Review
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The Role of Nanotechnology in Targeting Viral Infections at the Cellular Level

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Abstract

Introduction: To critically synthesise evidence on how nanotechnology can be used to prevent viral entry, deliver antiviral agents to infected cells, modulate intracellular antiviral processes and improve the safety or effectiveness of antiviral therapy.

Methods: We conducted a narrative review using the literature in the original manuscript as the core evidence base. We reorganised the evidence around the viral life cycle and the nanoparticle–cell interface, with an emphasis on nanoparticle composition, surface functionalisation, cellular uptake, drug and nucleic-acid delivery, safety, manufacturing, and translation. Bibliographic records were also checked during revision, and the implications for health systems in the Global South were explicitly considered.

Synthesis: Inorganic, lipid, polymeric and hybrid nanoparticles can interact with viruses or host cells through adsorption, receptor targeting, endocytosis, endosomal trafficking and controlled intracellular release. Experimental evidence supports applications in viral neutralisation, inhibition of entry, delivery of antiretroviral and other antiviral agents, vaccine development and diagnostic detection. However, much of the evidence remains preclinical. Heterogeneity in particle size, surface chemistry, formulation, dose and experimental models complicates comparisons across studies. Toxicity, reproducible scale-up, stability, regulatory requirements and cost remain important barriers to clinical implementation.

Conclusion: Nanotechnology provides a versatile platform for antiviral intervention, but biological plausibility should not be equated with clinical effectiveness. Future work should prioritise reproducible formulations, rigorous toxicology, clinically relevant efficacy studies and manufacturing pathways that are affordable and feasible in the Global South.

Keywords: Nanotechnology; Nanomedicine; Antiviral Agents; Virus Diseases; Drug Delivery Systems

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Introduction

Viral infections remain a major global health problem and can produce outcomes ranging from self-limited illness to chronic disease, severe respiratory disease, cancer, neurological complications and death. The burden is unevenly distributed, and infectious diseases continue to exert disproportionate pressure on health systems in low- and middle-income countries. Global changes in climate, mobility, population structure and human–animal interactions can also alter the distribution and transmission of infectious diseases, reinforcing the need for technologies that can be adapted rapidly to emerging threats (1, 2).

Antiviral treatment differs fundamentally from antibacterial therapy because viruses depend heavily on host-cell machinery for replication. Therapeutic strategies may therefore target viral entry, genome replication, protein processing, assembly or release, or may modify host pathways that are required for infection (3). Existing

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antivirals have changed the prognosis of infections such as HIV, but treatment can remain constrained by resistance, adherence, toxicity, drug interactions, tissue penetration and access. These constraints are particularly relevant where medicines are costly, or health systems have limited capacity for prolonged monitoring.

Nanotechnology provides a set of tools for modifying how therapeutic molecules interact with biological systems. Nanoparticles can encapsulate or conjugate small molecules, proteins, nucleic acids and other payloads, alter pharmacokinetics, protect unstable compounds and facilitate delivery to particular tissues or cellular compartments (4, 5, 6). The biological behaviour of a nanoparticle depends on more than its nominal size. Shape, surface charge, composition, protein adsorption, aggregation, ligand density and route of administration can all influence biodistribution and cellular uptake (7, 8, 9).

For antiviral applications, the attraction of nanotechnology lies in its ability to intervene at several stages of the virus–host interaction. Nanomaterials may bind virions directly and interfere with attachment; they may be functionalised with ligands that recognise host-cell receptors; or they may act as carriers that release antiviral agents after cellular uptake (10, 11, 12). Some platforms also support vaccine delivery or diagnostic detection. The same properties that make nanoparticles useful can, however, produce unexpected biological effects, including altered biodistribution, persistence or toxicity (13, 14).

A clinically useful antiviral nanomedicine must therefore satisfy several conditions simultaneously: it must demonstrate reproducible physicochemical characteristics, deliver an appropriate payload to a relevant site, retain antiviral activity at a clinically meaningful dose, avoid unacceptable toxicity, and be manufacturable at scale. These requirements become more demanding when the intended users are populations served by resource-constrained health systems. The broader principles of equity, contextual relevance and local research capacity that are central to Global South scholarship are therefore directly applicable to nanomedicine development (15, 16).

This review examines the cellular mechanisms, antiviral applications, limitations and translational prospects of nanotechnology-based interventions against viral infections, with particular attention to the gap between experimental efficacy and practical implementation. It also considers the implications of nanomedicine for the Global South, where affordability, manufacturing capacity, regulation and access may determine whether scientific advances translate into population health benefit.

Methods

Review design and scope

This article was prepared as a narrative review rather than a systematic review or meta-analysis. The literature contained in the submitted manuscript constituted the core evidence base. During revision, the cited literature was reorganised according to the biological pathway being targeted, and bibliographic details were checked where necessary. The synthesis prioritised literature addressing nanoparticle properties, cellular uptake, viral binding and entry, antiviral drug or nucleic-acid delivery, vaccine and diagnostic applications, toxicity, manufacturing and translational barriers. The review also incorporated a Global South implementation perspective because applicability and access are central to the scope of Global South Health Horizons (15, 16).

Approach to evidence synthesis

Evidence was grouped conceptually into four levels: direct interaction with virions; targeting of host-cell entry or intracellular trafficking; delivery of antiviral payloads; and broader enabling applications such as vaccination and diagnostics. Care was taken to distinguish laboratory or preclinical findings from established clinical applications. Because the source manuscript did not document a reproducible database search, search dates, screening process or formal eligibility criteria, this review does not claim systematic evidence retrieval. The absence of a formal systematic-search protocol is treated as a limitation of the evidence synthesis.

Conceptual framework

The review was organised around the principle that antiviral nanotechnology operates at the virus–host interface rather than through a single universal mechanism. The resulting framework links nanoparticle composition and surface engineering to viral binding, receptor interaction, endocytosis, intracellular trafficking, release of the therapeutic payload and the resulting antiviral effect. This framework is presented in Figure 1.

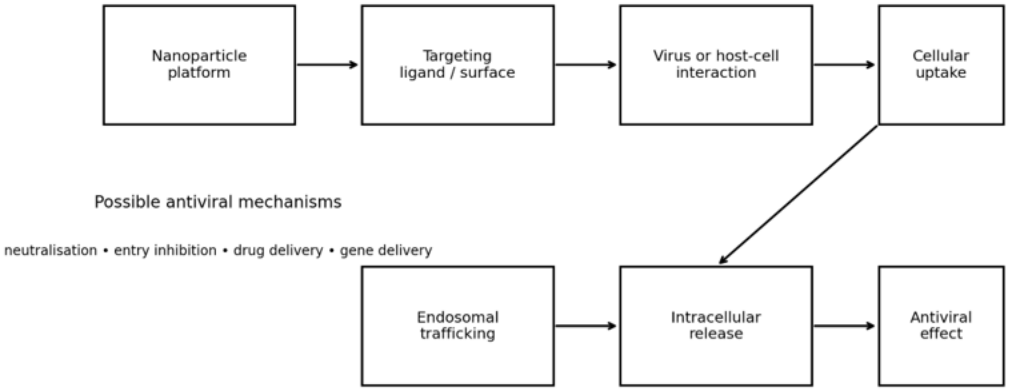


Figure 1: Conceptual framework for nanoparticle-mediated antiviral action at the virus–cell interface

Synthesis

Results

Nanoparticle platforms relevant to antiviral therapy

Nanoparticles are generally described as structures in the nanoscale range whose physicochemical properties differ from those of the corresponding bulk material. The commonly used platforms in biomedical research include inorganic nanoparticles, lipid-based systems, polymeric nanoparticles, dendrimers, carbon-based materials and hybrid formulations (4, 5, 6). These platforms differ in loading capacity, surface chemistry, degradation, stability, manufacturing complexity and the types of payload they can accommodate.

Lipid systems, including liposomes and lipid nanoparticles, are particularly useful for encapsulating hydrophobic or hydrophilic compounds and for delivering nucleic acids. Polymer-based systems such as poly(lactic-co-glycolic acid) can provide controlled release and protection of encapsulated molecules. Inorganic materials, including gold, silver, silica and iron oxide nanoparticles, offer distinctive optical, magnetic or surface properties that can be exploited for detection, imaging or antiviral activity (7, 8, 9, 14, 17). The principal platforms and their potential antiviral roles are summarised in Table 1. The choice of platform should therefore be driven by the intended biological function rather than by the label “nanoparticle” alone.

Table 1: Major nanoparticle platforms and their potential antiviral roles

Platform	Examples	Potential role	Key translational considerations
Lipid-based	Liposomes; lipid nanoparticles	Encapsulation and delivery of small molecules, proteins and nucleic acids; vaccine delivery	Stability, storage, formulation reproducibility, pharmacokinetics
Polymeric	PLGA and related polymers	Controlled release; protection of biologically active payloads; targeted delivery	Degradation profile, scale-up, drug loading and release consistency
Inorganic	Gold; silver; silica; iron oxide	Virion interaction, imaging, diagnostics, delivery and experimental antiviral activity	Dose-dependent toxicity, clearance, surface chemistry
Hybrid / virus-derived	Polymer–inorganic hybrids; viral nanoparticles	Combined targeting, imaging or payload delivery	Manufacturing complexity and regulatory characterisation
Carbon-based/other nanomaterials	Carbon nanomaterials; dendrimers	Antiviral surface activity, delivery and experimental diagnostic applications	Long-term safety, aggregation, reproducibility and environmental considerations

Particle size, shape, surface charge and functionalisation influence how nanoparticles behave in biological fluids and interact with cell membranes (7, 8, 9, 18). Surface modification can alter protein adsorption, cellular uptake, immune recognition and tissue distribution. However, adding targeting ligands does not guarantee selective delivery. Targeting performance depends on ligand density, receptor abundance, particle stability, the biological environment and the accessibility of the target site.

Nanoparticle interaction with viruses and host cells

Nanotechnology can intervene before a virus enters a cell, during cellular entry, or after uptake into the cell. Direct antiviral activity may occur when a nanoparticle binds to structural components of a virion and prevents attachment or

fusion. Surface charge and other physicochemical properties influence these interactions, while multivalent binding can increase the avidity of nanoparticle–virus interactions (10, 12, 19).

A second mechanism involves host-cell targeting. Nanoparticles can be functionalised with antibodies, peptides, carbohydrates or other ligands to promote interaction with selected receptors. Once a particle has engaged the cell surface, internalisation commonly occurs through endocytic pathways. The subsequent fate of the nanoparticle may include trafficking through endosomes, lysosomal processing, recycling or escape into the cytosol (20, 21). For nucleic-acid delivery systems, successful endosomal escape is often a critical determinant of biological activity.

The stages of nanoparticle-mediated antiviral action are summarised in Figure 1. The framework emphasises that successful targeting is a multistep process: a formulation must reach the relevant site, interact with its intended target, enter the appropriate cellular compartment and release an active payload without producing unacceptable toxicity.

Nanotechnology-based antiviral drug delivery

Drug delivery is one of the most developed applications of nanotechnology in antiviral research. Nanocarriers can protect compounds from premature degradation, alter solubility, improve apparent bioavailability and provide controlled or sustained release (6, 12). Polymeric and lipid formulations have also been explored for delivery of proteins, nucleic acids and other macromolecules that are difficult to administer using conventional dosage forms.

The evidence suggests that nanotechnology is particularly valuable where the therapeutic challenge is pharmacokinetic rather than simply pharmacodynamic. A nanoparticle can be engineered to change exposure, prolong retention or alter the distribution of a drug. In principle, the same approach can reduce systemic exposure while increasing delivery to infected tissues. These advantages remain formulation-specific; they cannot be assumed from nanoparticle size alone.

Surface functionalisation provides a route to active targeting. Ligands can be selected to recognise receptors expressed preferentially on particular cell populations, creating an opportunity for selective uptake (3, 6, 15). Nonetheless, biological identity at the nanoscale is shaped by adsorption of proteins from the surrounding environment, so the intended surface characteristics may change after administration (15, 16). This is one reason why in vitro targeting results may not translate directly to living systems.

HIV

HIV provides an important example because long-term treatment depends on sustained delivery of antiretroviral combinations and because viral reservoirs remain a major barrier to cure (22, 23). Nanotechnology has been investigated as a means of improving the pharmacological profile of existing antiretroviral agents, delivering therapeutic nucleic acids and supporting vaccine strategies (18, 23, 24).

Lipid and polymeric systems can encapsulate antiretroviral drugs or biological payloads and may be engineered to modify release or tissue distribution. The wider concept is attractive for HIV because effective treatment requires suppression of viral replication over long periods, while eradication of reservoir-associated infection would require access to biologically protected cell populations. Nanoparticles could theoretically facilitate delivery into such compartments, although the existence of a plausible delivery mechanism does not establish clinical efficacy.

Nanotechnology has also been investigated in HIV vaccine development. Lipid nanoparticle delivery of nucleoside-modified mRNA has generated HIV-1 antibody responses in non-human primate models, demonstrating the ability of nanocarriers to support complex vaccine platforms (18). These findings are relevant to antiviral preparedness more broadly because they illustrate how the delivery platform can be as important as the biological payload.

Influenza

Influenza viruses enter respiratory epithelial cells through receptor-mediated processes involving viral surface proteins and host-cell glycans. The respiratory tract is therefore a plausible anatomical target for nanotechnology-based prevention, detection and therapy (10).

Polymeric nanoparticles, liposomes, nanofibres, nanowires, dendrimers and gold-based nanostructures have been investigated for influenza-related applications, including antiviral drug delivery, pathogen capture and vaccine delivery (12, 25). Some approaches exploit interactions with viral surface proteins such as haemagglutinin or neuraminidase, while others use nanoparticles as carriers without requiring direct antiviral activity from the particle itself.

The applications discussed for HIV, influenza and viral hepatitis are compared in Table 2. The most credible near-term role of nanotechnology in influenza is likely to remain that of an enabling platform, for example, improving delivery or detection, rather than a universal nanoparticle that independently eradicates infection. This distinction matters because many reported antiviral effects have been demonstrated in vitro, where particle concentration and contact time can be controlled more precisely than in clinical settings.

Table 2: Illustrative antiviral applications discussed in the reviewed literature

Virus/disease	Nanotechnology application	Principal mechanism or rationale	Evidence level in reviewed literature
HIV	Antiretroviral and nucleic-acid delivery; vaccine platforms	Modify pharmacokinetics, improve cellular delivery and support immune responses	Predominantly preclinical/experimental
Influenza	Drug and vaccine delivery; virus capture and detection	Target respiratory infection pathways or provide enabling delivery/detection functions	Predominantly preclinical/experimental
Hepatitis B	Drug and vaccine delivery; experimental nanoparticle-mediated antiviral activity	Liver-directed or controlled delivery; immune modulation	Predominantly preclinical/experimental
Hepatitis C	Drug and nucleic-acid delivery; experimental antiviral nanomaterials	Targeted delivery and combination approaches	Predominantly preclinical/experimental
Emerging respiratory viruses	Diagnostic biosensors; vaccine and antiviral delivery platforms	Rapid adaptation of nanoparticle-enabled detection and delivery	Early translational/heterogeneous

Hepatitis B and C

Nanotechnology has also been explored in chronic viral hepatitis, particularly for targeted delivery, vaccination and direct antiviral activity. HBV and HCV present different biological challenges, but both provide opportunities for controlled drug delivery and for targeting the liver.

Polymeric, lipid, gold, silver and other nanomaterials have been investigated as antiviral agents or delivery systems (19, 26). In vaccine research, nanoparticle formulations may improve antigen presentation and influence cellular immune responses (11). However, antiviral activity observed with metal- or carbon-based nanoparticles cannot be regarded as evidence of therapeutic suitability without a parallel assessment of toxicity, pharmacokinetics and dose.

For HCV, advances in conventional direct-acting antivirals have changed the therapeutic landscape, so the rationale for nanotechnology is increasingly related to delivery, combination strategies and broader platform technologies rather than a simple search for another nonspecific antiviral particle. The same principle applies to HBV: a nanoparticle should solve a defined therapeutic problem, such as targeted delivery or controlled release, rather than be pursued solely because it has intrinsic in vitro antiviral activity.

Vaccine and diagnostic applications

Nanotechnology extends beyond therapeutic drug delivery. Nanostructures can be designed to present antigens, protect nucleic acids, improve antigen stability or amplify diagnostic signals (11, 18, 26). Gold nanoparticles, for example, have been extensively investigated in viral detection because their optical properties can be exploited in biosensor platforms (17, 27).

The value of these technologies is particularly apparent when a diagnostic or vaccine platform must be adapted quickly to a new pathogen. At the same time, rapid laboratory development does not remove the need for clinical validation, manufacturing controls and regulatory assessment. A platform that performs well analytically may still face problems with reagent stability, instrumentation, workforce requirements or supply chains.

Safety, toxicity and biocompatibility

Safety is inseparable from nanoparticle design. Nanomaterials can interact with proteins, membranes, organelles and immune pathways in ways that are not predicted adequately by conventional dose metrics alone (13, 14). Toxicity can vary with composition, particle size, shape, surface chemistry, aggregation state, concentration and duration of exposure.

A formulation may therefore be non-toxic at one concentration but harmful at another, or may behave differently after surface functionalisation. Long-term persistence is another consideration because particles that are poorly cleared may accumulate in tissues (13). Safety studies should consequently characterise the complete formulation rather than treating “nanoparticle” as a single exposure category.

Manufacturing, reproducibility and regulation

Translation from laboratory research to clinical use is constrained by reproducibility and scale-up (28). Small changes in synthesis can alter particle size distribution, surface chemistry, drug loading or release characteristics. These differences may be biologically important and can complicate comparison between studies.

Manufacturing also must satisfy quality-control requirements while maintaining stability throughout storage and distribution. Regulatory assessment must address product identity, purity, potency, toxicology, pharmacokinetics and batch-to-batch consistency (13, 14). These requirements are particularly demanding for formulations that combine a biologically active payload with a complex delivery system.

The principal translational barriers and potential responses are summarised in Table 3. The translational pathway is

summarised in Figure 2. The figure makes explicit that a promising laboratory formulation sits at the beginning, rather than the end, of development.

Table 3: Principal barriers to translation of antiviral nanotechnology and potential responses

Barrier	Why it matters	Priority response
Formulation heterogeneity	Small differences in size, surface chemistry or aggregation can change biological behaviour	Define and report critical quality attributes and use standardised characterisation methods
Toxicity and biocompatibility	Nanoparticles may interact with tissues and immune pathways unpredictably	Conduct formulation-specific toxicology, pharmacokinetics and biodistribution studies
Endosomal escape and intracellular delivery	Cellular uptake does not guarantee release of an active payload	Measure intracellular trafficking and functional payload release
Manufacturing and scale-up	Laboratory synthesis may not translate into reproducible large-scale production	Develop scalable processes, GMP-compatible controls and stability testing
Regulation	Complex products may require assessment of both carrier and therapeutic payload	Engage regulators early and define product-specific quality, safety and efficacy requirements
Cost and access in the Global South	High-cost or infrastructure-dependent products may have low population-level reach	Plan affordability, technology transfer, regional production and health-system fit early

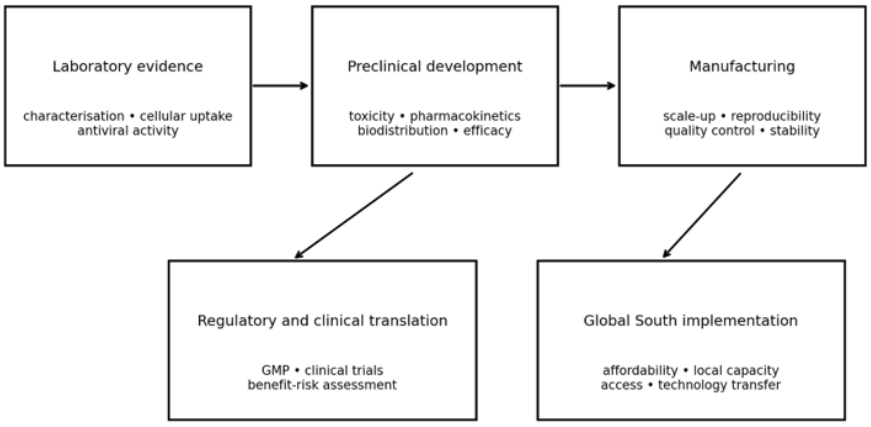


Figure 2: Translational pathway for antiviral nanomedicine, with Global South implementation considerations

Relevance to the Global South

The implications of antiviral nanotechnology for the Global South extend beyond the existence of a technically effective formulation. Equity depends on whether products can be manufactured, procured, regulated, distributed and monitored within health systems that may face higher costs of imported technologies, limited specialist infrastructure and constrained research and regulatory capacity (15, 16).

Nanomedicine development should therefore incorporate access considerations early. Technology transfer, regional manufacturing partnerships, appropriate quality-control infrastructure, locally relevant clinical research and affordable formulation strategies may be as important as molecular optimisation. The principle is consistent with the broader Global South research agenda: innovation should be assessed in relation to local needs, capacity and pathways to implementation rather than by laboratory performance alone city (15, 16).

For viral diseases that disproportionately affect lower-resource settings, this framing is especially relevant. A highly sophisticated nanomedicine that requires expensive cold-chain equipment, specialist administration, or imported consumables may have limited population impact even if its efficacy is demonstrated. Conversely, robust formulations that can be manufactured or assembled regionally and integrated into existing delivery systems may offer greater practical value.

Evidence synthesis by development stage

Across the reviewed literature, the strongest body of evidence concerns proof-of-concept experiments demonstrating that nanoparticles can interact with virions, alter cellular entry, or deliver antiviral compounds. (11, 19,

21, 25). The evidence becomes progressively thinner as one moves from in vitro studies to animal studies and then to routine human use. This gradient is clinically important.

The review therefore supports a cautious interpretation: nanotechnology is a versatile enabling technology rather than a single antiviral treatment class. Its eventual clinical value will depend on matching a defined biological problem to a well-characterised formulation and demonstrating benefit under realistic conditions.

Evidence across viral applications

The principal applications discussed in the reviewed literature are summarised in Table 2. The table deliberately distinguishes the type of application from the level of evidence so that experimental activity is not mistaken for established clinical use.

Translational barriers

The barriers that recur across the reviewed literature are summarised in Table 3. These barriers are interconnected: a formulation that is difficult to reproduce may also be difficult to regulate, and a formulation that requires specialised infrastructure may have limited value in settings where such infrastructure is scarce.

Conceptual framework for cellular targeting

The cellular pathway targeted by antiviral nanotechnology can be represented as a sequence from formulation design and surface engineering to virus or host-cell recognition, cellular uptake, intracellular trafficking and release of the active agent. Figure 1 provides a conceptual summary of these linked steps.

Translational pathway

The available evidence also supports viewing nanomedicine development as a progression from laboratory proof of concept through preclinical evaluation, manufacturing and regulation before routine clinical implementation. Figure 2 illustrates this pathway and places Global South considerations alongside, rather than after, conventional translational milestones.

Discussion

Nanotechnology occupies an unusual position in antiviral medicine because the same platform can influence several stages of the virus–host interaction. A nanoparticle may function as a virion-binding agent, a targeted carrier, an intracellular delivery vehicle, a vaccine platform or a diagnostic component. This versatility explains the breadth of the literature, but it also creates a risk of conceptual overreach. Different nanomaterials have very different mechanisms, toxicological profiles and development pathways; evidence generated for one formulation cannot automatically be extrapolated to another.

The most defensible interpretation of the available evidence is that nanotechnology can modify the delivery and biological context of antiviral interventions. The strongest arguments concern improved localisation, protection of fragile payloads, controlled release and the possibility of targeting specific cell populations (11, 21, 24, 25). These features may address limitations that conventional formulations cannot readily overcome. The challenge is to demonstrate that the resulting change in pharmacology translates into clinically meaningful outcomes.

The cellular level is particularly important because viral infection is a sequence of linked events rather than a single target. Attachment, receptor engagement, membrane fusion or endocytosis, intracellular trafficking, genome replication, and release each create potential intervention points (10). A useful nanomedicine should therefore be designed around a clearly defined step in this pathway. Claims of "cellular targeting" are too broad unless the intended receptor, intracellular compartment or mechanism of action is specified.

The HIV literature illustrates both the promise and the difficulty of this approach. Existing antiretroviral therapy is highly effective when taken consistently, meaning that a nanoparticle formulation must offer a meaningful advantage to justify additional complexity (22). The strongest rationale may arise where delivery to difficult compartments, prolonged drug exposure or biologically active nucleic-acid payloads creates an opportunity that conventional therapy cannot easily provide (18, 23, 24). At present, however, these applications remain developmental rather than established replacements for standard treatment.

Similar caution is appropriate for influenza and viral hepatitis. Nanotechnology can provide effective carriers and detection systems, but the existence of a nanoparticle with in vitro antiviral activity does not establish therapeutic superiority over modern standard-of-care treatment (12, 25, 26). In diseases where effective conventional antivirals already exist, the development question should be framed around incremental clinical value: Does the nanomedicine improve adherence, tissue exposure, dosing frequency, toxicity, combination delivery, or access?

The safety problem deserves equal weight. Nanoparticles interact dynamically with biological systems and may acquire a new "biological identity" through adsorption of host proteins (13, 14, 21). Surface chemistry can affect cellular uptake and immunological responses, and persistent particles may create delayed effects (13, 14, 21). Consequently, nanotoxicology cannot be reduced to a generic statement that a material is "biocompatible." Studies should report composition, dimensions, surface characteristics, aggregation state, concentration, exposure duration and relevant biological endpoints.

A second major issue is reproducibility (28). Nanotechnology often produces highly sensitive formulations in which apparently small changes in synthesis can alter biological behaviour. A formulation that works under carefully controlled laboratory conditions may be difficult to reproduce at industrial scale. This challenge is

particularly relevant to the Global South because imported, technically complex formulations may create dependence on external manufacturers and specialised supply chains.

The Global South perspective also changes the meaning of "successful translation." A product can be scientifically successful yet operationally unsuitable (15, 16). For many health systems, procurement cost, storage requirements, laboratory capacity, regulatory timelines and the availability of trained personnel will influence whether a new technology can be used routinely. Research programmes should therefore incorporate these considerations before late-stage development.

The review also supports a broader shift in how antiviral nanotechnology should be evaluated. Rather than asking whether nanoparticles "work against viruses," investigators should ask which formulation solves which therapeutic problem, by what mechanism, in which population, and with what evidence of benefit relative to existing care. This framing improves scientific precision and provides a clearer pathway from proof-of-concept studies to translational research.

Strengths of the evidence base

The reviewed literature spans several nanoparticle classes and several stages of the viral life cycle. This breadth allows consistent biological themes to be identified, particularly the importance of surface properties, receptor interaction, endocytosis and intracellular delivery (10, 18, 20, 21). The inclusion of both therapeutic and diagnostic applications also shows that nanotechnology is better understood as a platform technology than as a single intervention.

The review deliberately distinguishes mechanistic plausibility from clinical effectiveness. This is a strength because much of the available evidence comes from laboratory and preclinical models. A cautious synthesis is more appropriate than treating all reported antiviral activity as equivalent.

Study limitations

This review has limitations. First, it is a narrative review and was not based on a preregistered systematic-search protocol. The source manuscript did not provide search dates, database-specific strategies, screening procedures or formal study-selection criteria; these elements cannot be reconstructed reliably from the available material. Consequently, the review may not capture the full literature and should not be interpreted as an exhaustive systematic review.

Second, the source evidence is heterogeneous. Studies differ in nanoparticle composition, size, surface engineering, assay systems, viral strains, dosing approaches and outcome measures. Direct quantitative comparison is therefore inappropriate in the absence of harmonised methods.

Third, most of the evidence discussed is preclinical. Laboratory antiviral activity can overestimate real-world effectiveness because experimental systems allow controlled concentrations and prolonged particle–virus contact that may not occur after clinical administration.

Fourth, the Global South analysis is conceptual rather than supported by dedicated cost-effectiveness, manufacturing or implementation studies within the retrieved evidence base. These questions should be addressed by future empirical research rather than inferred from technological feasibility alone.

Future directions

Future studies should prioritise reproducible nanoparticle specifications, clinically relevant exposure models and transparent reporting of physicochemical properties. Antiviral activity should be linked to pharmacokinetic and toxicological data rather than reported in isolation. Where targeting is claimed, studies should identify the relevant receptor or cellular compartment and demonstrate that targeting persists in biologically realistic environments. Translation also requires prospective assessment of manufacturing yield, batch consistency, stability, storage requirements, regulatory classification and cost. For the Global South, research partnerships should include local universities, manufacturers, regulators and health-system stakeholders so that the resulting products are designed with implementation constraints in mind (15, 16).

Clinical development should focus on clear comparative questions: whether a nanoparticle reduces toxicity, improves adherence, increases delivery to a relevant compartment, extends dosing intervals, improves vaccine performance or lowers total delivery costs. These measurable advantages are more informative than claims of novelty based solely on nanoscale formulation.

Conclusion

Nanotechnology provides a flexible means of modifying the interaction between antiviral agents, viruses and host cells. Across the literature reviewed, nanoparticles have been investigated for direct virion neutralisation, inhibition of viral entry, targeted intracellular delivery, sustained drug release, vaccine development and diagnostic detection. The biological rationale is strong, particularly where conventional formulations have difficulty reaching a relevant cellular compartment or protecting a fragile therapeutic payload.

The evidence nevertheless remains predominantly experimental, and the term "nanotechnology" encompasses formulations with very different mechanisms and safety profiles. Clinical translation therefore depends on formulation-specific evidence covering efficacy, toxicity, pharmacokinetics, manufacturing consistency and regulatory quality. The most promising path is not the indiscriminate development of more nanoparticles, but the disciplined matching of a defined viral or delivery problem to a reproducible nanomedicine.

For the Global South, the test of success must include affordability, local or regional manufacturing potential,

regulatory feasibility, health-system fit and equitable access (15, 16). Addressing these factors early would increase the likelihood that advances at the virus–cell interface can become useful interventions rather than remaining laboratory demonstrations.

Abbreviations

ART: antiretroviral therapy
HBV: hepatitis B virus
HCV: hepatitis C virus
HIV: human immunodeficiency virus
LNP: lipid nanoparticle
NP: nanoparticle
PLGA: poly lactic-co-glycolic acid
RNAi: RNA interference
SARS-CoV-2: severe acute respiratory syndrome coronavirus 2

Declarations

Ethics Approval and Consent for Participation: Not applicable. This article is a narrative review of published literature and did not involve human participants, identifiable human data, animals, or primary data collection.

Data Availability: No datasets were generated or analysed during this review. The supporting literature is identified in the reference list, and further bibliographic clarification can be obtained from the corresponding author upon reasonable request.

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