Journal of Advances in Drug Research

ISSN: 2230-7761
www.jadr.co.in

Volume 17, Issue 04 | Received 16.09.2026 | Accepted 17.09.2026 | Online 21.09.2026

DEVELOPMENT OF STIMULI-RESPONSIVE NANOCARRIERS FOR CONTROLLED DRUG RELEASE

Dr. Lucas M. Reynolds
Department of Molecular and Cellular Biology,
Center for Advanced Biomedical Studies, USA
lucas.reynolds@example.org

Abstract.

Stimuli-responsive nanocarriers are engineered delivery systems that translate disease-associated biochemical signals or externally applied physical energy into controlled changes in carrier structure, permeability, charge, or chemical bonding. These systems are intended to reduce premature drug leakage, increase drug exposure at the desired site, and provide temporal control over therapeutic release. This structured review evaluates current strategies for pH-, redox-, reactive oxygen species (ROS)-, enzyme-, hypoxia-, temperature-, light-, ultrasound-, and magnetic-field-responsive nanocarriers, with emphasis on release mechanisms, material choices, translational advantages, and failure modes. Literature was synthesized from peer-reviewed international sources with priority given to mechanistic reviews and recent translational analyses. The evidence indicates that endogenous triggers can exploit pathological gradients without external equipment, whereas exogenous triggers provide stronger spatiotemporal control but depend on energy penetration and device accessibility. Multi-stimuli systems may improve selectivity, although design complexity can impair reproducibility, manufacturability, pharmacokinetic predictability, and regulatory assessment. Recent clinical-landscape analyses also show a major gap between the volume of preclinical publications and routine clinical use. Rational development should therefore prioritize a clinically meaningful trigger, robust stimulus-to-release contrast, simple and scalable chemistry, reproducible characterization, and early assessment of biodistribution and safety. Stimuli-responsive nanocarriers remain a powerful platform for precision drug delivery, but translation will depend on balancing mechanistic sophistication with pharmaceutical practicality.

Keywords: stimuli-responsive nanocarriers; controlled drug release; smart drug delivery; pH-responsive nanoparticles; redox-responsive systems; enzyme-responsive delivery; ultrasound-triggered release; nanomedicine.

1. INTRODUCTION

Conventional drug administration frequently exposes healthy tissues to pharmacologically active concentrations while failing to maintain an optimal concentration at the disease site. Nanocarriers can improve solubility, protect unstable cargos and alter circulation behavior, but passive encapsulation alone does not guarantee that a drug will be released at the correct place or time. Stimuli-responsive nanocarriers were developed to add an activation step to delivery: the carrier remains comparatively stable during

Journal of Advances in Drug Research
ISSN: 2230-7761
www.jadr.co.in
Volume 17, Issue 04 Received 16.09.2026 Accepted 17.09.2026 Online 21.09.2026

circulation and undergoes a defined physicochemical transition after encountering a selected endogenous or exogenous trigger. This concept converts local biological heterogeneity or applied energy into a drug-release signal and is a central theme of contemporary smart drug-delivery research (1,2).

The field includes a wide spectrum of carrier architectures such as polymeric nanoparticles, micelles, liposomes, lipid nanoparticles, nanogels, dendrimers, mesoporous silica particles, metallic and magnetic nanoparticles, and hybrid systems. Responsiveness is introduced through ionizable groups, cleavable linkers, thermosensitive polymers, photoswitches, gas-forming components, enzyme-labile sequences, redox-sensitive bonds or combinations of these elements. A single platform may therefore couple passive or ligand-mediated targeting with controlled activation and release (2,4).

Endogenous triggers include extracellular and intracellular pH gradients, glutathione (GSH), reactive oxygen species, disease-associated enzymes, hypoxia and ionic conditions. Their major advantage is autonomous activation in pathologic microenvironments. However, biological gradients are heterogeneous between patients and even within the same lesion, so trigger thresholds must be designed with sufficient separation from normal physiology (3,5,6). Exogenous triggers such as light, ultrasound, temperature and magnetic fields can be applied at a chosen time and location. They may offer superior temporal control, but their clinical feasibility depends on tissue penetration, device availability, dosing geometry and the risk of trigger-induced tissue injury (1,8-10).

The present article aims to synthesize design principles for stimuli-responsive nanocarriers, compare major trigger classes, evaluate controlled-release mechanisms, and identify the translational constraints that should guide next-generation development. Particular attention is given to the balance between release selectivity and pharmaceutical simplicity because increasingly complex constructs can improve laboratory responsiveness while simultaneously worsening manufacturing reproducibility and regulatory readiness (13-15).

Journal of Advances in Drug Research
ISSN: 2230-7761
www.jadr.co.in
Volume 17, Issue 04 Received 16.09.2026 Accepted 17.09.2026 Online 21.09.2026

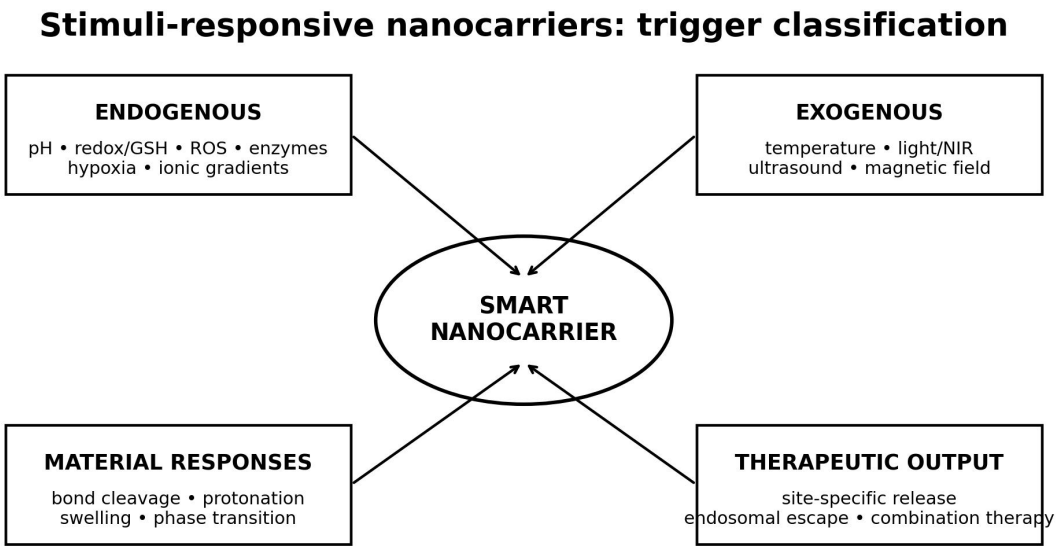


Figure 1. Conceptual classification of endogenous and exogenous stimuli used to activate smart nanocarriers. Original schematic prepared for this article.

2. MATERIALS AND METHODS

This work was designed as a structured narrative review with an IMRAD organization. The literature synthesis focused on peer-reviewed international publications describing the mechanisms, materials, biomedical applications and translational performance of stimuli-responsive nanocarriers. Priority was given to authoritative platform reviews, trigger-specific reviews and recent papers addressing clinical translation. The selected reference set spans foundational work and recent publications through 2026, thereby allowing comparison of established design principles with current translational priorities (1,15).

The analytical framework classified stimuli as endogenous (pH, redox/GSH, ROS, enzymes and hypoxia) or exogenous (temperature, light, ultrasound and magnetic fields). For each class, four attributes were evaluated: (i) biological or physical basis of the trigger; (ii) molecular mechanism that converts the trigger into carrier destabilization or cargo release; (iii) carrier formats commonly used; and (iv) limitations affecting reproducibility or clinical use. Multi-stimuli designs were assessed separately because their intended benefit is logical gating or sequential activation rather than simple sensitivity to one signal (4,13,14).

No new animal, human or laboratory experiments were performed. Figures 1 and 2 are conceptual schematics created for this article. Figure 3 reproduces only the quantitative publication share explicitly reported in the 2026 clinical-translation review: light-responsive approaches accounted for 44% of publications in the analyzed 2014–2024

Journal of Advances in Drug Research
ISSN: 2230-7761
www.jadr.co.in
Volume 17, Issue 04 Received 16.09.2026 Accepted 17.09.2026 Online 21.09.2026

landscape, and 361 clinical trials involved light-triggered approaches (15). Therefore, the diagrams should not be interpreted as experimental efficacy comparisons.

3. RESULTS

3.1. Endogenous stimulus-responsive strategies

pH-responsive nanocarriers exploit differences between physiologic pH, acidic disease microenvironments and intracellular compartments. Ionizable polymers can undergo protonation, charge reversal, swelling or loss of hydrophobic association, while acid-labile linkers can cleave after endosomal uptake. In oncology, mildly acidic extracellular tumor pH and the lower pH of endosomes and lysosomes create two potential activation stages. The main engineering problem is avoiding premature destabilization during circulation while still achieving sufficiently rapid release after the relevant pH threshold is reached (3,4).

Redox-responsive systems typically exploit differences in reducing or oxidizing conditions. Intracellular GSH can cleave disulfide bonds, whereas elevated ROS can oxidize thioethers, thioketals, boronic esters or other responsive groups. Redox-sensitive nanoplatforms can therefore combine extracellular stability with intracellular disassembly. Nevertheless, the absolute magnitude and spatial distribution of GSH and ROS are variable, making kinetic calibration essential. Excessively stable linkers may limit payload release, while overly labile linkers may compromise shelf stability or cause systemic leakage (7).

Enzyme-responsive carriers use disease-associated catalytic activity as a biochemical switch. Matrix metalloproteinases, cathepsins, phospholipases, hyaluronidase and other enzymes can cleave peptides, lipids, polysaccharides or linkers incorporated into nanosystems. Enzyme recognition offers high molecular specificity, but enzyme abundance depends on tissue type, disease stage and subcellular localization. Thus, successful design requires matching the enzyme-labile motif to both expression level and accessibility in the intended compartment (6).

Hypoxia and ROS are frequently integrated into tumor-responsive platforms because they are linked to pathologic metabolism. Hypoxia-sensitive moieties may be reduced or structurally transformed under low oxygen tension, whereas ROS-responsive carriers may cleave or become more hydrophilic after oxidative reactions. Such mechanisms can be useful in heterogeneous tumors, but the same heterogeneity can generate incomplete activation and variable exposure, especially when oxygenation changes during therapy (11,12).

Table 1. Major stimuli used in controlled-release nanocarriers and their principal mechanisms.

Stimulus	Typical trigger	Release mechanism	Common platforms	Main advantage	Key limitation
pH	Tumor acidity; endosome/lysosome	Protonation, charge switching,	Polymeric NPs, micelles,	Autonomous and compartme	Modest pH differences; variable

Journal of Advances in Drug Research
ISSN: 2230-7761
www.jadr.co.in
Volume 17, Issue 04 Received 16.09.2026 Accepted 17.09.2026 Online 21.09.2026

Stimulus	Typical trigger	Release mechanism	Common platforms	Main advantage	Key limitation
		swelling, acid-labile cleavage	liposomes	nt-specific	gradients
Redox/GSH	Intracellular reducing environment	Disulfide/diselenide cleavage; redox-sensitive destabilization	Micelles, nanogels, LNPs, prodrug NPs	Efficient intracellular release	Slow exchange kinetics or premature cleavage
ROS	Oxidative disease microenvironment	Oxidation-induced cleavage or hydrophilicity change	Polymeric and hybrid NPs	Links release to oxidative stress	ROS heterogeneity; oxidation-related instability
Enzymes	Overexpressed proteases/lipases etc.	Enzymatic cleavage of linker/shell/capping group	Silica NPs, liposomes, micelles, dendrimers	Molecular specificity	Expression varies by tissue and stage
Hypoxia	Low oxygen / bioreductive state	Reduction of hypoxia-sensitive groups	Polymeric and inorganic hybrids	Targets poorly oxygenated regions	Spatial and temporal heterogeneity
Temperature	Local hyperthermia / externally applied heat	LCST/UCST transition; membrane permeability change	Thermosensitive liposomes, polymer NPs	External timing control	Narrow thermal window; heating uniformity
Light/NIR	Externally applied photons	Photolysis, isomerization, photothermal conversion	Polymer NPs, liposomes, inorganic hybrids	High spatial precision	Penetration depth; phototoxicity
Ultrasound	Acoustic energy	Cavitation, membrane disruption, local heating	Liposomes, droplets, polymer NPs	Deep non-ionizing trigger; image guidance	Acoustic dose standardization

Journal of Advances in Drug Research
ISSN: 2230-7761
www.jadr.co.in
Volume 17, Issue 04 Received 16.09.2026 Accepted 17.09.2026 Online 21.09.2026

Stimulus	Typical trigger	Release mechanism	Common platforms	Main advantage	Key limitation
Magnetic field	Alternating/static magnetic field	Magnetic heating, motion or field-guided effects	Iron-oxide/hybrid NPs	Remote activation and guidance	Field hardware; heating control

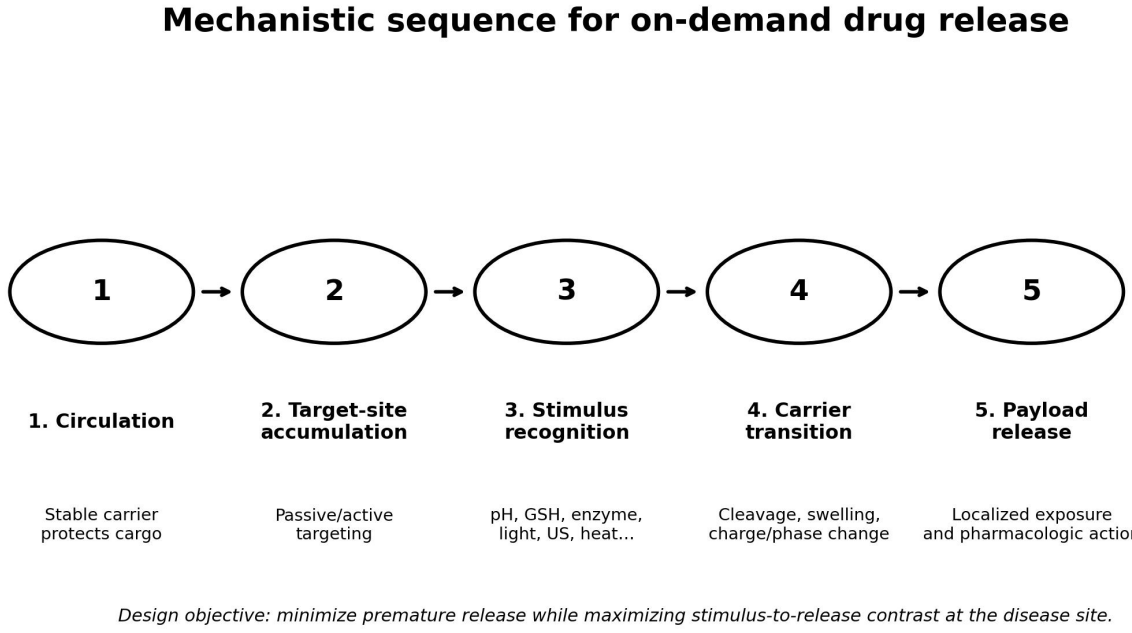


Figure 2. General mechanistic sequence from stable circulation to stimulus-triggered carrier transition and localized payload release. Original schematic prepared for this article.

3.2. Exogenous stimulus-responsive strategies

Thermoresponsive nanocarriers are often built from polymers with lower or upper critical solution temperatures (LCST or UCST). When the transition temperature is crossed, polymer hydration, conformation and self-assembly can change sufficiently to alter carrier permeability or disassemble the structure. Thermosensitive liposomes use a related principle by increasing membrane permeability in a defined thermal range. These systems are attractive when local hyperthermia can be generated, but their design must distinguish the therapeutic temperature from normal physiologic variation and avoid thermal injury (8).

Light-responsive systems offer precise spatial and temporal triggering. Photo-cleavable bonds, photoisomerization and photothermal conversion can be used to destabilize carriers or release drugs. Near-infrared (NIR) wavelengths are generally favored over ultraviolet light because of improved tissue penetration and lower photodamage; however, penetration remains limited in deep or optically inaccessible

Journal of Advances in Drug Research
ISSN: 2230-7761
www.jadr.co.in
Volume 17, Issue 04 Received 16.09.2026 Accepted 17.09.2026 Online 21.09.2026

tissues. Light-responsive approaches are nonetheless prominent in the current research landscape and are strongly represented in translational studies (9,15).

Ultrasound-activated delivery is attractive because acoustic energy can reach deeper tissues and can be coupled to diagnostic imaging. Mechanisms include stable or inertial cavitation, sonoporation, local heating and mechanical disruption of lipid or polymer structures. Microbubbles, nanodroplets and ultrasound-sensitive liposomes can therefore act as externally triggered depots. Clinical implementation requires careful control of frequency, pressure, duty cycle and local anatomy because the same variables that promote release can also influence tissue bioeffects (10).

Magnetic systems commonly incorporate iron oxide or other magnetic materials. Alternating magnetic fields can generate local heat and induce release from thermosensitive matrices, while static or gradient fields can assist localization. Their major advantage is remote activation without optical penetration constraints. Key limitations include the need for specialized hardware, control of nanoparticle heating and distribution, and careful evaluation of long-term material fate.

3.3. Multi-stimuli and sequentially activated nanocarriers

Dual- and multi-responsive systems are designed to reduce false activation by requiring two signals or to use one signal to expose a second functional component. Examples include pH/redox, pH/enzyme, redox/ROS, temperature/pH and light/pH combinations. These architectures can improve response selectivity and enable sequential processes such as tumor accumulation, charge reversal, endosomal escape and intracellular release. They can also combine therapeutic modalities, for example chemotherapy with photothermal, photodynamic or immunologic effects (5,13,14).

The theoretical advantage of additional logic must be weighed against practical complexity. Every extra responsive component introduces another synthesis step, analytical attribute, degradation product and possible source of batch variability. Multi-stimuli platforms are therefore most persuasive when each responsive element solves a defined biological bottleneck that cannot be addressed by a simpler carrier.

Table 2. Representative nanocarrier classes for stimuli-responsive drug release.

Platform	Typical cargo	Responsive design	Strength	Development concern
Polymeric nanoparticles / micelles	Hydrophobic small molecules; nucleic acids	Ionizable blocks, cleavable linkers, thermo-/photoresponsive polymers	Flexible chemistry and multistage design	Polymer heterogeneity; residual solvent; scale-up
Liposomes / lipid nanoparticles	Small molecules; RNA; proteins	pH-sensitive lipids, thermosensitive membranes,	Biocompatible compositions; clinical precedents	Leakage, oxidation, storage stability

Journal of Advances in Drug Research
ISSN: 2230-7761
www.jadr.co.in
Volume 17, Issue 04 Received 16.09.2026 Accepted 17.09.2026 Online 21.09.2026

Platform	Typical cargo	Responsive design	Strength	Development concern
		redox linkers		
Nanogels	Hydrophilic drugs; proteins	Swelling, crosslink cleavage, redox/pH response	High water content and tunable porosity	Mechanical stability; sterilization
Mesoporous silica nanoparticles	Small molecules, imaging agents	Enzyme-cleavable or pH-sensitive gates	High loading and controlled pore access	Biodegradation and long-term fate
Metallic / magnetic nanoparticles	Drugs plus imaging/thermal functions	Photothermal or magnetic activation	Theranostic functionality	Material persistence, heating and safety
Hybrid nanocarriers	Diverse combination cargos	Multiple triggers in composite structure	Combines strengths of organic/inorganic systems	High formulation complexity

3.4. Controlled-release performance and clinical translation

A useful stimuli-responsive carrier should show a high stimulus-to-background release ratio rather than merely demonstrating that release can occur after stimulation. In vitro characterization should therefore compare release under physiologically relevant triggered and non-triggered conditions and should quantify lag time, release rate, total released fraction, carrier integrity and the reversibility or irreversibility of the response. Kinetic measurements should be performed in biologically relevant media because proteins, salts and enzymatic components can modify the response observed in simple buffers.

Translation also requires reproducible particle size, dispersity, drug loading, surface chemistry, residual impurities, degradation products and sterility. Trigger parameters themselves become part of the product specification for externally activated systems. For example, light wavelength and fluence, ultrasound pressure/frequency, heating profile or magnetic-field settings can materially change both efficacy and safety. Thus, a device-dependent trigger creates a combination-product problem rather than a formulation-only problem.

A 2026 review mapping the 2014–2024 landscape analyzed more than 90,000 publications and over 1,000 clinical trials involving trigger-responsive therapeutics. Light was reported as the most prevalent external stimulus, accounting for 44% of publications and 361 trials. The same review emphasized that limited tissue penetration, device access,

Journal of Advances in Drug Research
ISSN: 2230-7761
www.jadr.co.in
Volume 17, Issue 04 | Received 16.09.2026 | Accepted 17.09.2026 | Online 21.09.2026

overly complex formulation design, economic constraints and clinical workflow remain major barriers to adoption (15).

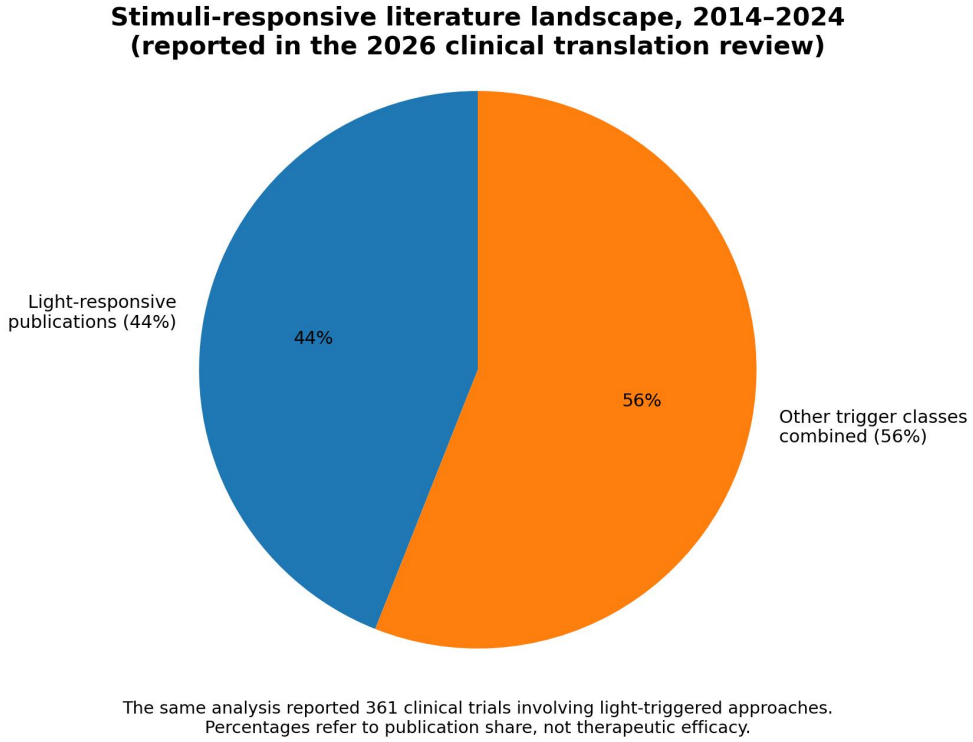


Figure 3. Publication landscape reported by Kobzev et al. (2026): light-responsive approaches represented 44% of publications in the analyzed 2014–2024 dataset; 361 clinical trials involved light-triggered approaches (15).

3.5. Release kinetics and analytical characterization

Release kinetics is a critical bridge between material responsiveness and pharmacologic usefulness. A formulation should be characterized not only by cumulative release after stimulation but also by baseline leakage, trigger threshold, activation delay, initial burst, release half-time and the fraction of cargo that remains irreversibly trapped. Depending on carrier architecture, release may be dominated by diffusion, polymer relaxation, erosion, bond cleavage, membrane permeabilization or combinations of these processes. Mechanistic interpretation is strengthened when release experiments are coupled with particle-size measurements, morphology, surface charge, chemical analysis of cleaved linkers and direct assessment of carrier integrity before and after stimulation.

Stimulus-specific assays should reproduce clinically relevant exposure. pH-responsive systems require buffered media spanning realistic extracellular and endosomal values; redox systems should be tested across plausible GSH or ROS ranges; enzyme-responsive constructs require enzyme concentrations and incubation times reflecting the intended tissue; and externally triggered carriers need a defined energy dose. Reporting only an extreme trigger condition can overestimate selectivity. A more informative dataset contains

Journal of Advances in Drug Research
ISSN: 2230-7761
www.jadr.co.in
Volume 17, Issue 04 Received 16.09.2026 Accepted 17.09.2026 Online 21.09.2026

a response curve across trigger intensity and includes a non-triggered control in serum-containing medium.

In addition to release behavior, nanocarrier characterization should address colloidal stability, drug loading, encapsulation efficiency, particle-size distribution, surface chemistry and degradation products. These parameters should be linked to the release mechanism because subtle manufacturing changes can shift the activation threshold. For translation, assay reproducibility and acceptance criteria are therefore as important as proof-of-concept responsiveness.

Table 4. Recommended analytical endpoints for development of stimuli-responsive nanocarriers.

Endpoint	Suggested measurement	Development rationale
Baseline stability	Leakage without trigger; size/PDI in biologic media	Demonstrates that circulation or storage does not activate the carrier
Trigger threshold	Release versus pH, GSH/ROS level, enzyme concentration or energy dose	Defines the therapeutic activation window
Release kinetics	Lag time, burst release, half-time, cumulative fraction	Determines onset and duration of local drug exposure
Structural response	DLS, microscopy, spectroscopy, linker cleavage analysis	Confirms the mechanism that causes release
Cargo integrity	Chemical/biological activity after release	Ensures the trigger does not damage the therapeutic payload
Reversibility	Recovery after stimulus removal, when relevant	Distinguishes switch-like from irreversible systems
Serum/protein effects	Release and colloidal behavior in protein-containing media	Detects protein-corona or ionic effects on responsiveness
Batch reproducibility	Critical quality attributes across independent batches	Supports scale-up and regulatory control

4. DISCUSSION

The major scientific value of stimuli-responsive delivery is not the carrier's ability to react, but its ability to convert a clinically relevant difference into a meaningful improvement in therapeutic exposure. Endogenous systems are convenient because they do not require an external device, yet their trigger levels are less controllable. Exogenous systems are controllable, but they shift part of the therapeutic burden to hardware,

Journal of Advances in Drug Research
ISSN: 2230-7761
www.jadr.co.in
Volume 17, Issue 04 Received 16.09.2026 Accepted 17.09.2026 Online 21.09.2026

treatment planning and tissue accessibility. Consequently, trigger selection should begin with the disease and treatment workflow rather than with material novelty (1,15).

pH-, redox- and enzyme-responsive approaches are among the most mature endogenous strategies because their mechanisms can be encoded through relatively well-defined chemical groups. However, a common weakness is that in vitro studies may use trigger conditions that exaggerate biological differences. For example, very acidic buffers, very high GSH concentrations or purified enzymes can produce impressive release curves that do not necessarily represent in vivo gradients. Translational development therefore requires threshold calibration under realistic concentrations and exposure times (3,6,7).

Exogenous triggers can provide on-demand release after the nanocarrier has reached the target. Light gives excellent spatial control but is restricted by tissue penetration; ultrasound penetrates more deeply but introduces complex acoustic variables; heat is conceptually simple but requires precise temperature control; and magnetic activation requires compatible materials and field-generating devices (8-10). The clinically optimal external trigger may therefore differ substantially by organ and indication.

Multi-stimuli systems are attractive because they can implement biological logic, but they should not be assumed to be superior simply because they are more sophisticated. Additional responsive modules increase synthetic burden and can introduce competing activation thresholds. A robust single-trigger system with strong stimulus discrimination may be more translatable than a highly complex multi-trigger construct. The 2026 translational analysis is particularly important in this regard because it argues that excessive complexity is one of the barriers separating the large research literature from routine clinical implementation (15).

Future development should incorporate quality-by-design principles from the beginning. Critical quality attributes should include particle size and distribution, morphology, encapsulation efficiency, release under triggered and baseline conditions, trigger threshold, serum stability, storage stability, degradation products and biological safety. For device-activated systems, energy-delivery parameters must be developed together with the formulation. This combined pharmaceutical and engineering strategy is necessary to make the release mechanism reproducible across laboratories, manufacturing batches and clinical sites.

Table 3. Translational challenges and practical development strategies for stimuli-responsive nanocarriers.

Challenge	Potential consequence	Recommended development strategy
Trigger heterogeneity	Variable activation and under-dosing	Define clinically relevant trigger ranges; test heterogeneous models; report threshold curves
Premature release	Systemic toxicity and reduced target exposure	Increase baseline stability; quantify release in serum/plasma; optimize linker kinetics
Overly complex	Poor reproducibility	Use the minimum number of functional

Journal of Advances in Drug Research
ISSN: 2230-7761
www.jadr.co.in
Volume 17, Issue 04 Received 16.09.2026 Accepted 17.09.2026 Online 21.09.2026

Challenge	Potential consequence	Recommended development strategy
architecture	and difficult CMC control	modules needed for a clinical purpose
Limited tissue penetration	Incomplete activation of deep lesions	Select ultrasound/magnetic/heat when optical access is inadequate; model energy deposition
Manufacturing scale-up	Changes in particle size, loading and response	Design scalable mixing/process controls early; identify critical quality attributes
Storage instability	Loss of responsiveness or cargo leakage	Stress-test temperature, oxidation and aggregation; establish protective formulation conditions
Safety of materials / degradation products	Unexpected toxicity or persistence	Prefer biodegradable components; characterize degradation pathways and long-term fate
Regulatory/device integration	Complex approval and clinical workflow	Co-develop formulation, trigger device, dosing protocol and monitoring strategy

5. CONCLUSION

Stimuli-responsive nanocarriers provide a rational route toward controlled drug release by linking therapeutic exposure to biochemical or externally applied signals. pH, redox state, ROS, enzymes and hypoxia offer autonomous endogenous activation, whereas temperature, light, ultrasound and magnetic fields provide externally programmable control. The strongest systems are those in which the chosen trigger reflects a reproducible disease characteristic or a clinically feasible energy source, and in which the carrier remains stable before activation but changes rapidly and predictably after stimulation. Multi-responsive platforms can increase selectivity, yet added complexity should be justified by a specific biological need. Future progress toward clinical use will require realistic trigger thresholds, rigorous release kinetics, scalable chemistry, integrated device–formulation development, and early evaluation of biodistribution, safety and manufacturability. The field is therefore moving from proof-of-concept responsiveness toward simpler, measurable and clinically implementable smart delivery systems.

DECLARATIONS

Conflict of interest: The author declares no conflict of interest.

Funding: No specific funding was received for this review.

Ethics statement: Not applicable; this article is based on published literature and contains no new human or animal experiments.

Data availability: No new datasets were generated.

Journal of Advances in Drug Research

ISSN: 2230-7761
www.jadr.co.in

Volume 17, Issue 04 | Received 16.09.2026 | Accepted 17.09.2026 | Online 21.09.2026

REFERENCES

1. Mura, S., Nicolas, J., & Couvreur, P. (2013). Stimuli-responsive nanocarriers for drug delivery. Nature Materials, 12(11), 991–1003. https://doi.org/10.1038/nmat3776
2. Mi, P. (2020). Stimuli-responsive nanocarriers for drug delivery, tumor imaging, therapy and theranostics. Theranostics, 10(10), 4557–4588. https://doi.org/10.7150/thno.38069
3. Shinn, J., Kwon, N., Lee, S. A., & Lee, Y. (2022). Smart pH-responsive nanomedicines for disease therapy. Journal of Pharmaceutical Investigation, 52(4), 427–441. https://doi.org/10.1007/s40005-022-00573-z
4. Zhou, W., Jia, Y., Liu, Y., Chen, Y., & Zhao, P. (2022). Tumor microenvironment-based stimuli-responsive nanoparticles for controlled release of drugs in cancer therapy. Pharmaceutics, 14(11), 2346. https://doi.org/10.3390/pharmaceutics14112346
5. Luo, S., Lv, Z., Yang, Q., Chang, R., & Wu, J. (2023). Research progress on stimulus-responsive polymer nanocarriers for cancer treatment. Pharmaceutics, 15(7), 1928. https://doi.org/10.3390/pharmaceutics15071928
6. Kapalatiya, H., Madav, Y., Tambe, V. S., & Wairkar, S. (2022). Enzyme-responsive smart nanocarriers for targeted chemotherapy: An overview. Drug Delivery and Translational Research, 12(6), 1293–1305. https://doi.org/10.1007/s13346-021-01020-6
7. Mollazadeh, S., Mackiewicz, M., & Yazdimamaghani, M. (2021). Recent advances in the redox-responsive drug delivery nanoplatforms: A chemical structure and physical property perspective. Materials Science and Engineering: C, 118, 111536. https://doi.org/10.1016/j.msec.2020.111536
8. Bordat, A., Boissenot, T., Nicolas, J., & Tsapis, N. (2019). Thermoresponsive polymer nanocarriers for biomedical applications. Advanced Drug Delivery Reviews, 138, 167–192. https://doi.org/10.1016/j.addr.2018.10.005
9. Zhao, W., Zhao, Y., Wang, Q., Liu, T., Sun, J., & Zhang, R. (2019). Remote light-responsive nanocarriers for controlled drug delivery: Advances and perspectives. Small, 15(45), e1903060. https://doi.org/10.1002/smll.201903060
10. Al Refaai, K. A., AlSawaftah, N. A., Abuwatfa, W., & Husseini, G. A. (2024). Drug release via ultrasound-activated nanocarriers for cancer treatment: A review. Pharmaceutics, 16(11), 1383. https://doi.org/10.3390/pharmaceutics16111383
11. Xia, Y., Duan, S., Han, C., Jing, C., Xiao, Z., & Li, C. (2022). Hypoxia-responsive nanomaterials for tumor imaging and therapy. Frontiers in Oncology, 12, 1089446. https://doi.org/10.3389/fonc.2022.1089446
12. Tian, M., Xin, X., Wu, R., Guan, W., & Zhou, W. (2022). Advances in intelligent-responsive nanocarriers for cancer therapy. Pharmacological Research, 178, 106184. https://doi.org/10.1016/j.phrs.2022.106184
13. Shaik, B. B., Katari, N. K., & Jonnalagadda, S. B. (2023). Internal stimuli-responsive nanocarriers for controlled anti-cancer drug release: A review. Therapeutic Delivery, 14(9), 595–613. https://doi.org/10.4155/tde-2023-0041
14. Saravanakumar, K., Hu, X., Ali, D. M., & Wang, M.-H. (2019). Emerging strategies in stimuli-responsive nanocarriers as the drug delivery system for enhanced cancer therapy. Current Pharmaceutical Design, 25(24), 2609–2625. https://doi.org/10.2174/1381612825666190709221141