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Clinical hurdles for curcumin and piperine nanoparticles in prostate cancer treatment: a bridge too far or a path to clinical reality?

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ABSTRACT

Introduction: Prostate cancer (PC) treatment is limited by resistance mechanisms and cumulative toxicities, necessitating novel therapeutic strategies. While curcumin and piperine exhibit potent anticancer properties, their clinical utility is severely compromised by poor bioavailability and rapid metabolism.

Areas covered: This review critically analyzes the preclinical and clinical landscape of curcumin and piperine nanoformulations (CPN) for the treatment of PC. We utilized PubMed and Scopus (2000–2025) to evaluate molecular mechanisms, focusing on CYP17A1 inhibition, PI3K/Akt/mTOR signaling, and ferroptosis. The report examines the physicochemical properties of nanocarriers, including PLGA and liposomes, and addresses translational barriers such as the heterogeneity of the Enhanced Permeability and Retention (EPR) effect, stromal density, and risks associated with piperine-mediated drug – drug interactions.

Expert opinion: While nano-encapsulation enhances the therapeutic index of curcumin, clinical translation remains stalled by a reliance on passive targeting and insufficient manufacturing scalability. Future success depends on shifting from 'beaker' synthesis to microfluidic production (Quality by Design) and adopting active targeting (e.g. PSMA-directed delivery) to penetrate the prostate stroma. Without these strategic pivots and biomarker-driven trials, CPNs risk remaining an academic curiosity rather than evolving into a viable clinical intervention.

PLAIN LANGUAGE SUMMARY

Can Turmeric and Black Pepper Treat Prostate Cancer? A Review of Nanotechnology's Promise and Challenges

What is the problem? Prostate cancer is one of the most common cancers in men. While treatments exist, advanced stages often become resistant to standard therapies that block male hormones (androgens). Additionally, standard chemotherapy can have severe side effects. Scientists are seeking safer, natural alternatives to combat these resistant tumors.

What is the potential solution? Curcumin (the active ingredient in turmeric) and Piperine (from black pepper) have shown powerful anti-cancer effects in laboratory tests. Curcumin can stop the tumor from making its own steroid hormones and trigger cancer cell death. Piperine helps Curcumin work better by preventing the body from breaking it down too quickly. However, there is a catch: if you simply eat these compounds, they are digested and eliminated so fast that they never reach the tumor in effective amounts.

How does nanotechnology help? To address the absorption issue, researchers package these compounds into nanoparticles, microscopic delivery vehicles composed of safe polymers or lipids. These 'Curcumin-Piperine Nanoparticles' (CPNs) protect the drug, facilitate its dissolution in the bloodstream, and deliver it directly to cancer cells.

What are the 'Hurdles' discussed in this article? This review found that while CPNs work well in mice, they are struggling to succeed in human patients for three main reasons:

1. **The 'Wall' around the tumor:** Human prostate tumors are surrounded by a dense tissue barrier (stroma). Simple nanoparticles often cannot push through this wall to reach the cancer cells.

2. **Manufacturing:** Making high-quality nanoparticles in a beaker is easy; making millions of identical, safe doses for humans is difficult and requires advanced technology like microfluidics.

3. **Safety Risks:** Piperine acts as a 'bio-enhancer,' which means it stops the liver from clearing drugs. If a patient takes CPNs alongside chemotherapy (like docetaxel), the Piperine might accidentally cause toxic levels of chemotherapy to build up in the blood.

What is the expert verdict? The authors conclude that 'passive' nanoparticles are not enough. To cross the bridge to clinical reality, future medicines must be 'active,' meaning the nanoparticles should be equipped with a GPS-like targeting system (such as PSMA ligands) to navigate through the tumor barriers. If these engineering and safety challenges are solved, CPNs could become a valuable tool for treating prostate cancer.

ARTICLE HISTORY

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KEYWORDS

Steroidogenesis; CYP17A1; prostate cancer; curcumin nanoparticles; androgen synthesis; nanoparticle formulations

Article highlights

- **Therapeutic Rationale:** Curcumin and piperine nanoformulations (CPNs) utilize a dual-mechanism approach, targeting CYP17A1-mediated androgen biosynthesis and inducing ferroptosis, potentially overcoming resistance to standard androgen deprivation therapies.
- **Bioavailability Solution:** Nanoparticle encapsulation addresses the critical limitations of free curcumin, specifically its negligible aqueous solubility and rapid hepatic metabolism, which have historically led to clinical trial failures.
- **Preclinical Model Bias:** Current efficacy data are heavily reliant on murine xenograft models that exhibit the Enhanced Permeability and Retention (EPR) effect, which is often absent or heterogeneous in the desmoplastic, stromal-rich microenvironment of human prostate tumors.
- **Safety & Interaction Risks:** Piperine, while acting as a bioenhancer, poses a quantifiable risk of Drug-Drug Interactions (DDIs) by inhibiting CYP3A4 and P-glycoprotein; this can increase the systemic exposure of co-administered taxanes by 30–60%, risking severe toxicity.
- **Manufacturing & Regulatory Barriers:** The transition from academic lab-scale synthesis to clinical application is stalled by the need for scalable, GMP-compliant manufacturing (e.g. microfluidics) that meets FDA Critical Quality Attribute (CQA) standards to ensure batch-to-batch consistency.
- **Future Directions:** Future clinical success depends on moving from passive targeting to active PSMA-directed delivery systems and implementing biomarker-driven patient stratification (e.g. PTEN status or ferroptosis sensitivity).

1. Introduction

Prostate cancer (PC) remains a major global health challenge, with limitations in current treatment options, particularly for advanced and castration-resistant forms of the disease [1,2]. While localized disease is often manageable through active surveillance, prostatectomy, or radiotherapy, the progression to metastatic castration-resistant prostate cancer (mCRPC) marks a lethal turn in the disease trajectory. The standard of care for advanced PC revolves around Androgen Deprivation Therapy (ADT), which aims to suppress the gonadal production of testosterone, the primary fuel for prostate cancer cell proliferation. However, the efficacy of ADT is invariably finite. Tumors inevitably develop resistance mechanisms, transitioning to a castration-resistant state characterized by androgen receptor (AR) amplification, mutations, and, crucially, the upregulation of intratumoral steroidogenesis enzymes that allow the cancer to synthesize its own androgens.

The limitations of current pharmacotherapy, including the significant side effect profiles of taxane chemotherapies (docetaxel, cabazitaxel) and second-generation anti-androgens (abiraterone, enzalutamide), have spurred an intense search for alternative therapeutic agents that offer high efficacy with a more favorable safety profile. Natural compounds, or phytochemicals, have garnered considerable attention in this domain [3,4]. Curcumin, the yellow pigment and principal bioactive component of turmeric, has been extensively studied for its anti-inflammatory, antioxidant, and anticancer properties. Preclinical studies have consistently shown that curcumin can downregulate AR expression, inhibit angiogenesis, and induce apoptosis in PC cells. Similarly, piperine, the pungent alkaloid found in black pepper, has demonstrated independent anticancer activity and, perhaps more importantly, the ability to function as a bioenhancer [5]. Despite this immense preclinical

promise, the translation of curcumin and piperine into clinical practice has been historically hampered by their dismal pharmacokinetic profiles. Curcumin is notorious for its poor aqueous solubility (approximately 11 ng/mL), instability at physiological pH, and rapid metabolism via hepatic glucuronidation and sulfation [6]. Oral administration of free curcumin yields negligible systemic concentrations, frequently failing to reach the threshold necessary for therapeutic activity in prostatic tissue. Piperine can partially mitigate this by inhibiting the metabolic enzymes responsible for curcumin's clearance, yet the co-administration of 'free' unencapsulated forms remains suboptimal due to asynchronous biodistribution and rapid clearance.

Nanotechnology offers a sophisticated solution to these pharmacological deficiencies. By encapsulating these bioactive agents within nanocarriers, such as polymeric nanoparticles, liposomes, or micelles, researchers aim to enhance solubility, protect the payload from premature degradation, and improve accumulation at the tumor site [7–10]. The hypothesis is that a well-engineered 'Curcumin-Piperine Nanoparticle' (CPN) system can synchronize the delivery of both agents, maximizing their synergistic potential while minimizing systemic exposure.

Recent research, including studies on the ability of curcumin and piperine nanoformulations to modulate steroidogenesis, highlights their therapeutic potential (Figure 1) [11]. However, the journey from a promising engineered nanoparticle in a petri dish to a clinically approved drug is fraught with challenges, often referred to as the 'valley of death' in drug development. This report aims to move beyond a superficial summary of 'promising results' to provide a critical, deep-dive analysis of the clinical hurdles that currently stall the progress of CPNs.

To provide a comprehensive analysis of this landscape, we conducted a systematic literature search using PubMed, Scopus, and Web of Science databases for articles published between January 2000 and November 2025. Keywords included 'Curcumin,' 'Piperine,' 'Nanoparticles,' 'Prostate Cancer,' 'CYP17A1,' 'Ferroptosis,' and 'Clinical Trials.' We prioritized studies that provided quantitative pharmacokinetic data, mechanistic insights into steroidogenesis, and those addressing specific translational barriers such as the EPR effect and manufacturing scalability. We analyzed the data regarding efficacy in human trials, the nuanced safety risks associated with piperine-mediated drug interactions, the physical barriers of the prostate tumor microenvironment that limit passive drug delivery, and the rigorous manufacturing standards required by regulatory bodies. Through this lens, we evaluate whether CPNs are indeed a viable path to clinical reality or a bridge too far.

2. The therapeutic rationale: unpacking the molecular mechanisms

The allure of curcumin and piperine nanoparticles in the context of prostate cancer stems from their multifaceted mechanisms of action and the inherent advantages offered by nanodelivery systems. One of the most compelling mechanisms recently elucidated for CPNs is their ability to interfere with androgen biosynthesis. In mCRPC, tumor cells adapt to low systemic testosterone levels by upregulating the enzyme cytochrome

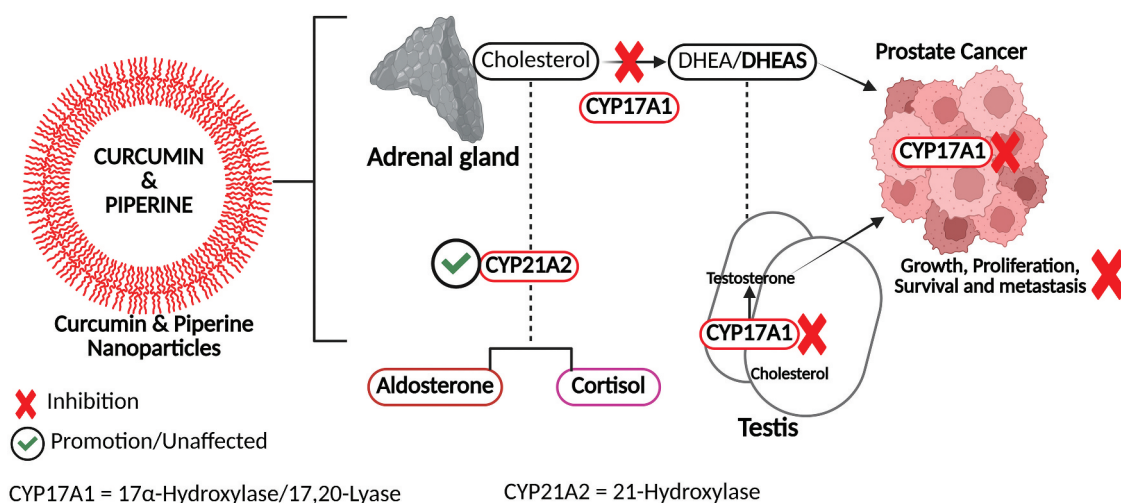


Figure 1. The dual-mechanism blockade of androgen biosynthesis by curcumin–piperine nanoparticles (CPNs). Schematic representation of the steroidogenic pathway within the endoplasmic reticulum of prostate cancer cells. Cholesterol is converted sequentially into active androgens (Testosterone and Dihydrotestosterone). The enzyme CYP17A1 serves as a critical gatekeeper, possessing both 17 α -hydroxylase and 17,20-lyase activities required for the synthesis of androstenedione from pregnenolone/progesterone. In the untreated state, upregulated CYP17A1 drives intratumoral androgen synthesis, fueling Androgen Receptor (AR) signaling. Treatment with CPNs results in the direct inhibition of CYP17A1 enzymatic activity. Curcumin occupies the active site, blocking substrate conversion, while piperine inhibits the efflux of curcumin, maintaining high intracellular inhibitory concentrations. The downstream effect is a depletion of AR ligands and suppression of tumor cell proliferation. Created in BioRender. Yakubu, J. (2025) <https://BioRender.com/o2zp211>.

P450 17A1 (CYP17A1). This enzyme possesses dual activities: 17 α -hydroxylase activity and 17,20-lyase activity, both of which are essential for the conversion of pregnenolone and progesterone into androgens like dehydroepiandrosterone (DHEA) and androstenedione [7,11].

2.1. Targeted enzyme inhibition

Preclinical evidence strongly suggests that curcumin and piperine, particularly in combination and when formulated as nanoparticles, can interfere with critical pathways driving prostate cancer progression. This is particularly relevant, as endogenous androgens play a pivotal role in the development and progression of PC. In mCRPC, tumor cells adapt to low systemic testosterone levels by upregulating the enzyme cytochrome P450 17A1 (CYP17A1). This enzyme exhibits dual activities: 17 α -hydroxylase activity and 17,20-lyase activity, both of which are crucial for the conversion of pregnenolone and progesterone into androgens, such as dehydroepiandrosterone (DHEA) and androstenedione. By targeting CYP17A1 [12,13], These nanoparticles can potentially reduce androgen levels, thereby impacting androgen receptor (AR) signaling, a key driver of prostate cancer growth.

2.1.1. Quantitative potency

In vitro assays using NCI-H295R human adrenal cells showed that curcumin nanoparticles exhibited an IC₅₀ of approximately 9.98 μ M for inhibiting 17 α -hydroxylase. While this is less potent than abiraterone on a molar basis, the inhibition is biologically significant given the high local concentrations achievable via nanoparticle delivery.

2.1.2. Selectivity profile

A critical limitation of abiraterone is its broad inhibition of steroidogenic enzymes, including CYP21A2, which leads to mineralocorticoid excess and necessitates the co-

administration of prednisone to prevent hypertension and hypokalemia. In contrast, curcumin and piperine appear to offer a more targeted inhibition profile, predominantly affecting the 17 α -hydroxylase and 17,20-lyase functions without broadly disrupting the cortisol axis to the same deleterious extent [11].

2.1.3. Synergistic suppression

The combination of curcumin and piperine in a single nanoparticle (CPN) resulted in a statistically significant reduction in downstream metabolites, specifically androstenedione and cortisol, compared to either agent alone. This suggests that the nanoformulation not only delivers the drugs but may facilitate a dual blockade of the steroidogenic pathway, directly starving the AR-positive prostate cancer cells of their requisite ligands.

2.2. Disruption of oncogenic signaling cascades

Beyond the androgen axis, prostate cancer progression relies on a network of survival signaling pathways. CPNs have been shown to exert pleiotropic effects, effectively targeting multiple sites simultaneously, a ‘polypharmacology’ approach that is challenging for cancer cells to bypass via single-point mutations.

2.2.1. The PI3K/Akt/mTOR axis

Aberrant activation of the PI3K/Akt/mTOR pathway occurs in approximately 40–50% of CRPC cases, often due to the loss of the tumor suppressor PTEN. This pathway drives cell proliferation and survival, rendering cells resistant to apoptosis (Figure 2). Curcumin nanoparticles have been shown to significantly downregulate the phosphorylation of Akt (at Ser473) and mTOR, effectively shutting down this survival signal [8]. In PC3 cells, which are PTEN-null and highly aggressive,

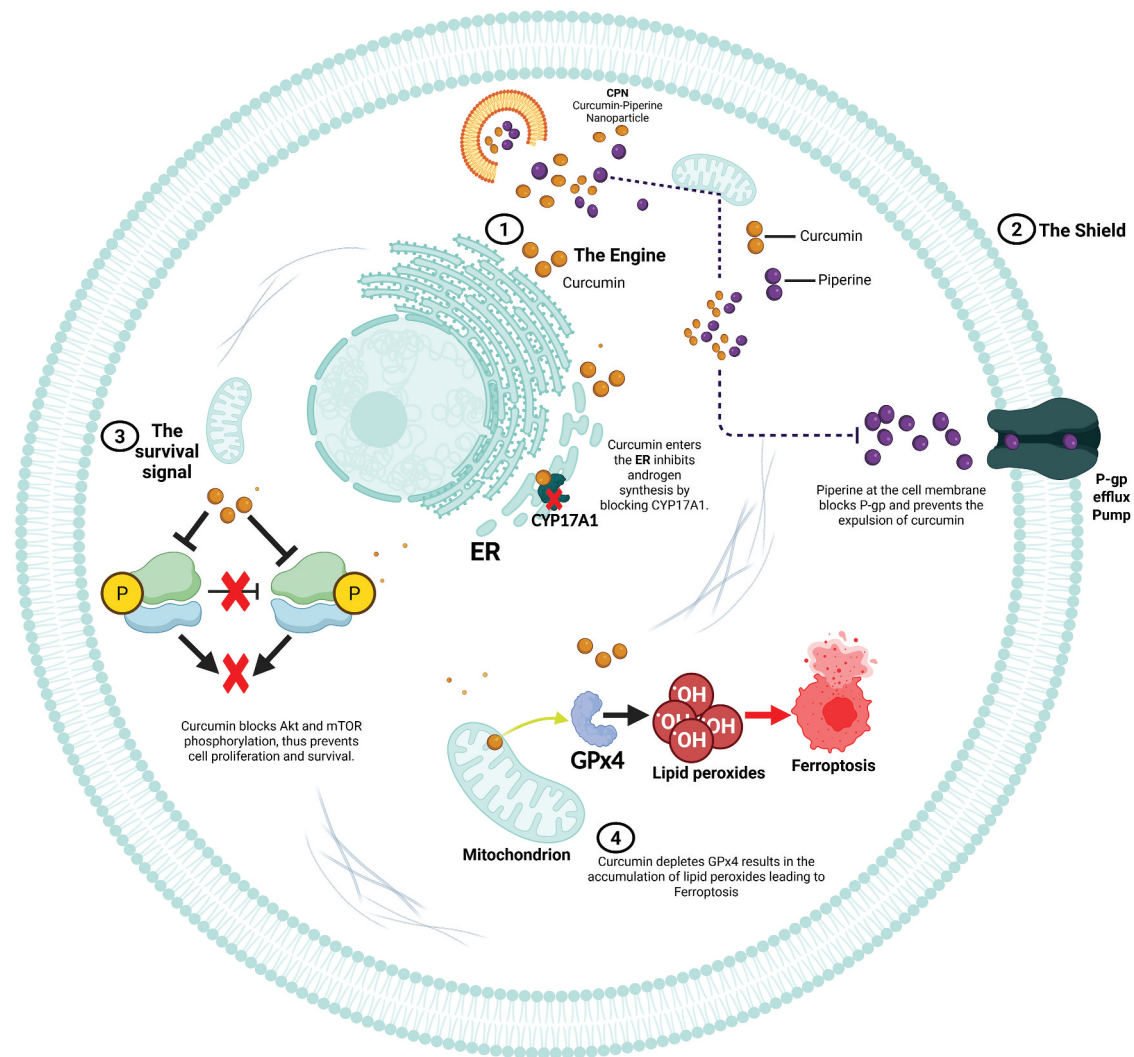


Figure 2. The integrated mechanisms by which curcumin–piperine nanoparticles (CPNs) inhibit prostate cancer beyond CYP17A1 suppression. (1) The Engine: Curcumin accumulates in the endoplasmic reticulum and inhibits CYP17A1, reducing androgen synthesis. (2) The Shield: Piperine blocks P-gp efflux pumps at the plasma membrane, preventing curcumin expulsion and increasing intracellular drug retention. (3) The Survival Signal: Curcumin inhibits phosphorylation of Akt and mTOR, downregulating pro-survival signaling pathways. (4) The Kill Switch: CPNs deplete GPx4, resulting in lipid peroxide buildup and subsequent ferroptosis. Together, these pathways form a coordinated, multi-node mechanism of prostate cancer cell inhibition. Created in BioRender. Yakubu, J. (2025) <https://BioRender.com/o2zp211>.

treatment resulted in a reduction in cell viability that correlated with the suppression of Akt phosphorylation, a result not achieved by free curcumin at equivalent doses due to poor cellular uptake.

2.2.2. Bcl-2 family modulation and apoptosis

The balance between pro-apoptotic and anti-apoptotic proteins dictates cell fate. CPNs shift this rheostat toward death. Treatment with curcumin-loaded nanoparticles has been observed to downregulate the anti-apoptotic proteins Bcl-2 and Bcl-xL, while simultaneously upregulating the pro-apoptotic effectors Bax and Bak. This disruption of the mitochondrial membrane potential leads to the release of cytochrome c and the activation of the caspase cascade (caspase-3 and caspase-9), culminating in programmed cell death (Figure 2) [14].

2.3. Emerging mechanisms: ferroptosis and autophagy

Recent research has expanded the mechanistic scope of curcumin to include non-apoptotic forms of cell death, which are particularly relevant for eradicating drug-resistant clones.

2.3.1. Ferroptosis induction

Ferroptosis is an iron-dependent form of regulated cell death characterized by the accumulation of lipid peroxides. It is distinct from apoptosis and necrosis. Curcumin has been identified as an inducer of ferroptosis in cancer cells. It operates by depleting glutathione peroxidase 4 (GPX4), a key enzyme that protects cells from oxidative damage, and by upregulating Acyl-CoA synthetase long-chain family member 4 (ACSL4), which promotes lipid peroxidation [15]. Since CRPC cells often develop resistance to apoptosis (e.g. via Bcl-2 overexpression), inducing ferroptosis

provides an alternative 'kill switch.' CPNs, by delivering high intracellular concentrations of curcumin, can overwhelm the cell's antioxidant defenses and trigger this iron-dependent death, a mechanism that is currently being explored as a way to reverse docetaxel resistance (Figure 2) [15].

2.3.2. Autophagy regulation

Autophagy acts as a double-edged sword in cancer, promoting survival under stress or leading to cell death ('autophagic cell death') if over-activated. Curcumin nanoparticles have been shown to induce autophagy in PC3 cells, evidenced by the upregulation of Beclin-1 and the conversion of LC3-I to LC3-II. Curcumin and piperine nanoparticles have been shown to reduce cancer cell viability and inhibit cell migration across various prostate cancer cell lines, including LNCaP, VCaP, DU145, and PC3 [11]. Curcumin-piperine nanoparticles (CPN) have demonstrated the highest efficacy in these studies. The anticancer effects also extend to the induction of apoptosis (programmed cell death) and cell cycle arrest, thereby directly impeding tumor growth. Interestingly, this autophagic flux can be linked to the suppression of the PI3K/Akt/mTOR pathway, which normally inhibits autophagy. In the context of CPN therapy, this massive induction of autophagy appears to exceed the cell's adaptive capacity, contributing to cytotoxicity.

Beyond these direct anticancer actions, curcumin is well-known for its potent anti-inflammatory and antioxidant properties, which can further contribute to a less favorable tumor microenvironment. Moreover, considering the recent advances in the development of novel non-steroidal anti-androgen compounds, the effect of curcumin-piperine nanoparticles can be further enhanced by combining selective CYP17A1 inhibitors in these nanoformulations [16–19].

3. Nanocarrier design and physicochemical attributes

The efficacy of curcumin and piperine is inextricably linked to the vehicle used to deliver them. 'Free' drugs are of little use if they cannot reach the target. The primary challenge hindering the clinical use of free curcumin is its poor pharmacokinetic profile, characterized by low aqueous solubility, rapid metabolism (primarily hepatic glucuronidation and sulfation), and consequently, poor bioavailability. Piperine is often co-administered with curcumin as it can inhibit enzymes involved in curcumin's metabolism, thereby increasing its systemic availability [20]. Nanoparticle formulations made from biocompatible, biodegradable, non-toxic, and non-immunogenic excipients offer a promising strategy to circumvent these limitations [21–23]. The development of nanocarriers is therefore not just a formulation exercise but a critical component of the therapeutic strategy. A summary of the physicochemical properties of various CPN formulations evaluated in prostate cancer models, highlighting the critical parameters of size, zeta potential, and drug loading that dictate biological performance, is presented in Table 1.

3.1. Polymeric nanoparticles (PLGA)

Poly(lactic-co-glycolic acid) (PLGA) remains the gold standard for biodegradable nanocarriers due to its FDA approval for

Table 1. Physicochemical properties and outcomes of curcumin/piperine nanoformulations in prostate cancer.

Nanoparticle Type	Components	Size (nm)	Zeta Potential (mV)	Drug Loading (DL)/ Encapsulation Efficiency (EE)	Model System	Key Biological Outcome	Reference
PLGA Nanoparticles	Curcumin + Piperine	202.5 ± 36.3	-30.3 ± 0.1	EE: ~73% (Cur), ~73% (Pip)	PC3, DU145, LNCaP, VCaP	Significant reduction in cell migration; inhibition of CYP17A1 steroidogenesis.	Yakubu et al. (2025) [11]
PLGA-PSMA NPs	Curcumin + PSMA Ab	~150–200	-28.0	EE: ~90%	C4-2 Xenografts	Active targeting resulted in superior tumor accumulation and regression compared to non-targeted nanoparticles.	Yallapu et al. (2014) [8]
Lipid-Polymer Hybrid	Curcumin + Docetaxel	169.6	+35.7	High efficiency	PC3 Xenografts	Synergistic cytotoxicity, co-delivery overcame resistance mechanisms.	Yan et al. (2016) [24]
Calcium alginate	Curcumin + Resveratrol	45–60	-22.01 ± 2.17	Cur 49.3 ± 4.3 Res 71.0 ± 6.1%	DU-145	Combination therapy significantly decreased prostatic adenocarcinoma incidence.	Saralkar et al. (2017) [25]
Liposomes	Curcumin + Resveratrol	100–150	N/A	N/A	PTEN Knockout Mice	Combination therapy significantly decreased prostatic adenocarcinoma incidence.	Narayanan et al. (2009) [26]

human use and controllable hydrolysis rates. The data indicate that PLGA nanoparticles co-loaded with curcumin and piperine typically fall within the 150–200 nm size range [11]. This size is theoretically optimal for passive tumor accumulation via the EPR effect (discussed in Section 6.1), as it is large enough to avoid renal filtration (< 10 nm) but small enough to extravasate through leaky tumor capillaries. The negative zeta potential (~-30 mV) observed in these formulations is crucial for colloidal stability, as it prevents particle aggregation through electrostatic repulsion. However, a highly negative charge can also repel interaction with the negatively charged cell membrane, which is why surface modification or active targeting ligands (like PSMA antibodies) are often employed to facilitate uptake [27].

3.2. Lipid-based and hybrid systems

Lipid-based carriers, such as liposomes and solid lipid nanoparticles (SLNs), offer the advantage of mimicking biological membranes, facilitating fusion and intracellular delivery provide excellent biocompatibility, but they often exhibit poor storage stability [28]. Lipid-polymer hybrid nanoparticles (LPNs) combine the structural integrity of polymers with the biocompatibility of lipids. Yan et al. demonstrated that LPNs could co-encapsulate the hydrophobic drug docetaxel with curcumin [24]. Interestingly, these particles exhibited a *positive* zeta potential (+35.7 mV), likely due to the specific lipid composition or surface coating (Table 1). While positive charges enhance interaction with cell membranes, they can also lead to nonspecific binding with serum proteins (opsonization) and rapid clearance by the immune system, a trade-off that requires careful balancing during formulation design [29].

Encapsulating curcumin and piperine within nanoparticles can significantly enhance their solubility and protect them from premature degradation and rapid metabolism [8,22,30–33]. This protection enables a higher bioavailability of the bioactive compounds in tumor tissues. Moreover, nanoparticles can improve cellular uptake. The size, surface properties, and composition of nanoparticles can be engineered to facilitate their passage across biological barriers and promote internalization by cancer cells, potentially through the enhanced permeability and retention (EPR) effect often observed in tumor vasculature [34]. This passive targeting, coupled with the potential for active targeting by functionalizing nanoparticles with specific ligands, can lead to preferential accumulation in tumor sites, thereby increasing therapeutic efficacy while minimizing exposure and potential damage to healthy tissues. Some formulations also aim for sustained release and prolonged circulation times, ensuring that the therapeutic agents remain active in the body long enough to exert their anticancer effects. Despite the compelling preclinical rationale, the journey of curcumin and piperine nanoparticles from the laboratory bench to the patient's bedside is fraught with significant clinical hurdles that demand rigorous investigation and innovative solutions.

4. Preclinical efficacy: the evidence base

The translation of CPNs is supported by a robust body of preclinical evidence demonstrating efficacy across *in vitro*

and *in vivo* models. However, interpreting this data requires understanding the nuances of the models used.

4.1. *In vitro* sensitivity and cell line specificity

The evaluation of Curcumin-Piperine Nanoparticles (CPNs) has relied heavily on a panel of immortalized cell lines that recapitulate distinct pathological stages of prostate cancer progression. The validity of these preclinical findings hinges on the specific genomic and phenotypic characteristics of the models employed. The vast majority of studies utilize the LNCaP, PC3, and DU145 cell lines, which form the gold standard triad for prostate cancer research [35].

LNCaP cells, derived from a lymph node metastasis, retain androgen receptor (AR) expression and PSA secretion [36]. They display a CD44^{low}/CD133^{low} phenotype. This makes them an ideal model for androgen-sensitive disease, where the CYP17A1-inhibitory mechanism of curcumin is most relevant. Efficacy in this model suggests potential in early CRPC where tumors still rely on the androgen axis. In contrast, PC3 and DU145 cells represent the lethal, androgen-independent phenotype (mCRPC). PC3 cells, derived from a bone metastasis, are AR-negative and typically PTEN-null [37]. They express high levels of CD44 (CD44^{high}/CD133^{low}), correlating with a stem-like, aggressive metastatic potential. DU145 cells, derived from brain metastasis, are also AR-negative but harbor distinct mutations. In these models, the efficacy of CPNs is not mediated by CYP17A1 inhibition but rather through alternative pathways, primarily the inhibition of the PI3K/Akt/mTOR survival cascade (highly active in PTEN-null PC3 cells) and the induction of ferroptosis [38].

This distinction is critical because the mechanism of CPN efficacy is context-dependent. A robust CPN formulation must demonstrate efficacy across these diverse phenotypes, targeting androgen synthesis in LNCaP-like tumors and survival signaling in PC3-like metastases, to be considered a viable candidate for the heterogeneous landscape of clinical prostate cancer [11]. The combination of curcumin and piperine in nanoparticles consistently outperforms single-agent nanoparticles. The 'Combination Index' (CI) values reported in these studies frequently fall below 1.0, indicating true synergy rather than just additive effects. This validates the hypothesis that piperine enhances curcumin's intracellular availability and efficacy [39].

4.2. *In vivo* xenograft performance

The acid test for any nanomedicine is its performance in an animal model. In C4-2 xenograft models (a model of CRPC), intratumoral or systemic administration of PLGA-curcumin nanoparticles resulted in significantly lower tumor volumes compared to free curcumin or vehicle controls [8]. Crucially, these studies often report a lack of systemic toxicity (weight loss, hematological changes), highlighting the safety advantage of the nanoparticle format.

It is important to acknowledge that most preclinical studies utilize subcutaneous xenografts, which are highly vascularized and exhibit a pronounced EPR effect. As discussed later, this may overestimate the delivery efficiency compared to the

Table 2. Ongoing and completed clinical trials of curcumin combinations in prostate cancer.

Trial ID	Phase	Intervention	Population	Endpoints	Status/Results
NCT03769766	Phase 3	Curcumin (BCM-95) vs Placebo	Low-risk Localized PC (Active Surveillance)	Primary: Disease Progression (pathologic/therapeutic) at 2 years.	[40] Recruiting https://www.clinicaltrials.gov/study/NCT03769766
NCT02724618 Saadipoor A et al.	Phase 2	Nanocurcumin (SinaCurcumin) vs Placebo	PC patients undergoing Radiotherapy	Primary: Radiation-induced cystitis/proctitis; Secondary: b-PFS.	Completed. Result: No significant difference in cystitis or tumor response [41,42]. https://clinicaltrials.gov/study/NCT02724618
NCT04731844	Phase 2	Curcumin (4g) + Piperine (5mg)	Early-stage PC/MGUS/Smoldering Myeloma	Primary: Response rate; Secondary: Progression Free Survival.	[43] Not yet recruiting https://clinicaltrials.gov/study/NCT04731844
NCT 02095717 Passildas- Jahanmohan et al.	Phase 2	Docetaxel + Curcumin (6g)	Metastatic CRPC	PSA Response: Overall Survival.	[44] Failed/Terminated. Result: No benefit over Docetaxel alone; discontinued for fertility. https://clinicaltrials.gov/study/NCT02095717

actual clinical scenario of human prostate tumors, which are often orthotopic and characterized by dense stromal barriers.

5. Clinical translation landscape

Despite the compelling preclinical rationale, the clinical translation of curcumin and piperine nanoparticles has been slow and fraught with mixed results (Table 2). A critical analysis of the clinical trial landscape reveals a disconnect between the promise seen in mice and the realities of human trials [45,46]. The most formidable barrier is the need for robust clinical validation of efficacy in human prostate cancer patients. While numerous preclinical studies showcase the potential of these nanoformulations, this success often does not translate directly to human trials. A critical lack of well-designed, large-scale Phase I, II, and III clinical trials specifically investigating curcumin and piperine nanoparticles for the persistence of prostate cancer. Although some clinical trials have explored curcumin (<https://clinicaltrials.gov/study/NCT03769766>) [40], often in combination with other agents, for various cancers, including prostate cancer, specific data on the nanoparticle formulations co-delivering curcumin and piperine remain scarce (<https://clinicaltrials.gov/study/NCT02724618>) [41,42]. One encouraging development is an ongoing Phase 2 clinical trial (<https://clinicaltrials.gov/study/NCT04731844>) exploring the use of curcumin and piperine supplementation in early-stage prostate cancer patients undergoing active surveillance, which may provide valuable insights [43].

Even with ongoing trials, defining optimal dosage and treatment regimens is a complex task [47]. Determining the most effective and safe dose, as well as the frequency of administration and the appropriate duration of treatment, requires meticulous dose-escalation and efficacy studies. Furthermore, patient selection and the development of predictive biomarkers are crucial for the effective treatment of these conditions. Not all prostate cancer patients will respond equally to this therapeutic approach. Identifying specific molecular signatures or clinical characteristics that predict a favorable response will be crucial for tailoring treatment and maximizing its benefits.

5.1. Analysis of clinical failures and ongoing efforts

The failure of the Passildas-Jahanmohan et al. trial is a pivotal learning point for the field [44]. In this study, mCRPC patients

received high-dose oral curcumin (6 g/day) in conjunction with docetaxel. Despite high compliance, the study was terminated early because the addition of curcumin showed no improvement in PSA response rates or overall survival compared to chemotherapy alone [48]. This failure strongly suggests that simple oral supplementation, even at massive doses, is insufficient to achieve therapeutic concentrations in the prostate tumor microenvironment of advanced patients. It validates the need for advanced delivery systems (nanoparticles) rather than just ‘more powder.’

The completed NCT02724618 trial, which used ‘Nanocurcumin’ (a micellar formulation) in radiotherapy patients, also failed to show a significant benefit in preventing radiation toxicity or improving biochemical progression-free survival (b-PFS) [41]. ‘Nano-sizing’ alone may not be a magic bullet. The formulation used (SinaCurcumin) acts as a micelle; however, without active targeting or specific release mechanisms, it may still suffer from insufficient accumulation in the prostate gland compared to the bladder or rectum.

5.2. The hope of active surveillance

The ongoing Phase III trial (NCT03769766) represents a strategic shift in the clinical application of these compounds. Rather than treating late-stage mCRPC (where the tumor burden is massive and resistance mechanisms are entrenched), this trial focuses on low-risk localized prostate cancer patients under active surveillance. In this setting, the goal is not rapid tumor shrinkage but rather prevention of progression. Curcumin’s anti-inflammatory and cytostatic properties may be sufficient to keep indolent tumors in check, delaying the need for radical prostatectomy or radiation. If successful, this could establish a new standard of care for the ‘watch and wait’ population, utilizing CPNs as a safe, long-term maintenance therapy.

The role of these nanoparticles in combination therapies also needs thorough investigation. Prostate cancer is often treated with a multi-modal approach, and understanding the synergistic or antagonistic interactions of curcumin and piperine nanoparticles with standard treatments like ADT, chemotherapy (e.g. docetaxel), or radiotherapy is vital. Preclinical studies combining curcumin with taxanes have shown synergistic cytotoxicity in sensitive PC3 cells, but clinical trials of curcumin with docetaxel have yielded

mixed outcomes [49,50], with one Phase II study in metastatic castration-resistant prostate cancer (mCRPC) patients showing no improvement in progression-free or overall survival when 6 g/day of oral curcumin was added to docetaxel [48]. For multiple drugs to exhibit synergism *in vivo*, it is crucial that they reach the tumor microenvironment simultaneously and in the appropriate synergistic dose ratios. While maintaining these ratios is relatively straightforward *in vitro*, achieving this scenario *in vivo* is notoriously challenging due to differences in drug solubility and biodistribution profiles. Nanoparticle-based co-delivery of drugs at synergistic dose ratios can synchronize pharmacokinetics, ensuring their simultaneous availability at the target site and in the precise concentrations required for synergistic efficacy. The authors of that study [27] also noted the need for improved formulations for *in vivo* synergism.

Finally, a key area of interest is the potential of these nanoformulations to overcome drug resistance, particularly in the context of CRPC, which represents an advanced and difficult-to-treat stage of the disease. Co-delivering multiple drugs with different molecular targets ensures that cancer cells are simultaneously exposed to all agents. This simultaneous pressure not only makes it harder for cells to survive and evolve resistance but also reverses the acquired resistance. For instance, studies suggest that curcumin nanoparticles may help restore sensitivity to drugs like docetaxel [51,52].

6. Critical hurdles to translation

The gap between preclinical success and clinical stagnation is not accidental. It is the result of specific, quantifiable hurdles that have yet to be fully addressed.

6.1. The heterogeneity of the EPR effect and stromal barriers

A fundamental weakness in the current CPN strategy is the overreliance on the Enhanced Permeability and Retention (EPR) effect (Figure 3). The EPR effect posits that nanoparticles accumulate passively in tumors due to 'leaky' blood vessels and poor lymphatic drainage [34]. While the EPR effect is robust in rapidly growing murine xenografts, it exhibits significant heterogeneity in human tumors. Clinical analyses show that the phenomenon is inconsistent, varying significantly between patients and even within different regions of the same tumor [53].

Prostate tumors are often characterized by desmoplasia, a dense, collagen-rich stromal matrix that creates high interstitial fluid pressure (IFP). This physical barrier actively resists the convective transport of nanoparticles from the blood vessel into the tumor mass [54]. Consequently, passive nanoparticles often accumulate in the perivascular space, failing to penetrate deep into the tumor to reach the cancer cells. This limitation explains why formulations that work beautifully in nude mice often fail in human trials.

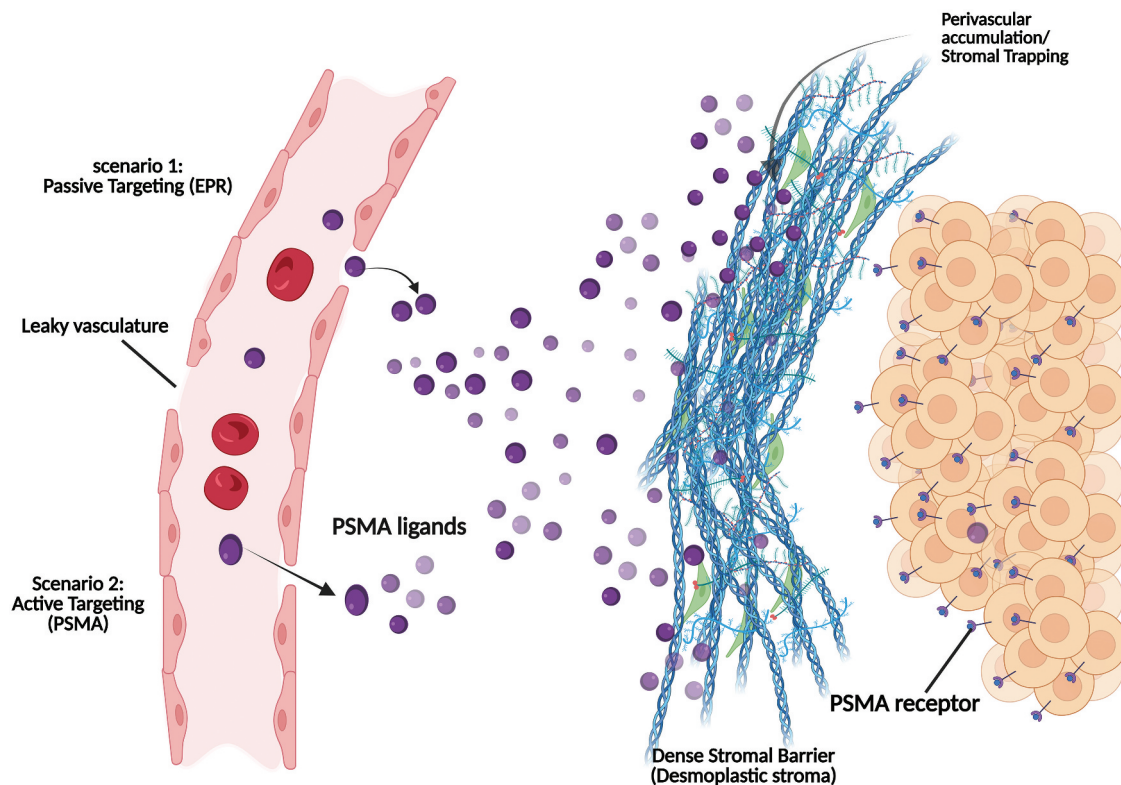


Figure 3. Overcoming the stromal barrier: passive vs. active targeting in prostate cancer. Comparison of nanoparticle transport mechanisms within the desmoplastic prostate tumor microenvironment. Conventional nanoparticles rely on the Enhanced Permeability and Retention (EPR) effect. While they extravasate through leaky tumor vasculature, their penetration is severely restricted by the dense collagen-rich stroma and high interstitial fluid pressure (IFP), leading to perivascular sequestration without reaching the tumor core. Nanoparticles functionalized with ligands targeting the Prostate-Specific Membrane Antigen (PSMA) utilize biochemical affinity to overcome physical barriers. These targeted carriers bind specifically to PSMA receptors overexpressed on PC cells, triggering receptor-mediated endocytosis. This active uptake mechanism facilitates the intracellular delivery of the payload, bypassing stromal entrapment and ensuring higher drug concentrations within the malignant cells. Created in BioRender. Yakubu, J. (2025) <https://BioRender.com/o2zp211>.

6.2. Safety and tolerability: piperine's double-edged sword

Ensuring the safety and tolerability of any new therapeutic agent is paramount. While curcumin is 'generally recognized as safe' (GRAS) by the FDA and has been used in clinical trials at high doses with minimal toxicity, in some cases, high doses have been associated with gastrointestinal disturbances such as nausea and diarrhea. In rare cases, concerns about hepatotoxicity have also been raised, though these effects are not consistently observed [55]. The addition of piperine introduces complex safety risks that are often underappreciated in the nutraceutical context but are critical in oncology. While nanoencapsulation strategies can minimize or even eliminate these side effects, they raise new questions about the long-term safety profile of the final pharmaceutical product: the curcumin- and piperine-loaded nanoparticles.

Another critical consideration is the potential for drug interactions. Prostate cancer patients, particularly those with advanced diseases or comorbidities, are often on multiple medications. Curcumin has been reported to potentially interact with cytochrome P450 enzymes or drug transporters, which could alter the pharmacokinetics and pharmacodynamics of co-administered drugs [56]. Piperine acts as a bioenhancer by inhibiting CYP3A4 (the primary drug-metabolizing enzyme in the liver) and P-glycoprotein (P-gp, the efflux pump). While this boosts curcumin levels, it indiscriminately boosts the levels of other drugs metabolized by these pathways (Figure 4) [57,58].

Preclinical studies demonstrate that co-administration of piperine with docetaxel in mice results in a 100% increase (doubling) of the docetaxel plasma Area Under the Curve (AUC) and a significant prolongation of its half-life [59]. In humans,

Physiologically Based Pharmacokinetic (PBPK) modeling predicts that a daily intake of just 20 mg of piperine can increase the Area Under the Curve (AUC) of CYP3A4 substrates (such as simvastatin, nifedipine, and cyclosporine) by 30% to 59% [57].

Prostate cancer patients are typically older men with comorbidities (cardiovascular disease, hypertension) who are on multiple medications. Furthermore, standard PC treatments, such as docetaxel and cabazitaxel, are CYP3A4 substrates. Co-administration of piperine-containing nanoparticles could inadvertently cause taxane toxicity by inhibiting their clearance, leading to severe neutropenia or neuropathy (Figure 4). This drug-drug interaction (DDI) liability must be rigorously quantified in Phase I trials before combination therapies can be deemed safe and effective.

The safety profiles of excipients and solvents used for nanoparticle preparation add another layer of complexity. Furthermore, the biodistribution of final nanoparticle formulations, their potential accumulation in healthy organs or tissues over time, and their clearance pathways must be thoroughly evaluated. The potential for inducing immunogenic reactions or inflammation should be extensively evaluated. The interaction of these nanosystems with various biological components, including proteins and cells of the immune system, needs careful characterization to avoid unintended adverse effects.

6.3. Pharmaceutical and manufacturing challenges (CMC)

Translating a promising nanoparticle formulation from a research laboratory to a clinical-grade product suitable for widespread use involves overcoming significant pharmaceutical and

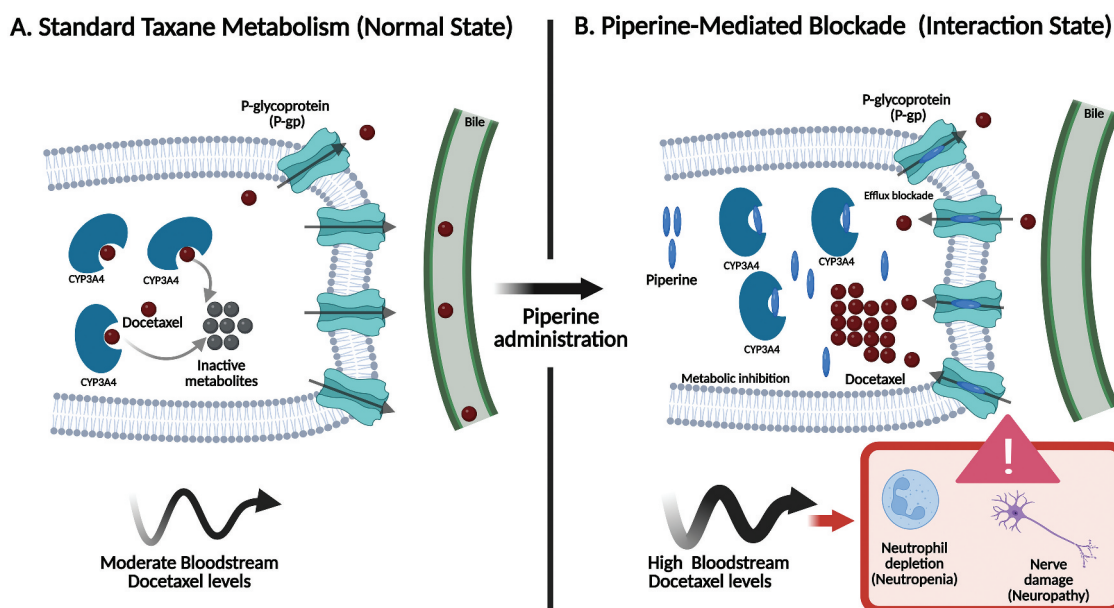


Figure 4. Mechanistic basis of piperine-taxane drug-drug interactions (DDIs). Schematic illustration of the 'Double-Edged Sword' of bioenhancement. (A) Under normal physiological conditions, taxane chemotherapies (e.g. Docetaxel, Cabazitaxel) are extensively metabolized by hepatic CYP3A4 enzymes and actively effluxed by P-glycoprotein (P-gp) transporters, limiting systemic toxicity. (B) The co-administration of piperine results in the dual blockade of these clearance pathways. Piperine acts as a potent inhibitor of both CYP3A4 and P-gp. This inhibition leads to a significant reduction in taxane clearance, causing supra-therapeutic accumulation of the chemotherapy agent in the plasma (increased AUC). While this may enhance tumor killing, it significantly elevates the risk of dose-limiting toxicities such as severe neutropenia and peripheral neuropathy, necessitating strict pharmacokinetic monitoring during combination therapy. Created in BioRender. Yakubu, J. (2025) <https://BioRender.com/o2zp211>.

manufacturing hurdles. One of the main obstacles lies in the translational gap between lab-scale method development and large-scale manufacturing, particularly under the constraints of GMP compliance [60,61]. For nanomedicine to be approved, it must be manufacturable at scale with extreme consistency and reproducibility. This Chemistry, Manufacturing, and Controls (CMC) aspect is often the downfall of academic formulations.

Additionally, unlike small molecule drugs, the efficacy and safety profiles of nanoparticles depend on their physicochemical properties, such as size, surface chemistry (e.g. PEGylation to extend circulation time), and composition, with a direct impact on biodistribution, clearance, and drug release patterns [62]. Therefore, the physicochemical and structural properties of nanoparticles should be maintained during scale-up manufacturing. Consequently, it is crucial to adopt an economically viable, robust, and scalable manufacturing technique from the earliest stages of development to ensure consistent quality and reproducibility during large-scale production. Fine-tuning these characteristics to achieve optimal delivery to prostate tumor tissue while minimizing off-target effects is an ongoing process.

Traditional 'beaker' methods of synthesis (e.g. bulk nanoprecipitation) are notoriously difficult to scale. They often suffer from batch-to-batch variability in particle size, polydispersity, and drug loading. Controlling particle size distribution effectively remains a challenge for some nanoformulations [63,64]. A deviation in size of just 50 nm can drastically alter the biodistribution and toxicity profile of the drug [11].

To overcome this, the field is moving toward microfluidic nanoprecipitation. Microfluidic devices use laminar flow in microscopic channels to mix solvents and anti-solvents with precise control over flow rates (FRR) and mixing times (Figure 5). Studies

show that microfluidic synthesis can produce PLGA nanoparticles with a narrower size distribution (lower polydispersity index) and a 30% improvement in drug loading efficiency compared to bulk methods [65]. This technology allows for the continuous production of high-quality nanoparticles that meet Good Manufacturing Practice (GMP) standards [66,67].

Regulatory agencies like the FDA now expect a Quality by Design approach [68]. This involves defining Critical Quality Attributes (CQAs), such as mean particle size (< 200 nm), zeta potential, and encapsulation efficiency, and mapping them to Critical Process Parameters (CPPs) like mixing speed, temperature, and polymer concentration [69]. Implementing QbD ensures that safety and efficacy are 'built-in' to the product, rather than just tested at the end. The stability and shelf-life of nanoparticle formulations are also crucial. Nanoparticles must remain stable and retain their physicochemical characteristics and drug content under defined storage conditions for an acceptable period [70]. This requires careful formulation development, lyophilization strategies, and stability testing [29]. Quality control and standardization are non-negotiable for any pharmaceutical product. Robust analytical methods must be established to ensure batch-to-batch consistency in terms of critical quality attributes such as particle size, size distribution, surface charge, drug encapsulation efficiency, drug loading, and *in vitro* release profiles. Any variability in these parameters can significantly impact the *in vivo* performance and therapeutic outcome [71].

6.4. Regulatory complexity and translational hurdles

Successfully navigating the complex regulatory landscape is a critical step in bringing any new drug, especially a novel nano-therapeutic, to market. Regulatory agencies like the U.S.

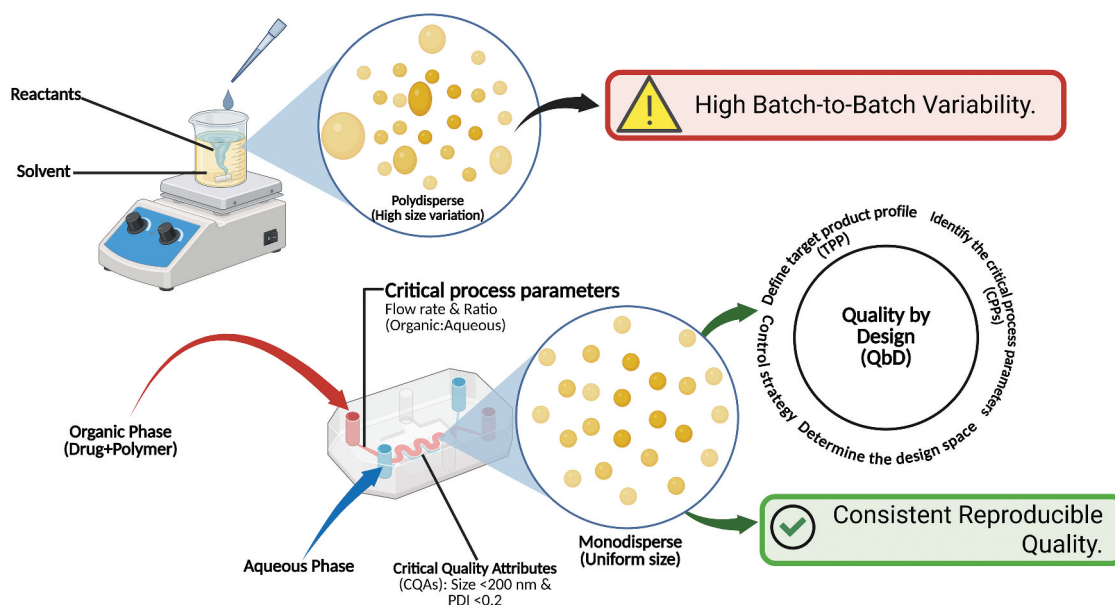


Figure 5. The traditional bulk 'beaker-based' synthesis with microfluidic, Quality-by-Design (QbD) – guided nanoparticle manufacturing. Bulk Synthesis: Mixing reactants and solvents in a batch reactor produces polydisperse particles with high batch-to-batch variability. Microfluidic Synthesis: Controlled mixing of organic (drug/polymer) and aqueous phases within microchannels allows precise regulation of critical process parameters (flow rate, phase ratio), enabling production of uniform, monodisperse nanoparticles (size < 200 nm; PDI < 0.2). The QbD framework ensures reproducibility, consistency, and predictable nanoparticle quality. Created in BioRender. Yakubu, J. (2025) <https://BioRender.com/o2zp211>.

Food and Drug Administration (FDA) and the European Medicines Agency (EMA) have specific guidelines and stringent requirements for the characterization, preclinical testing, and clinical evaluation of nanomedicines [72]. Meeting these requirements demands comprehensive data packages demonstrating safety, efficacy, and manufacturing quality.

Nanosimilars and complex generics face a higher regulatory bar. Because CPNs contain two active ingredients (curcumin and piperine), they may be classified as fixed-dose combination products. This requires demonstrating the contribution of *each* component to the overall efficacy and safety, adding high cost and complexity to the clinical trial design compared to a single-agent drug [10].

A thorough understanding of pharmacokinetics (PK) and pharmacodynamics (PD) in humans is essential. This includes characterizing the absorption, distribution, metabolism, and excretion (ADME) of both the nanoparticle carriers and the encapsulated curcumin and piperine. As previously noted, free curcumin suffers from rapid metabolism and poor absorption. While nanoparticles aim to overcome these limitations, their behavior in the human body needs to be fully elucidated through clinical PK/PD studies.

Effectively bridging the gap from promising preclinical data to tangible clinical efficacy in humans is a notorious challenge in drug development, often referred to as the valley of death. Many compounds that show remarkable activity *in vitro* cell cultures or animal models fail to deliver similar results in human clinical trials. This discrepancy can be due to species differences, the complexity of human disease, and the limitations of preclinical models in fully recapitulating the human tumor microenvironment. Most current studies on nanomedicines for prostate cancer, including those involving curcumin, are still in the preclinical phase, highlighting the long road ahead.

Finally, even with optimized formulations, there are inherent challenges in drug delivery to solid tumors like prostate cancer. These include tumor heterogeneity (different characteristics within the same tumor or between tumors in different patients), the presence of a complex and often immunosuppressive tumor microenvironment, poor vascularization in some tumor regions, and high interstitial fluid pressure, all of which can impede the efficient penetration and distribution of nanoparticles within the tumor mass.

7. Charting the course forward: strategies to overcome hurdles

Addressing these multifaceted clinical hurdles requires a concerted and strategic approach, leveraging advancements in nanotechnology, personalized medicine, and collaborative research [73]. If CPNs are to cross the bridge to clinical reality, the research strategy must evolve from 'passive encapsulation' to 'active engineering.'

7.1. From passive to active targeting

To bypass the limitations of the EPR effect and penetrate the stromal barrier, the next generation of CPNs must utilize active targeting. The field of nanomedicine is continuously evolving,

offering opportunities for more sophisticated nanocarrier designs. The development of actively targeted nanoparticles is a key strategy. This involves functionalizing the nanoparticle surface with ligands, such as antibodies, aptamers, or peptides, that specifically bind to receptors overexpressed on prostate cancer cells, like prostate-specific membrane antigen (PSMA). Such active targeting could enhance drug accumulation in the tumor and reduce off-target toxicities.

Prostate-Specific Membrane Antigen (PSMA) is highly overexpressed on the surface of prostate cancer cells (particularly in metastatic disease) but absent on most normal tissues. Conjugating nanoparticles with ligands that bind to PSMA, such as the J591 antibody or small-molecule RNA aptamers, can facilitate receptor-mediated endocytosis. Preclinical studies have demonstrated that PSMA-targeted PLGA nanoparticles exhibit an 8-fold increase in cellular internalization compared to non-targeted counterparts in LNCaP cells (Figure 3). *In vivo*, this translates to significantly higher tumor accumulation and improved regression of xenografts [74]. This shift from 'drifting' to 'homing' is essential for efficacy in human patients.

7.2. Stimuli-responsive 'smart' systems

Reducing systemic toxicity requires ensuring the drug is released *only* at the tumor site. A promising avenue is the development of stimuli-responsive nanoparticles. These smart carriers are designed to release their therapeutic payload (curcumin and piperine) specifically in response to internal or external stimuli characteristic of the tumor microenvironment (e.g. lower pH, specific enzymes, hypoxia) or applied externally (e.g. light, ultrasound, magnetic field) [75]. 'Smart' nanoparticles can be engineered to respond to the specific conditions of the tumor microenvironment (TME). Polymers that swell or degrade in the acidic pH of the tumor interstitium (pH 6.5) compared to healthy blood (pH 7.4). Linkers that are cleaved by enzymes overexpressed in PC, such as Matrix Metalloproteinases (MMPs) or Prostate-Specific Antigen (PSA) itself. This ensures the payload is dumped locally, sparing healthy organs [76].

7.3. Personalized medicine and biomarkers

The failure of 'all-comer' trials suggests that patient selection is critical. Recognizing that prostate cancer is a heterogeneous disease, a one-size-fits-all approach is unlikely to be optimal. Utilizing genomic, proteomic, and metabolomic data from individual patients can help tailor treatments. The development of companion diagnostics or predictive biomarkers will be crucial for identifying patients who are most likely to benefit from curcumin and piperine nanoparticle therapy. This would not only improve efficacy but also spare non-responders from potentially ineffective treatment and unnecessary side effects.

Clinical trials should utilize biomarkers to select patients most likely to respond. For example, patients with tumors exhibiting high CYP17A1 expression (LNCaP-like) are candidates for the steroidogenic inhibition mechanism or PTEN loss; and patients with PTEN-null tumors (like PC3) may benefit most from CPNs due to the strong inhibitory effect on the

PI3K/Akt pathway, given the specific molecular mechanisms of curcumin [77]. Emerging omics technologies could identify patients whose tumors have downregulation of GPX4 or high iron loads, predicting sensitivity to curcumin-induced ferroptosis.

7.4. Collaborative research efforts

Overcoming the complex challenges in translating nanomedicines from bench to bedside necessitates strong multidisciplinary collaborations. This includes fostering partnerships between academic researchers, clinicians specializing in prostate cancer, pharmaceutical industry experts with experience in drug development and manufacturing, and regulatory agencies. Open communication and data sharing within such consortia can accelerate progress and streamline the development pathway.

7.5. Focus on early-stage disease and prevention

While much of the focus for novel cancer therapies is on advanced disease, there may also be a role for curcumin and piperine nanoparticles in preventing prostate cancer progression or as an adjunctive therapy in early-stage disease management. Given their generally favorable safety profile, these natural compounds, when effectively delivered, could be explored in settings such as active surveillance for low-risk prostate cancer, potentially delaying or preventing the need for more aggressive interventions.

8. Conclusion

In conclusion, the bridge to clinical reality for curcumin and piperine nanoparticles is currently under construction. It requires structural reinforcement in the form of active targeting to overcome stromal barriers, safety guardrails regarding piperine's interactions, and a solid foundation of scalable, microfluidic manufacturing. If the research community can pivot from simply generating new formulations to rigorously addressing these specific translational hurdles, CPNs have the potential to evolve from a promising experimental concept into a valuable tool in the prostate cancer armamentarium.

9. Expert opinion

The exploration of curcumin and piperine nanoparticles (CPNs) for prostate cancer occupies a precarious space between nutraceutical hype and rigorous pharmacological science. While preclinical data are unequivocally promising, demonstrating the ability to target multiple oncogenic pathways and overcome the inherent pharmacokinetic limitations of free curcumin, the translation to clinical reality remains fragile. To date, no CPN regimen has impacted real-world outcomes such as overall survival or progression-free survival in prostate cancer patients. The negative results from trials involving high-dose free curcumin serve as a sobering reminder that 'natural' does not equate to 'effective' in the hostile and complex environment of metastatic

castration-resistant prostate cancer (mCRPC). However, the field is currently at a pivoted point. The shift from simple oral supplementation to sophisticated, standardized nanoformulations offers a legitimate second chance for these compounds, provided the research community addresses specific, entrenched weaknesses.

9.1. Weaknesses and the trap of passive targeting

The primary weakness in the current trajectory of CPN research is the over-reliance on the Enhanced Permeability and Retention (EPR) effect. For too long, the field has assumed that 'nano-sizing' a drug automatically ensures its accumulation in the tumor. While the EPR effect is robust in rapid-growth murine xenograft models, it exhibits significant heterogeneity in human prostate tumors. Prostate cancer is characterized by a 'cold' tumor microenvironment with significant dense desmoplasia, a collagen-rich stromal matrix that creates high interstitial fluid pressure. This physical barrier actively resists the convective transport of passive nanoparticles, causing them to accumulate in the perivascular space rather than penetrating deep into the tumor mass to reach the androgen-dependent cells. Continuing to push 'passive' PLGA or liposomal formulations into clinical trials without addressing this stromal barrier is a strategy likely to fail. The solution lies in precision engineering: the field must move decisively toward ligand-targeted systems. The integration of Prostate-Specific Membrane Antigen (PSMA) ligands onto the surface of CPNs is not merely an enhancement; it is a prerequisite for overcoming the stromal transport barrier. PSMA-targeted carriers utilize receptor-mediated endocytosis to actively internalize the payload, bypassing the limitations of passive diffusion.

9.2. The safety paradox of piperine

A further critical hurdle that is frequently underappreciated is the safety profile of piperine in the context of combination therapy. In the nutraceutical sector, piperine is lauded as a 'bioenhancer.' However, in clinical oncology, this bioenhancement comes at a cost. Piperine achieves its effect largely by inhibiting CYP3A4 and P-glycoprotein. In an elderly prostate cancer population, where polypharmacy is the norm, this presents a severe risk of drug-drug interactions (DDIs). Standard-of-care agents such as docetaxel and cabazitaxel are sensitive CYP3A4 substrates (Figure 6). The co-administration of piperine-containing nanoparticles could inadvertently inhibit the clearance of these chemotherapies, leading to unpredictable and potentially fatal toxicities (e.g. severe neutropenia). Therefore, a key challenge that must be solved is the quantification of this risk. Before large-scale efficacy trials can proceed ethically, rigorous Phase I pharmacokinetic studies are required to map the magnitude of interaction between CPNs and taxanes. It may be necessary to develop 'piperine-free' nanoformulations that utilize alternative solubilization strategies (such as amorphous solid dispersions or nanocrystals) if the DDI risk proves unmanageable.

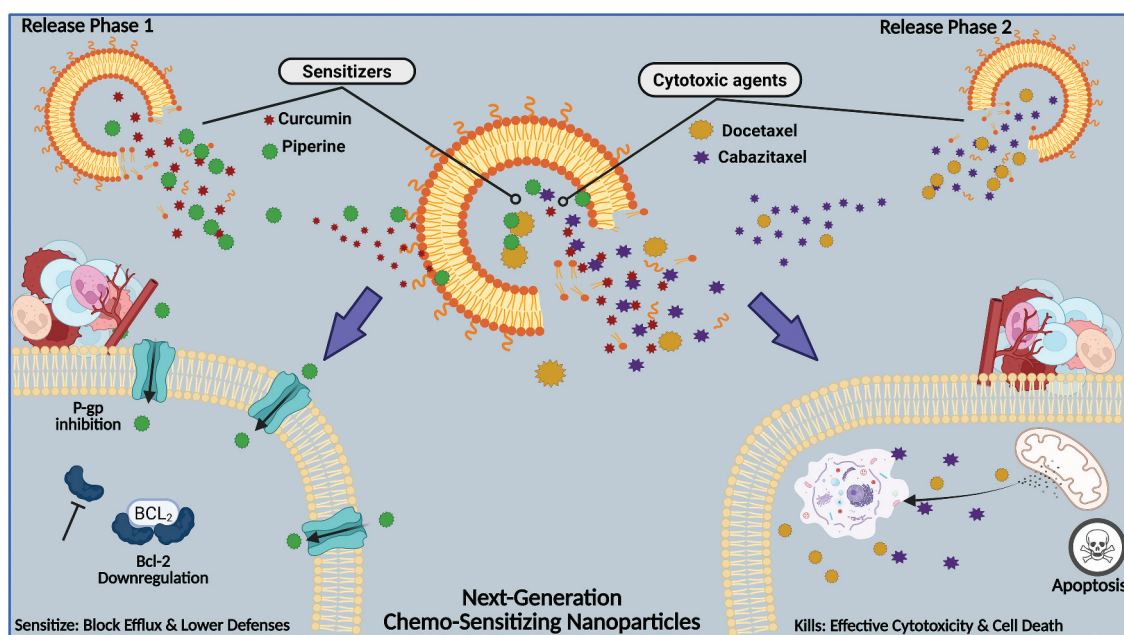


Figure 6. The 'Sensitize-then-Kill' paradigm: ratiometric co-delivery of chemotherapy and chemosensitizers. Design concept for a next-generation 'Combination Nanomedicine' aimed at reversing drug resistance in mCRPC. The nanoparticle is engineered to encapsulate both a chemosensitizer (Curcumin/Piperine) and a cytotoxic agent (Docetaxel) at a precise, synergistic molar ratio. Upon cellular internalization, the formulation is designed to rapidly release the sensitizers (Curcumin/Piperine). These agents inhibit efflux pumps (P-gp), downregulate anti-apoptotic proteins (Bcl-2), and suppress survival signaling (PI3K/Akt), effectively 'disarming' the cancer cell's defenses. The subsequent release of the cytotoxic payload (Docetaxel) strikes the sensitized cell, maximizing apoptotic death and preventing the emergence of resistant clones. This temporal and spatial synchronization is unachievable with separate oral administration. Created in BioRender. Yakubu, J. (2025) <https://BioRender.com/o2zp211>.

9.3. Manufacturing and regulatory complexity

Technical limitations in manufacturing also prevent research from advancing as it could. The 'Valley of Death' for nanomedicines often lies in the scale-up from the laboratory bench to the manufacturing plant. Many promising CPN formulations described in the literature are synthesized using bulk nanoprecipitation methods ('beaker chemistry') that are difficult to reproduce under Good Manufacturing Practice (GMP) standards. These methods often result in high batch-to-batch variability in terms of particle size and drug loading. The regulatory agencies (FDA, EMA) now demand a Quality by Design (QbD) approach. The future of this field depends on the adoption of continuous manufacturing technologies, specifically microfluidic nanoprecipitation. Microfluidics enables the precise control of mixing times and flow rates, resulting in nanoparticles with ultra-low polydispersity and consistent drug loading ratios. Without the implementation of these scalable technologies, CPNs will remain an academic curiosity, unable to meet the stringent CMC (Chemistry, Manufacturing, and Controls) requirements for a commercial pharmaceutical product.

9.4. Future evolution and ultimate goals

How will the field evolve in the future? In the next five to ten years, the standard procedure for advanced prostate cancer will likely not see CPNs replacing current anti-androgens (like enzalutamide) or taxanes. Instead, the future lies in the use of these 'botanical nanomedicines' as chemosensitizers (Figure 6). The goal is to utilize CPNs to restore sensitivity to standard therapies. The mechanisms of curcumin, specifically the downregulation of Bcl-2 and the induction of ferroptosis, are perfectly poised to counteract the resistance mechanisms that tumors develop against docetaxel.

Therefore, the future of study lies in the design of 'combination nanomedicines,' where curcumin is co-encapsulated with a chemotherapy drug in a single, ratiometric particle. This ensures that the sensitizer (curcumin) and the killer (chemotherapy) hit the cancer cell simultaneously and in the correct synergistic ratio, a feat impossible to achieve with separate oral administration. Furthermore, clinical application may shift toward earlier stages of the disease. The current 'wait and watch' or active surveillance protocols for low-risk prostate cancer offer a unique window of opportunity. In this setting, the goal is to prevent progression rather than debulk the tumor. Given the cytostatic and anti-inflammatory nature of curcumin, a daily, orally bioavailable CPN regimen could serve as a safe, long-term maintenance therapy to delay the need for radical prostatectomy or radiation. If ongoing trials in this specific population (e.g. NCT03769766) show positive results, this could redefine the standard of care for early-stage disease.

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Declarations of interest

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