, Karwowska A, et al. Amelanotic melanoma — biochemical and molecular induction pathways. Int J Mol Sci. 2024;25. doi:10.3390/ijms252111502
49. Malekan M, Haass NK, Rokni GR, Gholizadeh N, Ebrahimzadeh MA, Kazeminejad A. VEGF/VEGFR axis and its signaling in melanoma: current knowledge toward therapeutic targeting agents and future perspectives. Life Sci. 2024;345:122563. doi:10.1016/j.lfs.2024.122563
50. Ceci C, Ruffini F, Falconi M, Atzori MG, Falzon A, Lozzi F, et al. Pharmacological inhibition of PDGF-C/neuropilin-1 interaction: a novel strategy to reduce melanoma metastatic potential. Biomed Pharmacother. 2024;176:116766. doi:10.1016/j.biopha.2024.116766
51. Giammona A, De Vellis C, Crivaro E, Maresca L, Amoriello R, Ricci F, et al. Tumor-derived GLI1 promotes remodeling of the immune tumor microenvironment in melanoma. J Exp Clin Cancer Res. 2024;43:214. doi:10.1186/s13046-024-03138-0
52. Babaei S, Fadaee M, Abbasi-Kenarsari H, Shanehbandi D, Kazemi T. Exosome-based immunotherapy as an innovative therapeutic approach in melanoma. Cell Commun Signal. 2024;22:527. doi:10.1186/s12964-024-01906-1
53. Tang S, Zhang Y, Huang S, Zhu T, Huang X. Single-cell RNA sequencing in uveal melanoma: advances in heterogeneity, tumor microenvironment and immunotherapy. Front Immunol. 2024;15:1427348. doi:10.3389/fimmu.2024.1427348
54. Shi H, Tian H, Zhu T, Liao Q, Liu C, Yuan P, et al. Single-cell sequencing depicts tumor architecture and empowers clinical decision in metastatic conjunctival melanoma. Cell Discov. 2024;10:63. doi:10.1038/s41421-024-00683-y
55. Seo J, Ha G, Lee G, Nasiri R, Lee J. Modeling tumor–immune interactions using hybrid spheroids and microfluidic platforms for studying tumor-associated macrophage polarization in melanoma. Acta Biomater. 2024;190:233–46. doi:10.1016/j.actbio.2024.10.036
56. Bida M, Miya TV, Hull R, Dlamini Z. Tumor-infiltrating lymphocytes in melanoma: from prognostic assessment to therapeutic applications. Front Immunol. 2024;15:1497522. doi:10.3389/fimmu.2024.1497522
57. Kewitz-Hempel S, Windisch N, Hause G, Müller L, Sunderkötter C, Gerloff D. Extracellular vesicles derived from melanoma cells induce carcinoma-associated fibroblasts via miR-92b-3p mediated downregulation of PTEN. J Extracell Vesicles. 2024;13:e12509. doi:10.1002/jev2.12509
58. Cohen Shvefel S, Pai JA, Cao Y, Pal LR, Bartok O, Levy R, et al. Temporal genomic analysis of homogeneous tumor models reveals key regulators of immune evasion in melanoma. Cancer Discov. 2024. doi:10.1158/2159-8290.CD-23-1422
59. Chiffelle J, Barras D, Pétremand R, Orcurto A, Bobisse S, Arnaud M, et al. Tumor-reactive T-cell clonotype dynamics underlying clinical response to TIL therapy in melanoma. Immunity. 2024;57:2466–82.e12. doi:10.1016/j.immuni.2024.08.014

60. Theunis K, Vanuytven S, Claes I, Geurts J, Rambow F, Brown D, et al. Single-cell genome and transcriptome sequencing without upfront whole-genome amplification reveals cell state plasticity of melanoma subclones. Nucleic Acids Res. 2025;53. doi:10.1093/nar/gkaf173
61. Muddasani R, Wu HT, Win S, Amini A, Modi B, Salgia R, et al. The impact of Medicaid expansion on stage at diagnosis of melanoma patients: a retrospective study. Cancers. 2024;17. doi:10.3390/cancers17010061
62. Pozniak J, Pedri D, Landeloos E, Van Herck Y, Antoranz A, Vanwynsberghe L, et al. A TCF4-dependent gene regulatory network confers resistance to immunotherapy in melanoma. Cell. 2024;187:166–83.e125. doi:10.1016/j.cell.2023.11.037
63. Kim GH, Fang XQ, Lim WJ, Park J, Kang TB, Kim JH, et al. Cinobufagin suppresses melanoma cell growth by inhibiting LEF1. Int J Mol Sci. 2020;21. doi:10.3390/ijms21186706
64. Namdeo KP, Gupta RK, Baghel M, et al. Synthesis and bio evaluation of some hybrid molecules of tramadol: A new strategy in drug design. *Biocatal Agric Biotechnol*. 2024;58:103171. doi:10.1016/J.BCAB.2024.103171
65. Katendra NK, Chandel SC, Kumar DK, Verma VSV, Mandle NM. Quantum Dots in Materia Medica: Emerging Tools for Bioimaging and Targeted Drug Delivery *Indian Journal of Pharmaceutical Chemistry and Analytical Techniques*. 2026;2(1):45-66. doi:10.64062/IJPCAT.VOL2.ISSUE1.5
66. Hu R, Hou H, Li Y, Zhang M, Li X, Chen Y, et al. Combined BET and MEK inhibition synergistically suppresses melanoma by targeting YAP1. Theranostics. 2024;14:593–607. doi:10.7150/thno.85437
67. Hoch T, Schulz D, Eling N, Gomez JM, Levesque MP, Bodenmiller B. Multiplexed imaging mass cytometry of the chemokine milieus in melanoma characterizes features of the response to immunotherapy. Sci Immunol. 2022;7:eabk1692. doi:10.1126/sciimmunol.abk1692
68. Torphy RJ, Sun Y, Lin R, Caffrey-Carr A, Fujiwara Y, Ho F, et al. GPR182 limits antitumor immunity via chemokine scavenging in mouse melanoma models. Nat Commun. 2022;13:97. doi:10.1038/s41467-021-27658-x
69. Kashyap G, Pandey AP, Tiwari NT, Sahu MK, Verma VS. Meta-Analysis of Multi-Omics and Nanoparticle-Enhanced Therapeutics in Solid Tumors: Advancing Precision Oncology. *Journal of Pharmaceutical Research and Integrated Medical Sciences*. Published online February 18, 2026:63-76. doi:10.64063/3049-1681.VOL.3.ISSUE2.5
70. Carlino MS, Larkin J, Long GV. Immune checkpoint inhibitors in melanoma. Lancet. 2021;398:1002–14. doi:10.1016/S0140-6736(21)01206-X
71. Huang F, Goncalves C, Bartish M, Remy-Sarrazin J, Issa ME, Cordeiro B, et al. Inhibiting the MNK1/2–eIF4E axis impairs melanoma phenotype switching and potentiates antitumor immune responses. J Clin Invest. 2021;131. doi:10.1172/JCI140752