

Gastroretentive Floating Tablets for Herbal Extract Delivery: Formulation Strategies, Mechanistic Design, Evaluation, and Translational Challenges

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Abstract:

Background: Herbal extracts offer therapeutic potential for gastrointestinal disorders; however, rapid gastric emptying, physicochemical instability, and variable absorption may limit their pharmaceutical and therapeutic performance. Floating gastroretentive drug delivery systems (FDDS) may prolong gastric residence and modulate the release of relevant phytoconstituents. This review critically evaluates the scientific rationale, formulation strategies, optimization approaches, characterization methods, and translational challenges associated with herbal floating tablets.

Methods: Relevant literature on herbal gastroretentive formulations, gastric physiology, floating mechanisms, formulation variables, botanical standardization, Quality-by-Design (QbD), and in-vivo evaluation was critically analyzed to examine relationships among formulation performance, gastric retention, and therapeutic outcomes.

Results: Herbal floating tablet performance is governed by extract characteristics, polymer composition, gas-generating systems, tablet architecture, porosity, and manufacturing conditions. QbD and experimental design facilitate understanding of interactions among critical material attributes, process parameters, and quality attributes. Although numerous studies report prolonged buoyancy and controlled release, substantially fewer demonstrate gastric residence using appropriate in-vivo methods, improved phytoconstituent exposure, pharmacokinetic benefit, or therapeutic superiority. Furthermore, inadequate botanical standardization and batch-to-batch phytochemical variability remain major barriers to reproducibility and translation.

Conclusion: Future development should progress beyond formulation-centric buoyancy optimization toward evidence-linked gastroretentive delivery integrating standardized botanical materials, mechanistically justified formulation design, physiologically relevant testing, in-vivo gastric-retention assessment, and comparative therapeutic evaluation. The ultimate objective is to establish clinically meaningful relationships among extract quality, gastric residence, phytoconstituent exposure, and therapeutic benefit.

Keywords: Herbal extracts; Floating tablets; Gastroretentive drug delivery; Gastric retention; Quality-by-Design; Phytoconstituents; Botanical standardization; Controlled release.

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1. Introduction

Oral administration remains the predominant route for therapeutic delivery because of its convenience, patient acceptability, manufacturing flexibility, and relatively low cost. However, gastric emptying, gastrointestinal motility, luminal pH, food intake, and transit time can substantially influence the performance of orally administered dosage forms.⁽¹⁾ These factors are particularly important for therapeutic agents requiring prolonged gastric exposure, exhibiting an upper-gastrointestinal absorption window, showing enhanced solubility under acidic conditions, or intended to provide localized gastric effects.^(2,3)

Gastroretentive drug delivery systems (GRDDS) have consequently been developed to prolong the residence of dosage forms in the stomach and modify drug release. Approaches include floating, expandable, mucoadhesive, high-density, magnetic, and raft-forming systems.⁽⁴⁾ Among these, floating drug delivery systems (FDDS) are widely investigated because they are designed to remain buoyant in gastric contents while releasing therapeutic agents.⁽⁵⁾ Effervescent systems generate gas through acid-base reactions, whereas non-effervescent systems rely on polymer hydration, swelling, gel formation, or low-density structures.⁽⁶⁾

Importantly, floating ability and gastric retention are related but not synonymous phenomena. Gastric residence is influenced by gastric motility, feeding state, meal characteristics, dosage-form dimensions, density, mechanical integrity, and gastric-emptying patterns. Therefore, in-vitro floating lag time and total floating duration should be regarded as formulation-performance parameters rather than direct evidence of prolonged gastric residence.(6,7) The application of gastroretentive technology to herbal extracts introduces additional pharmaceutical complexity. Herbal preparations are chemically heterogeneous materials whose composition may vary according to botanical identity, plant part, geographical origin, cultivation, harvesting, post-harvest processing, extraction procedures, and storage conditions.(8,9) Such variability can influence identity, purity, chemical composition, and finished-product reproducibility.(10)

Consequently, botanical authentication, analytical characterization, and standardization should be integral components of herbal pharmaceutical development. Measurement of only one or two marker compounds may inadequately represent complex herbal extracts; chromatographic fingerprinting and quantitative analysis can provide broader evidence of chemical consistency.(10,11) When incorporated into floating matrix tablets, extract characteristics and loading may influence density, porosity, hydration, swelling, matrix integrity, and release behaviour, while polymer composition governs water penetration, gel formation, diffusion, and erosion. Therefore, herbal floating-tablet performance results from interactions among extract properties, polymers, gas-generating agents, tablet architecture, and manufacturing conditions.(12)

Importantly, not every herbal extract is an appropriate candidate for gastroretentive delivery. Candidate selection should be supported by a clear therapeutic or biopharmaceutical rationale, such as localized gastric activity, favourable upper-gastrointestinal absorption, or the need for prolonged gastric exposure. Conversely, gastroretention may provide limited benefit for constituents unstable under acidic conditions or requiring absorption at distal gastrointestinal sites.(13) A major challenge is the translation gap between in-vitro formulation performance and therapeutic benefit. Numerous studies report prolonged buoyancy and controlled release, whereas substantially fewer confirm gastric residence using appropriate in-vivo methods. Even demonstrated gastric retention does not automatically establish improved bioavailability or therapeutic activity; its relevance depends on whether prolonged residence produces measurable improvement in exposure or therapeutic response.(11)

Accordingly, this review critically examines gastroretentive floating tablets for herbal extract delivery, focusing on herbal candidate selection and standardization, gastric-retention mechanisms, formulation design, optimization, evaluation, and translational challenges. Particular emphasis is placed on distinguishing in-vitro buoyancy from genuine gastroretention and identifying the evidence required to demonstrate meaningful therapeutic benefit.

2. Herbal Extracts as Candidates for Gastroretentive Delivery

2.1 Therapeutic and Biopharmaceutical Rationale

The selection of an herbal extract for gastroretentive delivery should begin with a therapeutic and biopharmaceutical justification, rather than the assumption that prolonged gastric residence is inherently advantageous. Gastroretentive systems are most rational when prolonged residence can improve local gastric exposure, extend contact with a relevant absorption region, or provide a controlled exposure profile that cannot be satisfactorily achieved using a conventional oral dosage form.(11) Herbal extracts intended for local gastric activity represent particularly suitable candidates because prolonged residence may increase the duration of contact between the dosage form and gastric mucosa. Aloe vera-containing bilayer floating tablets have been investigated for gastric-ulcer therapy, while floating tablets containing liquorice extract have similarly been developed to prolong gastric residence and sustain herbal delivery.(9,14)

A more recent floating-mucoadhesive system containing encapsulated *Gentiana lutea* root extract further illustrates how the intended therapeutic application can guide gastroretentive formulation design. (15) However, poor oral bioavailability alone should not justify gastroretentive delivery. Limited systemic exposure may result from poor dissolution, low permeability, metabolism, or chemical instability rather than insufficient gastric residence. Therefore, the critical question is whether prolonged residence in the stomach or upper gastrointestinal tract can realistically improve local activity, absorption opportunity, or phytoconstituent exposure.(12)

2.2 Physicochemical and Gastric Suitability of Herbal Extracts

Once a therapeutic rationale has been established, the physicochemical characteristics of the extract should determine whether a floating-tablet platform is feasible. Solubility influences release from hydrated polymer matrices, whereas extract loading can alter tablet density, porosity, mechanical strength, water penetration, polymer hydration, and buoyancy. Highly soluble constituents may diffuse rapidly from the matrix, while poorly soluble constituents may exhibit incomplete release unless

additional formulation strategies are incorporated.(16)

The final dosage-form structure is equally important. Recent work with *G. lutea* extract demonstrated that powder exhibiting immediate flotation showed substantially different behaviour after compression into tablets.(15) This finding highlights that powder-level properties cannot be directly extrapolated to finished-tablet performance. Compression, porosity, hydration, swelling, and matrix integrity collectively determine the behaviour of the final dosage form.

Gastric stability should also be considered during candidate selection. Prolonged gastric residence is beneficial only when relevant phytoconstituents remain sufficiently stable under gastric conditions. Acid-mediated degradation may reduce, rather than improve, therapeutic performance. Therefore, stability assessment should focus on relevant markers or bioactive constituents rather than total extract mass alone.

2.3 Herbal Extract Standardization and Formulation Compatibility

A defining challenge in herbal pharmaceutical development is the chemical complexity and variability of botanical extracts. Herbal preparations contain multiple constituents whose composition may vary according to botanical identity, geographical origin, cultivation, harvesting, processing, extraction, and storage conditions.(11,17) Such variation can influence not only therapeutic consistency but also pharmaceutical properties relevant to tablet development.

A single marker compound may provide useful quantitative control but cannot always represent the complete chemical composition of a multicomponent extract.(11) Chemical fingerprinting and chemometric analysis can therefore complement marker-based analysis by providing broader information regarding extract consistency, similarity, authenticity, and potential batch variability.(11)

This has direct implications for floating formulations. Changes in extract composition may alter extract–polymer interactions, moisture behaviour, density, swelling, matrix formation, and release. Thus, extract standardization should be treated as a formulation input variable rather than merely a post-formulation quality-control requirement. Extract–excipient compatibility is particularly important because floating matrix tablets depend on coordinated interactions between the extract, hydrophilic polymers, and gas-generating components.(18) Excessive gas generation without sufficient matrix strength may cause premature structural failure, whereas excessive polymer concentration may maintain tablet integrity but retard release. Accordingly, extract loading, polymer concentration and grade,

gas-generating capacity, tablet porosity, and compression conditions should be considered as an interacting formulation system. A QbD-based investigation of *G. lutea* gastroretentive tablets illustrates the usefulness of systematically examining formulation and process variables affecting floating behaviour and release performance.(15)

2.4 Practical Constraints and Candidate-Selection Framework

Practical feasibility should also influence herbal candidate selection. High-dose extracts may require large tablets, potentially affecting swallowing, patient acceptability, and the amount of functional excipients available for buoyancy and controlled release. This issue becomes more challenging in polyherbal formulations because multiple extracts compete for limited tablet volume. Conversely, low-dose extracts require careful content-uniformity control.

Therefore, herbal extracts should be evaluated through an integrated framework incorporating therapeutic rationale, absorption characteristics, gastric stability, solubility, dose, chemical composition, standardization, extract–excipient compatibility, buoyancy feasibility, and desired release duration. The key therapeutic, biopharmaceutical, physicochemical, and formulation considerations for selecting suitable herbal extracts for gastroretentive floating-tablet development are summarized in Table 1.

Table 1. Criteria for selecting herbal extracts for gastroretentive floating-tablet development

Selection criterion	What should be established	Why it matters	Major risk if unsuitable
Therapeutic target	Gastric/local or upper-GI therapeutic rationale	Provides justification for gastric retention	No meaningful benefit from retention
Absorption characteristics	Evidence of relevant upper-GI absorption or exposure advantage	Determines whether retention can improve exposure	Drug absorbed mainly beyond the stomach

		ure	
Gastric stability	Stability of relevant markers/bioactives in gastric conditions	Determines whether prolonged exposure is appropriate	Acid-mediated degradation
Solubility	Solubility profile of extract and relevant constituents	Determines release strategy	Incomplete or excessively rapid release
Dose	Practical dose for tablet manufacture	Determines tablet size and excipient balance	Oversized dosage form
Chemical composition	Reproducible phytochemical profile	Reduces batch-related formulation variability	Unpredictable performance
Marker/quality compounds	Validated quantitative markers where appropriate	Enables potency and batch control	Poor reproducibility

Fingerprint	Representative chromatographic/spectroscopic profile	Captures broader extract composition	Inadequate characterization
Extract – excipient compatibility	No unacceptable chemical/physical interaction	Supports reproducible matrix formation and release	Instability or altered release
Buoyancy feasibility	Suitable density, matrix integrity and gas retention	Determines whether floating can be achieved	Rapid sinking/disintegration
Desired release duration	Therapeutically justified release window	Determines matrix architecture	Unnecessarily prolonged exposure
Stability	Adequate stability during processing/storage	Ensures finished-product quality	Loss of chemical potency

3. Gastroretentive Drug Delivery: Gastric Physiology and Mechanistic Basis

3.1 Gastric Physiology and Determinants of Gastroretention

The design of gastroretentive dosage forms requires an understanding of the physiological processes governing gastric storage, mixing, propulsion, and emptying. The stomach functions as both a reservoir and a mechanically active organ that

progressively processes ingested material before transferring it to the duodenum.(6) Consequently, gastroretentive performance depends on the interaction between the dosage form and the continuously changing mechanical and hydrodynamic environment of the stomach rather than on a single formulation property.(19)

Functionally, the stomach comprises proximal and distal regions with distinct roles. The fundus and body primarily accommodate and store ingested material, whereas the antrum contributes substantially to grinding, mixing, and propulsion toward the pylorus.(6) The pylorus acts as a dynamic regulator of gastric emptying, requiring gastroretentive dosage forms to resist premature passage while maintaining sufficient mechanical integrity.(19,20)

Gastric motility differs substantially between fasted and fed conditions. During fasting, the migrating motor complex (MMC) produces cyclic motor activity, with phase III generating intense contractions that can clear residual and indigestible materials from the stomach.(6,21) Food intake interrupts this pattern and produces a different contractile environment, while meal composition and physical properties can further influence gastric emptying.(20) Therefore, the fasted and fed states should be considered physiological determinants of formulation performance rather than merely experimental variables.

3.2 Dosage-Form Properties Governing Gastric Retention

Gastric retention is influenced by dosage-form dimensions, density, structural integrity, and interaction with gastric contents. Smaller particles generally pass through the pyloric region more readily, whereas larger indigestible units may remain in the stomach until appropriate motor activity permits emptying.(20) This principle forms the basis of expandable and swelling systems, which increase their dimensions after administration to reduce premature pyloric passage.(2)

However, increasing dosage-form size is not unrestricted because the formulation must remain swallowable and eventually leave the gastrointestinal tract safely.(19) For herbal floating tablets, dimensions interact with extract loading, polymer concentration, density, and porosity.

Density is particularly important for floating systems. A dosage form with an effective density lower than the surrounding gastric fluid experiences buoyant force according to Archimedes' principle.(22) However, initial tablet density does not necessarily predict in-use performance. Following contact with gastric fluid, hydration, swelling, gas generation, gas entrapment, erosion, and changes in porosity continuously alter effective density.(23) Accordingly, dynamic buoyancy is more relevant

than initial tablet density, particularly for herbal formulations where extract properties may modify hydration, swelling, porosity, and matrix integrity.

3.3 Gastroretentive Strategies and Floating Mechanisms

Several strategies have been developed to prolong gastric residence, including floating, swelling or expandable, mucoadhesive, high-density, and magnetic systems. No single mechanism is universally superior because the optimal approach depends on the therapeutic objective, extract properties, desired residence time, formulation constraints, and physiological environment.(24)

Among these approaches, floating systems are particularly relevant to oral herbal delivery because they can combine buoyancy with controlled release. Floating systems are broadly classified as effervescent and non-effervescent. Effervescent systems incorporate gas-generating components, commonly bicarbonates and acidic agents, which generate carbon dioxide after contact with gastric fluid. The gas becomes entrapped within the hydrated matrix, reducing effective density and promoting flotation. (22,23)

Non-effervescent systems primarily depend on hydrophilic polymers that hydrate, swell, and form gel barriers capable of maintaining structural integrity while controlling release. Low-density excipients and porous or hollow structures may further promote buoyancy.(22,23) The choice of mechanism is particularly important for herbal extracts because extract composition may influence hydration, swelling, gas generation, matrix integrity, and phytoconstituent release.

3.4 Formulation Variables Controlling Floating Performance

The floating behaviour of a tablet results from interactions among multiple formulation and manufacturing variables rather than the action of a single excipient. Polymer type and concentration influence hydration, gel strength, matrix integrity, diffusion, and erosion, whereas gas-generating components determine the rate and extent of carbon dioxide generation.(22,23) Gas generation alone is insufficient; the matrix must retain the generated gas without premature structural failure.

Tablet porosity and compression conditions further influence fluid penetration, internal void formation, density, and buoyancy development.(23) In herbal formulations, extract loading adds further complexity because the extract can represent a substantial proportion of the tablet and alter density, hydration, polymer behaviour, and mechanical strength.

The overall relationship can therefore be summarized as: Herbal extract properties + excipient composition + manufacturing conditions → tablet microstructure → hydration/swelling/gas entrapment → dynamic density and mechanical

integrity → buoyancy → gastric residence → phytoconstituent release.

Thus, buoyancy should be regarded as an emergent property of the complete dosage-form system, rather than a characteristic determined solely by polymer concentration or gas generation.

4. Floating Drug Delivery Systems: Mechanisms, Classification and Formulation Design

4.1 Classification and Fundamental Mechanisms of Floating Systems

Floating drug delivery systems (FDDS) are gastroretentive platforms designed to maintain an apparent density lower than that of the surrounding gastric medium, thereby promoting buoyancy.(25) However, the objective is not simply to produce a dosage form that floats; effective systems must combine buoyancy, structural integrity, and controlled release to potentially achieve therapeutically meaningful gastric residence.(25)

Floating systems are principally classified as effervescent and non-effervescent systems according to the mechanism responsible for maintaining low apparent density. Effervescent systems generate gas after contact with gastric fluid, whereas non-effervescent systems rely primarily on polymer hydration, swelling, gel formation, porous structures, or intrinsically low-density materials.(22)

A complementary classification is based on dosage-form architecture. Single-unit systems, including floating tablets, offer relatively straightforward manufacturing and can accommodate comparatively high extract loads, whereas multiple-unit systems, such as microspheres, beads, and hollow particles, distribute the dose across several units and may reduce the consequences of individual-unit failure.(25) For herbal extracts, this choice should consider extract dose, powder flow, moisture sensitivity, chemical heterogeneity, manufacturability, and reproducibility.

4.2 Effervescent and Non-effervescent Floating Mechanisms

Effervescent floating systems generate carbon dioxide through acid–base reactions after exposure to gastric fluid. Sodium bicarbonate is commonly used alone or with acidic components such as citric or tartaric acid.(22) The generated gas becomes entrapped within the hydrated polymer matrix, reducing the effective density of the dosage form and promoting buoyancy: $\text{NaHCO}_3 + \text{H}^+ \rightarrow \text{CO}_2 \uparrow + \text{H}_2\text{O} + \text{Na}^+$

Critically, gas generation alone does not guarantee successful flotation. Carbon dioxide must be retained within the matrix for sufficient time, making gas generation and gas-retention capacity interdependent formulation variables.(25) Excessive sodium bicarbonate may accelerate gas generation but can disrupt the matrix, whereas insufficient gas generation may result in prolonged floating lag time or inadequate buoyancy. Thus,

optimization requires balancing gas generation, matrix strength, gas entrapment, and release requirements.

The importance of separating in-vitro buoyancy from actual gastric retention is demonstrated by ciprofloxacin floating tablets containing HPMC and gas-generating agents, where abdominal X-ray imaging provided direct in-vivo evidence of gastric residence.(26) Such evidence is more informative than prolonged floating alone.

In contrast, non-effervescent systems achieve buoyancy primarily through polymer hydration, swelling, gel formation, and low-density structures rather than acid–base gas generation. Hydrophilic polymers regulate water penetration, matrix swelling, diffusion, erosion, and structural integrity.(27) HPMC, polyethylene oxide, sodium alginate, xanthan gum, chitosan, pectin, carbomers, and cellulose derivatives have all been investigated for gastroretentive systems.(28)

Hydrodynamically balanced systems represent an important example in which polymer hydration forms a gel barrier while maintaining sufficiently low apparent density. Their performance depends on achieving an appropriate balance between hydration, swelling, mechanical integrity, erosion, buoyancy, and release.(25)

4.3 Polymers and Gas-generating Agents as Interacting Design Variables

Polymer selection is one of the most critical decisions in floating-tablet development because a polymer may simultaneously function as a matrix former, swelling agent, release modifier, structural support, and gas-retention environment.(27) Therefore, polymer concentration should not be interpreted solely in terms of drug-release retardation.

Polymer performance depends on molecular weight, viscosity, hydration rate, gel strength, concentration, compatibility, and interactions with other formulation components.(28) Increasing polymer concentration may strengthen the matrix and retard diffusion and erosion, but excessive polymer may also delay hydration or produce unnecessarily slow release. Conversely, insufficient polymer may accelerate release but compromise structural integrity and buoyancy.(27)

In effervescent systems, polymer hydration and gas generation are strongly coupled because the polymeric matrix provides the structural environment necessary for carbon dioxide entrapment.(22) Consequently, simply increasing sodium bicarbonate does not necessarily improve floating performance. Contemporary formulations such as effervescent neratinib floating tablets further demonstrate the importance of coordinating polymer composition, gas generation, matrix integrity, and sustained release.(29)

For herbal extracts, polymer selection becomes more complex because phytochemical composition

and extract loading may modify hydration, swelling, powder properties, matrix formation, and release. Therefore, polymer–extract compatibility should be considered a critical formulation attribute, particularly when the extract represents a substantial proportion of the tablet.

4.4 Tablet Architecture, Porosity, and Manufacturing Effects

Tablet microstructure is an important but often underestimated determinant of floating performance. Porosity influences gastric-fluid penetration, polymer hydration, gas generation, gas entrapment, apparent density, and release behaviour.(22) Excessive porosity may accelerate fluid penetration and cause premature structural failure, whereas excessive compaction can reduce hydration and delay gas generation, increasing floating lag time.

Therefore, compression force should be considered a critical process variable rather than merely a manufacturing parameter. This issue is particularly relevant for herbal extracts because particle size, moisture content, compressibility, and flow behaviour may vary between batches and alter tablet microstructure even when nominal composition remains unchanged.(30)

Single-unit tablets remain attractive because of their simplicity and capacity for relatively high extract loading. However, their performance depends on one dosage unit; premature disintegration or loss of buoyancy may compromise the intended delivery profile. Multiple-unit systems distribute the dose across several particles and may provide more distributed gastric behaviour, although manufacturing and characterization complexity are greater.(25)

Emerging architectures, including 3D-printed gastroretentive systems, provide greater control over geometry, internal voids, density distribution, and release pathways.(31) Their potential value lies not merely in technological novelty but in the possibility of independently engineering buoyancy and release. Nevertheless, evidence for their application to complex herbal extracts remains less mature than that for conventional polymeric tablets.

4.5 Floating Formulation as an Interacting System

Floating-tablet development should not be approached as simple trial-and-error optimization. The final performance results from interactions among extract properties, excipient composition, and manufacturing conditions: Herbal extract properties → particle properties, dose, moisture and compressibility → polymer/gas-generating system → compression conditions → tablet density, porosity and matrix strength → hydration, swelling and gas entrapment → buoyancy and release → potential gastric retention and therapeutic exposure. This systems-level relationship provides a strong rationale for applying Quality-by-Design (QbD)

principles to herbal floating tablets rather than optimizing individual variables independently.(32)

A major limitation in the literature is the oversimplified assumption that increasing polymer concentration automatically improves floating duration and decreases release. Polymer concentration simultaneously affects hydration, gel strength, density, swelling, diffusion resistance, and erosion.(27) Similarly, the assumption that more sodium bicarbonate necessarily produces better floating performance is scientifically inadequate because gas generation must be balanced against gas entrapment and matrix integrity.(22)

These relationships become even more complex when the active material is a chemically heterogeneous herbal extract rather than a single defined API. Extract composition may alter powder properties, tablet architecture, polymer interactions, and finished-product performance. The recent QbD-based gastroretentive formulation of encapsulated *Gentiana lutea* extract illustrates the importance of examining both formulation and process variables when developing herbal gastroretentive systems.(15)

5. Formulation Strategies for Floating Herbal Tablets: Evidence, Optimization and Critical Design Considerations

5.1 From Empirical Screening to Extract-Centred Formulation Design

The formulation of floating herbal tablets differs fundamentally from conventional floating systems containing chemically defined drugs because the herbal extract itself may substantially influence formulation behaviour. Development must simultaneously address extract variability, dose loading, matrix formation, buoyancy, controlled release, chemical stability, and reproducibility. These factors are interdependent and should not be optimized independently(33).

Early herbal floating-tablet studies largely relied on empirical screening of polymer concentrations and gas-generating agents. For example, floating tablets containing standardized liquorice extract were formulated using HPMC K100M and sodium bicarbonate, producing a floating lag time of 3.5 min and approximately 98% release within 8 h.(14) Similarly, silymarin floating formulations compared effervescent and non-effervescent systems using different grades of HPMC, Carbopol, xanthan gum, sodium alginate, and gas-generating components.(34)

These studies established important proof-of-concept evidence but also reveal a major limitation: formulation optimization was commonly based on floating duration and dissolution performance, while the mechanistic relationship between formulation variables, actual gastric retention, and therapeutic outcome remained largely unestablished. Thus, the field should move from selecting the formulation with the longest floating

duration toward identifying how extract properties and formulation variables collectively determine clinically relevant performance.(35)

This transition requires treating herbal extract loading as a critical material attribute (CMA) rather than merely the amount of active material incorporated into the tablet. Unlike low-dose synthetic drugs, herbal extracts may constitute a substantial fraction of tablet mass and consequently alter density, compressibility, porosity, hydration, and mechanical properties.(36) The recent development of gastroretentive tablets containing *Gentiana lutea* root extract provides a more advanced example. The extract was incorporated into solid lipid microparticles before tablet compression, and a QbD framework was applied to evaluate variables affecting encapsulation efficiency, powder properties, floating lag time, and gentiopicroside release.(15) This approach is significant because upstream processing of the herbal material was integrated into the final formulation-development strategy.

5.2 Coordinated Optimization of Extract Loading, Polymer Matrix and Gas Generation

The performance of a floating herbal tablet depends on interactions among extract loading, polymer characteristics, gas-generating capacity, and matrix structure. These variables should therefore not be optimized individually. Hydrophilic polymers provide hydration, gel formation, structural integrity, controlled release, and in effervescent systems—a structural environment for gas retention.(37) However, selecting a polymer solely because it produces prolonged flotation can be misleading. Recent work comparing HPMC grades demonstrated that high-viscosity HPMC 2208 provided sustained release for up to 12 h but resulted in an excessively prolonged floating lag time, whereas increasing lower-viscosity HPMC 2910 improved flotation onset while maintaining sustained-release characteristics.(38)

This demonstrates a fundamental formulation trade-off: greater matrix strength does not necessarily produce better overall performance. Highly viscous polymers may improve mechanical integrity but delay hydration and gas generation or excessively retard release.(39) Conversely, lower-viscosity polymers may promote rapid hydration and flotation but provide insufficient matrix strength. Polymer selection should therefore be based on the target combination of floating lag time, buoyancy duration, structural integrity, and phytoconstituent release.(37)

A similar interaction exists between polymer composition and gas-generating agents. Sodium bicarbonate must generate carbon dioxide sufficiently rapidly to establish buoyancy, but the hydrated matrix must retain the gas without premature structural failure. Increasing sodium bicarbonate may reduce floating lag time while

simultaneously increasing matrix erosion and altering the release mechanism.(38)

Accordingly, gas generation cannot be optimized independently of matrix integrity. Extract loading, polymer concentration, sodium bicarbonate content, tablet porosity, and compression conditions should be evaluated as interacting variables, ideally through factorial or response-surface experimental designs rather than sequential one-factor-at-a-time screening.

5.3 Material Variability, Natural Polymers and Advanced Formulation Strategies

Natural polymers provide attractive opportunities for herbal floating systems because materials such as psyllium husk, sodium alginate, xanthan gum, and related polysaccharides can contribute swelling, gel formation, viscosity enhancement, and matrix integrity. The liquorice floating-tablet formulation, for example, incorporated psyllium husk together with HPMC K100M and sodium bicarbonate.(14)

However, natural materials introduce an important reproducibility challenge. Natural polymers may vary according to botanical source, harvesting, processing, molecular characteristics, and composition. When a variable herbal extract is combined with a variable natural polymer, the formulation may experience a two-layer variability problem: Variable herbal extract + variable natural polymer → increased formulation-performance variability(7,39)

Therefore, the critical material attributes of natural polymers should be characterized rather than assuming that nominal polymer concentration adequately predicts functional performance. More sophisticated strategies may also combine multiple gastroretentive mechanisms. The *G. lutea* formulation combined floating and mucoadhesive mechanisms with encapsulated extract-containing lipid microparticles.(15) Such hybrid systems may provide complementary retention mechanisms, but increased formulation complexity also increases the number of variables requiring characterization. Therefore, hybrid systems should not automatically be considered superior. Their advantage must be demonstrated through comparative evidence showing improved gastric retention, exposure, or therapeutic performance.

Another important consideration is solubility. Gastric retention alone cannot compensate for poor dissolution of relevant phytoconstituents. Curcumin provides an illustrative example: its poor aqueous solubility and chemical instability have motivated approaches combining solubility enhancement with floating delivery. A cyclodextrin-complexed curcumin floating tablet demonstrated rapid flotation, prolonged buoyancy, and sustained release.(40)

The broader principle is therefore: When dissolution is the limiting step, solubility

enhancement and gastroretention may need to be engineered together. For complex herbal extracts, where multiple constituents may exhibit different solubility profiles, strategies such as complexation, encapsulation, lipid-based delivery, micronization, or amorphization may be justified before or alongside gastroretentive formulation.

5.4 Evidence-Based Formulation Strategies: Beyond In-Vitro Buoyancy

The strongest evidence supporting herbal floating tablets comes from studies that connect formulation performance with in-vivo gastric retention and therapeutic benefit. The *Artemisia princeps* gastroretentive floating formulation represents an important example. The optimized floating tablet demonstrated sustained release of eupatilin, while X-ray imaging in beagle dogs demonstrated gastric retention exceeding 2 h. Importantly, the floating formulation also produced greater improvement in experimentally induced gastric lesions than the non-floating control.(18)

This study provides a more meaningful chain of evidence: Herbal pharmacology → formulation design → sustained release → in-vivo gastric retention → comparative therapeutic benefit. Similarly, the gastroretentive formulation of DA-9601, a standardized *Artemisia asiatica* extract containing eupatilin and jaceosidin, demonstrated approximately 14 h of in-vitro buoyancy and more than 4 h of gastric retention in beagle dogs using radiographic evaluation. The formulation also demonstrated gastroprotective effects and supported reduced dosing frequency compared with an immediate-release formulation.(41)

These examples are substantially stronger than studies reporting buoyancy and dissolution alone because they address the critical translational question: does gastroretention provide a measurable therapeutic advantage? By contrast, studies involving liquorice, silymarin, *G. lutea*, and curcumin demonstrate different levels of technological sophistication but still vary substantially in the strength of in-vivo validation. The evidence therefore suggests a progression in the field from simple proof-of-concept floating systems toward standardized extracts, multifunctional architectures, QbD approaches, in-vivo retention studies, and comparative therapeutic evaluation.(42)

5.5 A Translational Framework for Herbal Floating-Tablet Development

Based on the available literature, formulation development should follow a structured progression rather than the traditional approach of preparing multiple formulations and selecting the one with the longest floating duration. A more defensible pathway is: Herbal material characterization → therapeutic and biopharmaceutical justification → preformulation → formulation design → QbD optimization → in-

vitro performance evaluation → translational validation

This begins with botanical authentication, extraction, chemical fingerprinting, marker quantification, and stability assessment. Candidate selection should then establish the therapeutic target, gastric stability, absorption characteristics, required residence time, and dose feasibility. Preformulation should evaluate flow, density, moisture, solubility, particle characteristics, and extract–excipient compatibility.

Formulation design should subsequently integrate polymer selection, gas-generating components, extract loading, and manufacturing conditions. QbD tools can then link the quality target product profile (QTPP) with critical quality attributes (CQAs), critical material attributes (CMAs), and critical process parameters (CPPs). Performance evaluation should extend beyond floating lag time and duration to include swelling, erosion, release kinetics, matrix integrity, and phytochemical stability.

Most importantly, promising formulations should undergo translational validation, including physiologically relevant testing, in-vivo gastric-retention assessment, pharmacokinetic or pharmacodynamic evaluation where relevant, and comparison with appropriate non-gastroretentive formulations. The critical relationships between formulation and process variables, tablet performance, and the specific evidence gaps relevant to herbal gastroretentive systems are summarized in Table 2.

Table 2. Critical evidence map of herbal and phytochemical gastroretentive floating systems: from in-vitro buoyancy to translational validation

Herbal material	Therapeutic rationale	Formulation strategy	Evidence beyond in-vitro buoyancy	Translational contribution	Critical limitation
Liquorice extract	Local gastric therapy	HPMC + psyllium + NaHCO ₃	Mainly dissolution evidence	Proof of formulation on feasibility	No in-vivo retention

Silymarin	Prolonged phytoconstituent delivery	Multiple polymer systems	Primarily in-vitro	Compared formulation architectures	Retention largely inferred
<i>Artemisiprincipes</i>	Gastroprotection	Floating tablet	X-ray retention + therapeutic comparison	Links retention with therapeutic benefit	Animal evidence
DA-9601	Gastritis/gastroprotection	Controlled-release floating tablet	X-ray retention + pharmacological evidence	Strong translation chain	Limited human evidence
<i>Gentianalutea</i>	Gastric/systemic exposure	Encapsulation + floating/mucoadhesion + QbD	Mucoadhesion and controlled release	Advanced formulation strategy	Further in-vivo validation needed
Curcumin	Gastric/peptic-ulcer application	Cyclodextrin complex + floating system	Mainly in-vitro performance	Integrates solubility and gastroretention	Therapeutic validation limited

6. Quality-by-Design, Characterization and Performance Evaluation

6.1 QbD Framework for Herbal Gastroretentive Tablet Development

The development of gastroretentive herbal tablets requires simultaneous control of extract quality, tablet integrity, buoyancy, hydration, release

behaviour, and chemical stability. Because these attributes interact, conventional one-factor-at-a-time development is poorly suited to such systems. Quality-by-Design (QbD) provides a systematic framework in which the intended product performance is prospectively defined, relevant quality attributes and risks are identified, relationships among formulation and process variables are investigated, and an appropriate control strategy is established. This approach is consistent with the principles of ICH Q8 Pharmaceutical Development, which emphasizes predefined product objectives and improved understanding of formulation and manufacturing variables.(42,43)

For herbal floating tablets, QbD should begin with a therapeutically justified Quality Target Product Profile (QTPP) rather than simply defining the product as a “floating sustained-release tablet.” The QTPP should translate the therapeutic objective into measurable requirements, including standardized herbal material, appropriate marker or fingerprint specifications, feasible dose and tablet dimensions, predefined buoyancy characteristics, therapeutically justified residence time, controlled phytoconstituent release, and acceptable chemical and physical stability.(44)

A critical point is that the desired floating duration should not be selected arbitrarily. A target of 12 or 24 h has limited scientific value unless it is connected to the therapeutic objective, gastric physiology, and intended release profile. Thus, QbD should begin with the clinical or therapeutic need and work backward toward formulation attributes, rather than beginning with a formulation and subsequently maximizing floating duration.(42) The subsequent identification of Critical Quality Attributes (CQAs), Critical Material Attributes (CMAs), and Critical Process Parameters (CPPs) should reflect this therapeutic objective. Relevant CQAs may include buoyancy, swelling, erosion, tablet integrity, density, porosity, marker-compound assay, chemical fingerprint, release profile, and stability. For herbal products, chemical identity and consistency deserve particular emphasis because marker content alone may not adequately represent a complex multicomponent extract.

6.2 Material and Process Risk: Integrating CMAs and CPPs

A floating herbal tablet should be considered an integrated material–process system. Relevant CMAs may include extract loading, extract moisture, particle-size distribution, density, polymer type and viscosity, polymer concentration, gas-generating-agent concentration, acid–base ratio, and excipient moisture. These factors may collectively influence hydration, swelling, matrix formation, gas entrapment, density, and release behaviour.(45) This issue is particularly important

for herbal formulations because the extract itself may contribute substantially to tablet mass and may exhibit batch-to-batch variation in moisture, particle characteristics, density, and chemical composition. Therefore, extract variability should not be considered only an analytical problem; it can directly affect pharmaceutical performance.

Process variables are equally important. Blending, granulation, drying, milling, residual moisture, compression force, compression speed, and dwell time can modify the final tablet microstructure. Compression force is particularly important because it can simultaneously alter porosity, density, hydration, gas generation, matrix integrity, buoyancy, and release. Experimental evidence from effervescent gastroretentive tablets demonstrates that polymer amount and compression force substantially influence tablet properties, while sodium bicarbonate significantly affects floating and release performance.(46)

Accordingly, compression force should not be treated merely as a manufacturing setting used to achieve acceptable hardness. In floating systems, it can be a genuine CPP capable of changing several CQAs simultaneously.

6.3 Risk-Based Experimental Design and Optimization

A scientifically defensible QbD strategy should begin with risk assessment before experimental design. Tools such as Ishikawa diagrams, Failure Mode and Effects Analysis (FMEA), and risk-ranking matrices can help identify material and process variables most likely to influence CQAs. The value of this approach is that DoE can then focus on variables with a scientifically justified risk basis rather than evaluating numerous factors simply because statistical software is available.(47) This is particularly relevant because floating-tablet performance results from interacting variables. Polymer concentration, gas-generating-agent content, and compression force may jointly influence tablet density, hydration, gas entrapment, floating lag time, matrix integrity, and release rate. Consequently, changing one variable while keeping all others constant can obscure important interactions.

Design-of-experiments approaches are therefore generally more informative than one-factor-at-a-time screening because they permit simultaneous investigation of multiple variables and their interactions. Studies involving gastroretentive rebamipide and metformin formulations illustrate how risk assessment and experimental design can be integrated to optimize formulation variables and establish design spaces.(47,48)

However, DoE is not inherently evidence of scientific quality. A statistically optimized formulation may still have limited value if the selected responses do not represent therapeutically relevant performance. Therefore, response selection

is as important as experimental design itself. A more robust optimization strategy should simultaneously consider buoyancy, structural integrity, swelling and erosion, phytochemical release, chemical consistency, stability, and where feasible gastric residence. No single response should dominate optimization when multiple CQAs collectively determine formulation performance.(48)

6.4 Integrated Characterization of Buoyancy, Release and Matrix Behaviour

Characterization of herbal floating tablets should extend beyond conventional hardness, friability, floating lag time, and dissolution testing. A mechanistic evaluation should investigate how the formulation behaves after contact with gastric fluid. Buoyancy testing should include both floating lag time and persistence of flotation, but these parameters should be interpreted as in-vitro performance indicators rather than evidence of actual gastric retention.(49) Structural characterization should assess swelling, erosion, matrix integrity, density or porosity where relevant, and the ability of the formulation to maintain its architecture throughout the intended release period. Dissolution testing remains essential, but conventional dissolution methods cannot reproduce the complex mechanical and hydrodynamic environment of the stomach. Therefore, dissolution performance should not be interpreted as direct evidence of gastroretention. More importantly, for herbal formulations, “drug release” should preferably be quantified using validated chemical markers or relevant phytoconstituents rather than total extract mass. This is a particularly important distinction for complex botanical extracts. Different constituents may have substantially different solubilities, diffusion rates, and interactions with the polymeric matrix. A single bulk measurement may therefore fail to describe the release behaviour of pharmacologically relevant constituents.(50)

Release-kinetic modelling can assist in comparing formulations, but the mathematical model with the best statistical fit should not automatically be presented as proof of the release mechanism. Zero-order, first-order, Higuchi, Korsmeyer–Peppas, and Weibull models are useful descriptive tools, but mechanistic interpretation should also be supported by swelling, erosion, structural analysis, and physicochemical understanding of the matrix. Thus, this review should distinguish clearly between descriptive model fitting and mechanistic evidence supporting the proposed release process.

6.5 Design Space, Control Strategy and Formulation Robustness

The ultimate objective of QbD is not simply to identify a single statistically “optimized” formulation. A stronger outcome is the establishment of a design space within which predefined CQAs remain within acceptable limits.

Studies of gastroretentive formulations have demonstrated the application of screening and response-surface approaches to identify variables affecting floating lag time and release before defining an experimentally supported design space. (43)

Design-space development may be particularly valuable for herbal products because natural variability in extract composition and physical properties can shift formulation performance. A robust formulation should therefore tolerate realistic variation in relevant extract and excipient attributes without losing critical performance characteristics. The control strategy should consequently extend beyond finished-tablet testing. Consistent with the pharmaceutical quality-system perspective of ICH Q10, development knowledge should be translated into controls throughout the product lifecycle.(51,52)

For herbal floating tablets, the control pathway should extend across: Botanical authentication → raw-material specifications → extract standardization → marker/fingerprint control → excipient specifications → process controls → finished-product CQAs → stability monitoring. This is a crucial distinction because variability introduced during cultivation, extraction, or raw-material processing cannot necessarily be corrected through finished-product testing alone. The literature-derived relationships between critical formulation variables, manufacturing conditions, and key performance attributes of herbal gastroretentive floating tablets are summarized in Table 3.

Table 3. Literature-derived formulation variable–performance relationships

Variable	Reported response influenced	Direction/relationship observed	Evidence interpretation	Formulation implication
Polymer amount	Release, floating behavior, tablet strength	Higher polymer can retard release and alter buoyancy	Strong but formulation-dependent	Optimize within a multidimensional design
Polymer viscosity/grade	Floating lag time and release	Higher viscosity can strengthen matrix but	Demonstrated experimental	Select grade according to both

		may delay hydration/buoyancy	ly	buoyancy and release
Sodium bicarbonate	Floating lag time and release	Increasing level can accelerate flotation but alter release	Significant formulation variable	Optimize jointly with polymer
Compression force	Porosity, tablet strength, floating behavior	Greater compaction can reduce porosity and alter hydration	Demonstrated in DoE studies	Treat as CPP
Extract loading	Density, matrix properties, release	Highly formulation-specific	Limited systematic evidence for herbal systems	Requires extract-specific DoE
Low-density carrier	Density/buoyancy	Can facilitate flotation	Evidence mainly from synthetic APIs	Potential strategy for high-dose extracts
Polymer combination	Release and matrix integrity	Can produce synergistic or competing effects	System-specific	Evaluate interaction rather than individual effects
Manufacturing moisture	Compression and matrix behavior	Can alter tablet structure and reproducibility	Important for botanical materials	Include in material/process

re	r	bility	als	control
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7. Standardization, Stability, Regulatory Considerations and Future Directions

7.1 Translational Challenges Beyond In-Vitro Formulation Performance

The successful development of herbal floating tablets requires more than prolonged buoyancy and controlled release. Translation depends on whether the formulation can maintain consistent pharmaceutical performance across batches, demonstrate physiologically meaningful behaviour, satisfy regulatory requirements, and provide a practical therapeutic advantage. An important limitation is that gastric performance is influenced by physiological variability, including food intake, gastric-fluid volume, motility, and interindividual differences. Therefore, the intended dosing condition should be incorporated into product development rather than treating fed or fasted status as an incidental experimental variable.(51)

A major translational challenge is therefore the following: In-vitro formulation performance → physiological behaviour → reproducible exposure → therapeutic benefit. Failure to establish this chain limits the scientific significance of even technically sophisticated floating formulations.

7.2 Herbal Extract Standardization and Batch-to-Batch Reproducibility

Herbal extract standardization is not merely an analytical requirement; it is fundamental to pharmaceutical reproducibility. Unlike conventional synthetic drugs containing a defined molecular entity, botanical preparations are chemically complex mixtures whose composition may vary with botanical identity, geographical origin, cultivation, harvesting, processing, extraction, and storage. Regulatory agencies recognize this complexity. The FDA Botanical Drug Development guidance emphasizes appropriate control of botanical raw materials and finished products, while comparability between materials used at different stages of development is essential.(53)

For floating tablets, extract variability may affect both therapeutic consistency and pharmaceutical performance. Differences in extract composition can alter moisture content, density, hygroscopicity, particle characteristics, compressibility, and interactions with the polymeric matrix. Therefore: A floating tablet cannot be considered truly reproducible if the incorporated herbal extract itself is poorly standardized.(54)

A robust strategy should integrate: Botanical authentication + physicochemical characterization + quantitative marker analysis + chromatographic fingerprinting + contaminant control + stability

monitoring. Marker compounds remain useful for quantitative control, but a single marker may not adequately represent a chemically complex extract. Chromatographic fingerprinting and broader chemical characterization should therefore complement marker-based specifications. This approach is consistent with expectations described by the European Medicines Agency (EMA) guideline on specifications for herbal substances and preparations.(55)

An important future research opportunity is to determine whether extract-batch variability directly produces statistically measurable changes in tablet performance. This would establish a more meaningful relationship: Phytochemical fingerprint → powder properties → tablet microstructure → hydration → buoyancy → phytoconstituent release. Such an approach could move botanical standardization beyond chemical identity toward performance-linked standardization.

7.3 Stability and Product Quality

Stability assessment of herbal floating tablets is more complex than that of conventional tablets because both the herbal material and the gastroretentive delivery architecture must remain stable. Chemical degradation may alter relevant phytoconstituents, whereas physical changes can affect moisture uptake, tablet hardness, porosity, matrix hydration, buoyancy, and release. Therefore, stability testing should not focus exclusively on marker-compound content.

A meaningful stability programme should assess:

- chemical marker and fingerprint consistency;
- degradation products where relevant;
- moisture content;
- tablet appearance and mechanical integrity;
- floating lag time and buoyancy duration;
- swelling and erosion;
- phytoconstituent release;
- microbiological quality where applicable.

The critical principle is that a formulation may remain chemically acceptable while losing its intended gastroretentive performance. Consequently, functional performance should be incorporated into stability assessment rather than treating stability solely as chemical assay retention.(56)

7.4 Future Directions: From Simple Floating Tablets to Evidence-Linked Gastroretention

Future gastroretentive technologies may increasingly combine multiple retention mechanisms, including floating, swelling, mucoadhesion, expandable architectures, lipid-polymer systems, and advanced manufacturing approaches such as three-dimensional printing. However, increasing technological complexity also increases manufacturing, characterization, stability, and regulatory burdens.

Therefore: Formulation complexity should be justified by therapeutic benefit, not technological novelty.

Another important direction is the application of model-informed and physiologically relevant development approaches. Because gastric physiology differs among individuals and changes with food intake and other physiological conditions, future systems may benefit from modelling formulation–physiology interactions rather than assuming identical gastric residence in every individual. The FDA guidance on Model-Informed Drug Development provides a broader framework that may support such approaches, although its application to herbal gastroretentive systems remains an emerging research area.

The most promising future direction is therefore not simply developing formulations that float for increasingly long periods. Instead, research should establish evidence-based relationships between: Herbal extract quality → formulation properties → gastric physiology → dosage-form behaviour → phytoconstituent exposure → therapeutic response. The major translational barriers and priority research directions required to advance herbal floating tablets toward clinically meaningful gastroretentive delivery are summarized in Table 4.

Table 4. Major translational barriers and future research priorities for herbal floating tablets

Translational challenge	Why it matters	Current limitation	Future priority
Herbal variability	Alters therapeutic and physical properties	Batch effects rarely linked to tablet performance	Performance-linked extract specifications
Marker selection	Single markers may not represent extract complexity	Overreliance on one marker	Multi-marker and fingerprint-based control
Stability	Chemical and functional properties may change independently	Buoyancy often excluded from stability testing	Functional stability evaluation

	ntly		
Gastric physiological variability	Influences in-vivo performance	Standardized in-vitro tests are simplified	Biorelevant and model-informed evaluation
High extract dose	May require impractically large tablets	Dose feasibility often overlooked	Early dose–size feasibility assessment
Advanced formulation technologies	Increase design flexibility	Complexity may exceed therapeutic benefit	Benefit-driven formulation complexity
Clinical translation	Determine real therapeutic value	Limited comparative evidence	Demonstrate advantage over conventional formulations

8. Conclusions

Herbal floating tablets represent a promising strategy for improving gastric residence and controlling the release of phytoconstituents, particularly when prolonged gastric exposure is therapeutically justified. However, the development of such systems is more complex than conventional floating formulations because herbal extracts exhibit inherent chemical and physicochemical variability that can influence both therapeutic consistency and dosage-form performance. The present evidence indicates substantial progress in polymeric matrix design, effervescent systems, extract encapsulation, and QbD-based optimization. Nevertheless, a major translation gap remains. Many studies demonstrate prolonged in-vitro buoyancy and controlled release, whereas comparatively few confirm actual gastric retention in vivo, and still fewer establish improved phytoconstituent exposure or therapeutic benefit compared with appropriate non-gastroretentive formulations. Therefore, prolonged floating should not be considered equivalent to successful gastroretention or therapeutic superiority. Future development should integrate botanical authentication and standardization, extract

characterization, mechanistically justified formulation design, QbD-based optimization, functional stability testing, and physiologically relevant evaluation. Importantly, gastric-retention studies should be followed, where justified, by pharmacokinetic, pharmacodynamic, or comparative therapeutic assessment. Ultimately, the field should move beyond developing herbal tablets that merely float toward evidence-linked gastroretentive systems, in which a reproducible relationship is established between herbal extract quality, formulation properties, gastric residence, phytoconstituent exposure, and therapeutic benefit.

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9. References

1. Streubel A, Siepmann J, Bodmeier R. Gastroretentive drug delivery systems. *Expert Opinion on Drug Delivery*. 2006 Mar;3(2):217–33. doi:10.1517/17425247.3.2.217
2. Lopes CM, Bettencourt C, Rossi A, Buttini F, Barata P. Overview on gastroretentive drug delivery systems for improving drug bioavailability. *International Journal of Pharmaceutics*. 2016 Aug;510(1):144–58. doi:10.1016/j.ijpharm.2016.05.016
3. Awasthi R, Kulkarni GT. Decades of research in drug targeting to the upper gastrointestinal tract using gastroretention technologies: where do we stand? *Drug Delivery*. 2016 Feb 12;23(2):378–94. doi:10.3109/10717544.2014.936535
4. Bardonnet PL, Faivre V, Pugh WJ, Piffaretti JC, Falson F. Gastroretentive dosage forms: Overview and special case of *Helicobacter pylori*. *Journal of Controlled Release*. 2006 Mar;111(1–2):1–18. doi:10.1016/j.jconrel.2005.10.031
5. Tadros MI. Controlled-release effervescent floating matrix tablets of ciprofloxacin hydrochloride: Development, optimization and in

vitro–in vivo evaluation in healthy human volunteers. *European Journal of Pharmaceutics and Biopharmaceutics*. 2010 Feb;74(2):332–9. doi:10.1016/j.ejpb.2009.11.010

6. Tripathi J, Thapa P, Maharjan R, Jeong SH. Current State and Future Perspectives on Gastroretentive Drug Delivery Systems. *Pharmaceutics*. 2019 Apr 20;11(4):193. doi:10.3390/pharmaceutics11040193

7. Razavi M, Karimian H, Chai Hong Y, Chung LY, Noordin MI, Nyamathulla S. Gamma scintigraphic evaluation of floating gastroretentive tablets of metformin HCl using a combination of three natural polymers in rabbits. *DDDT*. 2015 Aug;4373. doi:10.2147/DDDT.S86263

8. Zhao Q, Gao B, Ma L, Lian J, Deng L, Chen J. Innovative intragastric ascaridole floating tablets: Development, optimization, and in vitro–in vivo evaluation. *International Journal of Pharmaceutics*. 2015 Dec;496(2):432–9. doi:10.1016/j.ijpharm.2015.10.007

9. Ranade AN, Wankhede SS, Ranpise NS, Mundada MS. Development of Bilayer Floating Tablet of Amoxicillin and Aloe vera Gel Powder for Treatment of Gastric Ulcers. *AAPS PharmSciTech*. 2012 Dec;13(4):1518–23. doi:10.1208/s12249-012-9882-4

10. Balekundri A, Mannur V. Quality control of the traditional herbs and herbal products: a review. *Futur J Pharm Sci*. 2020 Dec;6(1):67. doi:10.1186/s43094-020-00091-5

11. Noviana E, Indrayanto G, Rohman A. Advances in Fingerprint Analysis for Standardization and Quality Control of Herbal Medicines. *Front Pharmacol*. 2022 Jun 2;13:853023. doi:10.3389/fphar.2022.853023

12. Fukuda M, Peppas NA, McGinity JW. Floating hot-melt extruded tablets for gastroretentive controlled drug release system. *Journal of Controlled Release*. 2006 Oct;115(2):121–9. doi:10.1016/j.jconrel.2006.07.018

13. Bera H, Gaini C, Kumar S, Sarkar S, Boddupalli S, Ippagunta SR. HPMC-based gastroretentive dual working matrices coated with Ca²⁺ ion crosslinked alginate-fenugreek gum gel membrane. *Materials Science and Engineering: C*. 2016 Oct;67:170–81. doi:10.1016/j.msec.2016.05.016

14. Aswatha Ram H, Lachake P, Kaushik U, Shreedhara C. Formulation and evaluation of floating tablets of liquorice extract. *Phcog Res*. 2010;2(5):304. doi:10.4103/0976-4836.72329

15. Mudrić J, Đekić L, Krgović N, Medarević Đ, Šavikin K, Radan M, et al. Dual-Mechanism Gastroretentive Tablets with Encapsulated Gentian Root Extract. *Pharmaceutics*. 2025 Jan 7;17(1):71. doi:10.3390/pharmaceutics17010071

16. Timmermans J, Moës AJ. How well do floating dosage forms float? *International Journal of Pharmaceutics*. 1990 Jul;62(2–3):207–16. doi:10.1016/0378-5173(90)90234-U
17. Li S, Han Q, Qiao C, Song J, Lung Cheng C, Xu H. Chemical markers for the quality control of herbal medicines: an overview. *Chin Med*. 2008 Dec;3(1):7. doi:10.1186/1749-8546-3-7
18. Kim JI, Park SW, Lim JJ, Sohn SI, Shin JS, Park SC, et al. Gastroprotective effects of the isopropanol extract of *Artemisia princeps* and its gastroretentive floating tablets on gastric mucosal injury. *Acta Pharmaceutica*. 2017 Dec 20;67(4):479–94. doi:10.1515/acph-2017-0037
19. Pawar VK, Kansal S, Garg G, Awasthi R, Singodia D, Kulkarni GT. Gastroretentive dosage forms: A review with special emphasis on floating drug delivery systems. *Drug Delivery*. 2011 Feb;18(2):97–110. doi:10.3109/10717544.2010.520354
20. Hou SYE, Cowles VE, Berner B. Gastric Retentive Dosage Forms: A Review. *Crit Rev Ther Drug Carrier Syst*. 2003;20(6):28. doi:10.1615/CritRevTherDrugCarrierSyst.v20.i6.30
21. Kotreka UK, Adeyeye MC. Gastroretentive Floating Drug-Delivery Systems: A Critical Review. *Crit Rev Ther Drug Carrier Syst*. 2011;28(1):47–99. doi:10.1615/CritRevTherDrugCarrierSyst.v28.i1.20
22. Ishak RAH. Buoyancy-Generating Agents for Stomach-Specific Drug Delivery: An Overview with Special Emphasis on Floating Behavior. *J Pharm Pharm Sci*. 2015 Mar 9;18(1):77. doi:10.18433/J3602K
23. Arora S, Ali J, Ahuja A, Khar RK, Baboota S. Floating drug delivery systems: A review. *AAPS PharmSciTech*. 2005 Sep;6(3):E372–90. doi:10.1208/pt060347
24. Das S, Kaur S, Rai VK. Gastro-retentive drug delivery systems: a recent update on clinical pertinence and drug delivery. *Drug Deliv and Transl Res*. 2021 Oct;11(5):1849–77. doi:10.1007/s13346-020-00875-5
25. Reddy LHV, Murthy RSR. Floating Dosage Systems in Drug Delivery. *Crit Rev Ther Drug Carrier Syst*. 2002;19(6):553–85. doi:10.1615/CritRevTherDrugCarrierSyst.v19.i6.20
26. Tadros MI. Controlled-release effervescent floating matrix tablets of ciprofloxacin hydrochloride: Development, optimization and in vitro–in vivo evaluation in healthy human volunteers. *European Journal of Pharmaceutics and Biopharmaceutics*. 2010 Feb;74(2):332–9. doi:10.1016/j.ejpb.2009.11.010
27. Blynskaya EV, Tishkov SV, Vinogradov VP, Alekseev KV, Marakhova AI, Vetcher AA. Polymeric Excipients in the Technology of Floating Drug Delivery Systems. *Pharmaceutics*. 2022 Dec 12;14(12):2779. doi:10.3390/pharmaceutics14122779
28. Waqar MA, Mubarak N, Khan AM, Khan R, Shaheen F, Shabbir A. Advanced polymers and recent advancements on gastroretentive drug delivery system; a comprehensive review. *Journal of Drug Targeting*. 2024 Jul 2;32(6):655–71. doi:10.1080/1061186X.2024.2347366
29. Rahamathulla M, Alshahrani SM, Al Saqr A, Alshetali A, Shakeel F. Effervescent floating matrix tablets of a novel anti-cancer drug neratinib for breast cancer treatment. *Journal of Drug Delivery Science and Technology*. 2021 Dec;66:102788. doi:10.1016/j.jddst.2021.102788
30. Bhardwaj BY, Vihal S, Pahwa R, Agarwal S, Gupta B, Yang JC, et al. Recent advancements in xanthan gum-based gastroretentive floating formulations: Chemical modification, production and applications. *Carbohydrate Polymers*. 2025 Jan;348:122809. doi:10.1016/j.carbpol.2024.122809
31. Omidian H. Gastroretentive drug delivery systems: A holy grail in oral delivery. *Drug Discovery Today*. 2025 Apr;30(4):104340. doi:10.1016/j.drudis.2025.104340
32. Kriangkrai W, Puttipipatkachorn S, Sriamornsak P, Sungthongjeen S. Design and Evaluation of New Gel-Based Floating Matrix Tablets Utilizing the Sublimation Technique for Gastroretentive Drug Delivery. *Gels*. 2024 Sep 9;10(9):581. doi:10.3390/gels10090581
33. Jain S, Sankar. Development and characterization of gastroretentive sustained-release formulation by combination of swelling and mucoadhesive approach: a mechanistic study. *DDDT*. 2013 Dec;1455. doi:10.2147/DDDT.S52890
34. Garg R, Gupta GD. Preparation and Evaluation of Gastroretentive Floating Tablets of Silymarin. *Chem Pharm Bull*. 2009;57(6):545–9. doi:10.1248/cpb.57.545
35. Vasir JK, Tambwekar K, Garg S. Bioadhesive microspheres as a controlled drug delivery system. *International Journal of Pharmaceutics*. 2003 Apr;255(1–2):13–32. doi:10.1016/S0378-5173(03)00087-5
36. Al Shawakri E, Ashour EA, Elkanayati RM, Almutairi M, Omari S, AlShammari N, et al. Fabrication of Gastroretentive and Extended-Release Famotidine Floating Tablets via Fused Deposition Modeling. *AAPS PharmSciTech*. 2025 Oct 14;26(8):240. doi:10.1208/s12249-025-03237-x
37. Panraksa P, Chaiwarit T, Chanabodeechalermrung B, Worajittiphon P, Jantrawut P. Fabrication of Cellulose Derivatives-Based Highly Porous Floating Tablets for Gastroretentive Drug Delivery via Sugar Templating Method. *Polymers*. 2025 Feb 12;17(4):485. doi:10.3390/polym17040485
38. Kam LY, Wong JW, Yuen KH. HPMC Substitution Influences the Buoyancy and Release

- in Gastroretentive Floating Tablets. AAPS PharmSciTech. 2026 Jan 15;27(1):77. doi:10.1208/s12249-025-03306-1
39. Mahalingam R, Jasti B, Birudaraj R, Stefanidis D, Killion R, Alfredson T, et al. Evaluation of Polyethylene Oxide Compacts as Gastroretentive Delivery Systems. AAPS PharmSciTech. 2009 Mar;10(1):98–103. doi:10.1208/s12249-008-9182-1
40. Gupta C, Sahu GK, Parashar AK, Singh K, Bukke SPN, Udom GJ. Novel Curcumin Floating Tablets for Spatial Delivery in Peptic Ulcer. Banerjee B, editor. BioMed Research International. 2025 Jan;2025(1):6622146. doi:10.1155/bmri/6622146
41. Kang MJ, Cha KH, Kang SY, Won D, Jang SW, Son MH, et al. In vivo gastric residence and gastroprotective effect of floating gastroretentive tablet of DA-9601, an extract of *Artemisia asiatica*, in beagle dogs. DDDT. 2016 Jun;1917. doi:10.2147/DDDT.S102918
42. Patel C, Shelat P, Lalwani A. Fabrication of Gastroretentive Tablets of Rifaximin for Twice a Day Dosing Using Quality by Design Approach. DDL. 2015 Jun 18;5(1):52–62. doi:10.2174/2210303105666150115223646
43. Chudiwal VS, Shahi S, Chudiwal S. Development of sustained release gastro-retentive tablet formulation of nicardipine hydrochloride using quality by design (QbD) approach. Drug Development and Industrial Pharmacy. 2018 May 4;44(5):787–99. doi:10.1080/03639045.2017.1413111
44. Shah HP, Prajapati ST, Patel CN. Quality by Design enabled Development and Optimization of Gastroretentive Floating Matrix Tablets of Dipyridamole.
45. Ahmad S, Khan JA, Kausar TN, Mahnashi MH, Alasiri A, Alqahtani AA, et al. Preparation, Characterization and Evaluation of Flavonolignan Silymarin Effervescent Floating Matrix Tablets for Enhanced Oral Bioavailability. Molecules. 2023 Mar 13;28(6):2606. doi:10.3390/molecules28062606
46. Thapa P, Jeong SH. Effects of Formulation and Process Variables on Gastroretentive Floating Tablets with A High-Dose Soluble Drug and Experimental Design Approach. Pharmaceutics. 2018 Sep 17;10(3):161. doi:10.3390/pharmaceutics10030161
47. Ha JM, Seo JW, Kim SH, Kim JY, Park CW, Rhee YS, et al. Implementation of Quality by Design for Formulation of Rebamipide Gastroretentive Tablet. AAPS PharmSciTech. 2017 Nov;18(8):3129–39. doi:10.1208/s12249-017-0797-y
48. Kim B, Byun Y, Lee EH. DoE-Based Design of a Simple but Efficient Preparation Method for a Non-Effervescent Gastro-Retentive Floating Tablet Containing Metformin HCl. Pharmaceutics. 2021 Aug 8;13(8):1225. doi:10.3390/pharmaceutics13081225
49. Prakash M, Nallasamy V, Venkatachalam S, Raman N. QUALITY-BY-DESIGN ASSISTED DEVELOPMENT AND EVALUATION OF A MICROBALLOON-BASED GASTRORETENTIVE DRUG DELIVERY SYSTEM. Int J App Pharm. 2026 Jan 10. doi:10.22159/ijap.2026v18i2.56652
50. Gaikwad SS, Avari JG. Improved bioavailability of Azelnidipine gastro retentive tablets-optimization and in-vivo assessment. Materials Science and Engineering: C. 2019 Oct;103:109800. doi:10.1016/j.msec.2019.109800
51. Pinto JF. Site-specific drug delivery systems within the gastro-intestinal tract: From the mouth to the colon. International Journal of Pharmaceutics. 2010 Aug;395(1–2):44–52. doi:10.1016/j.ijpharm.2010.05.003
52. Qin C, Wu M, Xu S, Wang X, Shi W, Dong Y, et al. Design and optimization of gastro-floating sustained-release tablet of pregabalin: In vitro and in vivo evaluation. International Journal of Pharmaceutics. 2018 Jul;545(1–2):37–44. doi:10.1016/j.ijpharm.2018.04.011
53. Center for Drug Evaluation and Research. Botanical Drug Development: Guidance for Industry [Internet]. US Food and Drug Administration; 2020 [cited 2026 Aug 22]. Available from: <https://www.fda.gov/regulatory-information/search-fda-guidance-documents/botanical-drug-development-guidance-industry?>
54. Juère E, Del Favero G, Masse F, Marko D, Popat A, Florek J, et al. Gastro-protective protein-silica nanoparticles formulation for oral drug delivery: In vitro release, cytotoxicity and mitochondrial activity. European Journal of Pharmaceutics and Biopharmaceutics. 2020 Jun;151:171–80. doi:10.1016/j.ejpb.2020.03.015
55. Guideline on specifications: test procedures and acceptance criteria for herbal substances, herbal preparations and herbal medicinal products/traditional herbal medicinal products.
56. Davis SS. Formulation strategies for absorption windows. Drug Discovery Today. 2005 Feb;10(4):249–57. doi:10.1016/S1359-6446(04)03351-3