

Nanoengineering of Functional Foods for Obesity Prevention: The Future of Nutraceutical Delivery Systems

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ABSTRACT

Obesity is driven by chronic energy surplus, sedentary lifestyles and environments that promote overconsumption of calorie-dense, nutrient-poor foods. Alongside pharmacotherapy and lifestyle interventions, functional foods enriched with bioactive nutraceuticals are increasingly explored as low-risk, population-wide tools for obesity prevention. Yet many promising compounds, including polyphenols, carotenoids, fatty acids and peptides, suffer from poor solubility, instability during processing and digestion, low oral bioavailability and limited targeting of metabolically relevant tissues. Nanotechnology-based delivery systems offer a way to overcome these barriers directly within the food matrix. Nanoengineered functional foods use nanoemulsions, nanoliposomes, solid lipid nanoparticles, biopolymer nanogels, nano-complexes and hybrid carriers to protect labile nutraceuticals, enhance gastrointestinal bioaccessibility and control their release and absorption. Recent work demonstrates that nanostructured systems can significantly increase bioavailability of key anti-obesity nutraceuticals such as curcumin, resveratrol and catechins and improve metabolic readouts in preclinical models. This review outlines the rationale for nanoengineering in functional foods for obesity prevention, describes major nanoencapsulation platforms, highlights representative nanonutraceuticals and smart “personalized” food concepts, and discusses safety, regulatory and consumer acceptance issues. Finally, we consider how nanostructured delivery systems might integrate into multi-level obesity prevention strategies and what evidence is needed for responsible translation from bench to supermarket shelf.

Keywords: Functional foods; Nanonutraceuticals; Obesity prevention; Nanoencapsulation; Bioavailability

INTRODUCTION

Obesity prevalence continues to rise globally, driven by urbanization, reduced physical activity and ubiquitous access to ultra-processed foods[1–3]. Conventional management relies on behavioral change, pharmacotherapy and, for severe cases, bariatric surgery. These approaches are effective for some but costly, difficult to sustain and often inaccessible at population level. Functional foods and nutraceuticals have therefore attracted attention as complementary strategies that may shift population risk curves by subtly improving metabolic health and body weight trajectories over time[4].

Functional foods are typically defined as conventional foods that provide physiological benefits beyond basic nutrition due to added or naturally occurring bioactive components. Nutraceuticals are more concentrated, often supplement-like preparations of bioactives[5]. In the context of obesity, relevant nutraceuticals include polyphenols (e.g., catechins, resveratrol, quercetin), curcuminoids, carotenoids (e.g., fucoxanthin, lycopene), omega-3 fatty acids, phytosterols, fermentable fibers, plant peptides and probiotic or postbiotic preparations. These compounds can influence appetite, adipogenesis, lipid absorption, energy expenditure, insulin sensitivity, oxidative stress, gut microbiota composition and low-grade inflammation[6].

Epidemiological and interventional data suggest that diets rich in such bioactives, as part of plant-forward eating patterns, are associated with lower weight gain and reduced cardiometabolic risk[7]. Yet when isolated and delivered as conventional supplements or food fortificants, many nutraceuticals show modest and inconsistent effects. The gap between strong mechanistic data and modest clinical performance is often pharmacokinetic. Numerous bioactives are poorly water soluble, chemically unstable during processing and storage, sensitive to pH, light and oxygen and extensively degraded or transformed in the gastrointestinal tract[7].

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Curcumin illustrates the problem well: it is highly hydrophobic, rapidly metabolized and exhibits very low oral bioavailability, so that only trace amounts of free curcumin reach systemic circulation after ingestion of conventional formulations. Polyphenols like resveratrol and catechins are similarly susceptible to poor solubility, enzymatic and microbial degradation and efflux transport[8–11]. As a result, high doses are often required to achieve biological effects, increasing cost and raising questions about long-term safety.

Another limitation is limited spatiotemporal control. In most foods and supplements, bioactives are dispersed relatively randomly and released rapidly in the upper gastrointestinal tract. This may be suboptimal when targets lie in more distal segments, such as the colon and its microbiota, or when gradual release aligned with postprandial physiology is desirable[12]. Moreover, naked bioactives may strongly interact with other food components, reducing their effective dose or altering sensory properties.

Nanotechnology-based delivery addresses these challenges by structuring bioactives at the nano-scale within the food matrix[13–16]. Nanoencapsulation refers to entrapping, coating or complexing nutraceuticals into carriers with characteristic dimensions typically below 200 nm, made from lipids, proteins, polysaccharides or hybrid materials. These structures can increase apparent solubility, shield against adverse processing and digestive conditions, modulate interfacial behavior and control release and absorption [17]. Importantly, they can be manufactured using food-grade, biodegradable materials, enabling incorporation directly into beverages, dairy products, baked goods, snacks and other everyday foods[12].

Recent overviews of nanonutraceuticals emphasize that nanostructured systems consistently enhance bioavailability and efficacy of diverse nutraceutical classes, including carbohydrates, lipids, proteins, vitamins, minerals and phytochemicals, and that several of these enhancements have direct relevance to obesity-related pathways. For example, nanoemulsions and nanogels can transform hydrophobic compounds like curcumin into water-dispersible forms with substantially improved gastrointestinal bioaccessibility and cellular uptake, while preserving or even enhancing their antioxidant and anti-inflammatory activity[18].

From an obesity-prevention perspective, nanoengineered functional foods offer several conceptual advantages. First, they could enable lower, more physiologically appropriate doses of potent nutraceuticals to be embedded in daily diets, reducing the need for pill-based supplements and improving adherence[19]. Second, by tuning release and absorption profiles, it may be possible to align bioactive exposure with metabolic “windows” such as postprandial periods, when modulation of glucose and lipid excursions is most impactful. Third, delivery systems can be designed to preferentially act in the gut lumen and mucosa, where they can influence satiety hormones, barrier function and microbiota without requiring high systemic concentrations[19].

These potential benefits must be balanced against concerns about safety, regulatory oversight and consumer acceptance of “nanofoods.” International bodies such as EFSA and FDA have issued guidance on risk assessment and regulatory handling of nanotechnology in food and feed, emphasizing the need for detailed characterization, exposure assessment and toxicity testing specific to nanomaterials[20]. Public perceptions of nanotechnology in food are ambivalent, shaped by trust in regulators, perceived naturalness and understanding of benefits versus risks. In this evolving landscape, nanoengineering of functional foods for obesity prevention sits at the intersection of nutrition science, materials engineering, regulatory policy and consumer behavior. The following sections outline the main nanoencapsulation platforms, survey anti-obesity nanonutraceuticals, explore their gastrointestinal and metabolic mechanisms, examine emerging smart and personalized food concepts and discuss the safety and governance frameworks needed to ensure that future nanofoods are both effective and acceptable as tools for obesity prevention[21].

2. Nanoencapsulation Platforms for Functional Foods

Nanoengineering of functional foods relies on encapsulation platforms that are both technologically effective and compatible with food regulations and processing conditions. Broadly, nanoencapsulation systems in foods can be categorized into lipid-based, protein-based, polysaccharide-based and hybrid structures, often produced by high-energy homogenization, antisolvent precipitation, self-assembly, complex coacervation or electrospraying[22].

Lipid-based systems include nanoemulsions, solid lipid nanoparticles, nanostructured lipid carriers and liposomes.[16, 23–25] Nanoemulsions are kinetically stable dispersions of oil droplets (20–200 nm) stabilized by surfactants and sometimes biopolymers. They are particularly suitable for solubilizing hydrophobic nutraceuticals such as carotenoids, curcumin and vitamin D in aqueous beverages and dairy matrices, enhancing bioaccessibility and providing transparency or slight turbidity desirable for many products. Solid lipid nanoparticles and nanostructured lipid carriers, which remain less common in mainstream foods, offer more controlled release profiles and better oxidative protection for highly labile compounds[26].

Protein-based nanostructures use food proteins such as casein, whey proteins, zein or plant proteins to form nanoparticles, nanogels or nanofibrils that entrap bioactives[27]. Their amphiphilic nature enables interaction with both hydrophilic and hydrophobic compounds, and their nutritional status facilitates incorporation into dairy and plant-based products. Polysaccharide-based systems, often using chitosan, alginate, pectin, starch or cellulose derivatives, form nanogels, nanofibers or polyelectrolyte complexes and are particularly attractive for pH-responsive and colon-targeted delivery[27].

Hybrid nanoencapsulation systems combine natural biopolymers with synthetic or inorganic nanomaterials to achieve more precise control over size, surface chemistry and responsiveness. Recent reviews highlight the potential of hybrid systems that integrate chitosan, alginate or starch with synthetic polymers like PLGA or with mesoporous silica to create next-generation platforms offering improved stability, tunable release and multi-compartment loading[28]. Such platforms are particularly promising for multi-nutrient delivery and for co-encapsulation of nutraceuticals with different physicochemical characteristics.

In food applications, formulation constraints differ from pharmaceuticals. Carriers must withstand processing conditions such as heat, shear, freezing and drying, while maintaining sensory quality[29]. They must be constructed from GRAS materials, avoid organic solvent residues and be compatible with large-scale, cost-effective manufacturing. Practical studies on nanoencapsulated nutraceuticals in real food systems demonstrate that incorporation into yogurts, juices, breads, chocolates and gummies is feasible, but also highlight interactions between carriers and food components that can alter stability, release and sensory attributes[29].

Overall, the toolbox of nanoencapsulation technologies for functional foods is broad and rapidly evolving. The challenge is less about inventing new structures and more about judiciously selecting and adapting platforms that balance enhanced delivery performance with safety, regulatory compliance, sensory acceptability and manufacturability for obesity-targeted applications.

3. Anti-Obesity Nanonutraceuticals and Their Functional Food Formats

A growing catalogue of bioactives has been nanoengineered for potential anti-obesity benefits. Recent reviews of “emerging nanonutraceuticals against obesity” categorize these into carbohydrates, lipids, proteins, vitamins, minerals and phytochemicals, with phytochemicals and lipids particularly prominent[30].

Curcumin is among the most extensively studied. Nanoemulsions, nanogels, liposomes and polymeric nanoparticles have all been used to improve curcumin’s stability and bioavailability, with several studies showing enhanced gastrointestinal bioaccessibility and increased systemic exposure compared to free curcumin when delivered in food-like matrices. These systems have been incorporated into drinks, dairy products and confectionery prototypes and in animal models have produced superior effects on body weight, adiposity and inflammatory markers relative to non-encapsulated curcumin[8, 10, 31].

Green tea catechins, resveratrol, quercetin and other polyphenols have likewise been nanoencapsulated to support incorporation into functional beverages, snacks and dairy products. Co-delivery of curcumin and resveratrol via core-shell nanoparticles, for instance, has been explored to exploit their synergistic antioxidant and metabolic effects, with the system embedded into customized 3D-printed hydrogels as a prototype functional food[32–34]. Such combinations are attractive for obesity prevention, as they can simultaneously influence adipogenesis, lipid oxidation, mitochondrial function and inflammatory pathways at modest doses [34, 35].

Lipid-derived nutraceuticals, including conjugated linoleic acid, omega-3 fatty acids and phytosterols, have been nanoemulsified or encapsulated in lipid carriers for improved stability and delivery[36]. These bioactives can reduce adiposity, improve lipid profiles and modulate inflammatory tone when consumed regularly, and nanoengineering helps mitigate issues of oxidation, off-flavors and poor dispersion in aqueous foods[36]. Fermentable fibers and resistant starches, while not typically nanoencapsulated in the classical sense, can be processed into nano- or micro-structured systems that alter digestibility and fermentation patterns, influencing satiety, glycemic response and microbiota-derived metabolites relevant to obesity. Probiotic and postbiotic components have also been incorporated into nano-structured carriers to improve viability and targeted release in the intestine, although such systems blur the line between functional foods and live biotherapeutics[37].

Importantly, many obesity-oriented nanonutraceuticals are still at preclinical or early prototype stages with limited human data[38]. The translation pathway typically starts with *in vitro* digestion and Caco-2 uptake models, progresses to animal studies assessing weight, adiposity and metabolic markers and, in a smaller subset, moves into short-term human trials focused on bioavailability and surrogate biomarkers rather than hard outcomes[38]. Demonstrating that nanoengineered functional foods can meaningfully alter long-term weight trajectories or prevent progression to metabolic disease remains a major unmet evidence need.

4. Gastrointestinal Fate, Bioavailability and Mechanisms of Nanonutraceuticals

The central rationale for nanoengineering nutraceuticals is to enhance their journey from ingestion to target tissues without compromising safety[39]. Gastrointestinal fate is influenced by particle size, composition, interfacial properties and the surrounding food matrix. In simulated digestion models and *in vivo* studies, nanoencapsulation typically increases bioaccessibility, defined as the fraction of a compound that becomes solubilized and available for absorption, particularly for hydrophobic molecules[39].

Lipid-based nanoparticles and nanoemulsions are digested by pancreatic lipase and bile salts, generating mixed micelles that ferry encapsulated nutraceuticals to the intestinal epithelium. Smaller droplets and appropriate interfacial structures accelerate lipid digestion and micelle formation, increasing the driving force for absorption[24]. Protein and polysaccharide nanocarriers may undergo partial digestion or swelling before releasing their cargo, sometimes in a pH- or enzyme-dependent fashion that can be tuned for segment-specific delivery[40].

Once absorbed, nanostructured systems can alter first-pass metabolism and tissue distribution. For instance, delivering curcumin or resveratrol within certain nanoemulsions or lipid particles can favor lymphatic transport, partially bypassing hepatic first-pass metabolism and increasing systemic levels of parent compounds [41]. Even when systemic exposure of the parent is not dramatically increased, nanoencapsulation may change the spectrum and timing of metabolites formed, some of which may themselves be biologically active [41].

Mechanistically, enhanced bioavailability of anti-obesity nutraceuticals can strengthen known pathways such as AMPK activation, PPAR modulation, antioxidant and anti-inflammatory effects, and modulation of adipokine profiles [42]. At the gut level, higher local concentrations of polyphenols and related compounds can alter microbiota composition, favoring taxa associated with leanness, increasing production of short-chain fatty acids and improving barrier function, which together help reduce metabolic endotoxemia [42]. Another emerging concept is that nanoencapsulation can decouple sensory exposure from metabolic delivery. For example, nanoencapsulated bitter compounds that stimulate GLP-1 and PYY release might be shielded from taste receptors, allowing their inclusion at higher levels without affecting palatability while still targeting enteroendocrine cells in the small intestine [43]. Similarly, structured delivery of slowly digestible starches or lipids at the nano-scale can modulate postprandial glycemic and lipemic responses without overtly altering food volume or texture.

Together, these mechanisms support the idea that nanoengineered functional foods can exert meaningful metabolic effects at lower doses and with better alignment to physiological processes than conventional fortification. However, the same features that improve absorption and tissue penetration also raise questions about unintended exposure and off-target effects, underscoring the need for careful risk assessment in parallel with efficacy studies.

5. Smart and Personalized Nanoengineered Functional Foods

Beyond simple bioavailability enhancement, nanoengineering opens the door to “smart” functional foods that respond to physiological cues or are tailored to individual metabolic phenotypes [44]. Smart foods are designed to sense and adapt to environmental conditions within the gastrointestinal tract, such as pH, enzyme activity, redox status or microbial composition, to control nutraceutical release [44].

pH-responsive nanocarriers constructed from polysaccharides and proteins can remain intact in the acidic stomach and release their cargo in the neutral small intestine or slightly acidic colon, allowing segment-specific targeting [45]. Enzyme-responsive systems use linkers or matrices that are degraded by pancreatic enzymes or microbial glycosidases, coupling release to digestive state or microbiota activity. Such designs can concentrate bioactives where they most effectively modulate lipid digestion, glycemic response or gut hormone secretion, all key levers in obesity prevention [46].

Personalization involves matching functional foods to individual metabolic and behavioral patterns [47]. As continuous glucose monitors, wearable devices and microbiome profiling become more accessible, it is conceivable to design nanonutraceutical formulations tuned to a person’s glycemic variability, lipid responses, satiety signals or microbiome configuration [48]. For instance, an individual with pronounced postprandial hypertriglyceridemia might benefit from meals enriched with nanoencapsulated phytosterols and omega-3 fatty acids targeted to the small intestine, whereas someone with insulin resistance and gut dysbiosis might receive polyphenol-rich, colon-targeted formulations that modulate microbiota and incretin release. [48] Smart packaging and 3D food printing further extend possibilities. Nanonutraceuticals can be incorporated into printable inks or layers that allow spatial patterning of bioactive release within a single food item. Electrospayed core-shell nanoparticles containing curcumin and resveratrol, delivered through customized 3D-printed hydrogels, exemplify how structural design can be integrated with nanoscale delivery to fine-tune release kinetics and mouthfeel [49].

In practice, fully personalized nanoengineered foods for obesity prevention remain aspirational. Challenges include the complexity of formulation, regulatory oversight for highly customized products, economic viability and the risk of widening health disparities if such technologies are only accessible to affluent consumers [50]. Nonetheless, the conceptual framework is valuable: it encourages moving beyond “one-size-fits-all” fortification to more nuanced, context-aware design of functional foods that can be adapted to different cultures, dietary patterns and risk profiles while leveraging common nanoencapsulation platforms.

Smart and personalized nanofoods will also depend on a robust data infrastructure linking dietary intake, sensor outputs, and clinical outcomes [50]. Without a clear demonstration that such tailored interventions meaningfully improve weight or metabolic trajectories beyond simpler approaches, their complexity may not be justified. Careful, stepwise evaluation from proof-of-concept to pragmatic trials will be essential.

6. Safety, Regulation and Consumer Acceptance

The use of nanotechnology in food inevitably raises questions about safety, regulation and public trust. Unlike pharmaceuticals, functional foods and nutraceuticals are often consumed daily by large segments of the population, including vulnerable groups, which heightens the importance of robust safety frameworks and transparent communication [51].

Regulatory agencies such as EFSA and FDA have developed guidance documents on the risk assessment of nanomaterials in the food and feed chain. EFSA's updated guidance emphasizes the need for detailed physicochemical characterization, including size distributions, surface properties and agglomeration behavior; consideration of nano-specific toxicokinetics; and tailored exposure assessment for different population groups[52]. The FDA similarly notes that products involving nanotechnology may warrant particular attention and that safety assessment should consider whether nanoscale features alter bioavailability or toxicity relative to conventional counterparts.

Potential risks include increased absorption and tissue accumulation of certain nanomaterials, unexpected interactions with biological membranes, induction of oxidative stress or inflammation and off-target effects due to altered distribution[53]. For many food nanoencapsulation systems based on biopolymers and food-grade lipids, these risks may be low, as carriers are digested into familiar nutrients. However, hybrid systems involving inorganic cores or novel synthetic polymers require more extensive evaluation. Emerging literature warns that some nanomaterials, such as certain silica nanoparticles used as anticaking agents, can exhibit cytotoxicity under specific conditions, underscoring the need for case-by-case risk assessment[53].

Consumer acceptance hinges on perceived naturalness, trust in regulatory oversight and clear communication of benefits. Surveys suggest that consumers may be wary of "nanofoods," particularly if nanotechnology is framed as artificial or poorly understood, but more accepting when nanostructures are based on natural ingredients and clearly linked to health benefits and safety evaluations. Transparent labeling, avoidance of hype and meaningful engagement with stakeholders are crucial to prevent backlash that could stall beneficial innovations[53].

Regulatory classification also matters. Nanonutraceuticals marketed as supplements may undergo less stringent pre-market evaluation than those integrated into foods with explicit health claims, yet from the consumer's perspective, both are "eaten." Harmonizing regulations, clarifying when nano-specific safety data are required and ensuring that products claiming obesity-related benefits are supported by credible evidence are key policy challenges[54].

Ethically, it is important to ensure that nanoengineered functional foods do not distract from structural measures to address obesogenic environments or convey a message that technological fixes alone can solve obesity. They should be positioned as supportive tools within broader lifestyle and policy frameworks. Equity considerations are central: if nanofoods are significantly more expensive, they may be adopted first by higher-income groups, potentially widening health disparities rather than reducing them. Thoughtful design of affordable, culturally appropriate nanoengineered products and inclusive regulatory and public health strategies will be needed.

7. Positioning Nanoengineered Functional Foods in Obesity Prevention

The potential of nanoengineered functional foods lies not in replacing established obesity interventions but in complementing them across the prevention-treatment continuum. At the population level, modest shifts in energy balance, glycemic excursions, lipid handling and inflammatory tone, achieved through daily consumption of enhanced foods, could translate into meaningful reductions in the incidence of obesity and its complications over decades[55].

In primary prevention, nanoengineered foods might be targeted to high-risk groups such as children with familial obesity risk, individuals with prediabetes, women with a history of gestational diabetes or communities undergoing rapid nutrition transition. Incorporating nanostructured nutraceuticals into culturally familiar staples and beverages could support healthier metabolic profiles without requiring disruptive dietary changes, provided that cost and accessibility are addressed[56].

In secondary prevention, individuals with overweight and early metabolic disturbances could use nanoenhanced functional foods as adjuncts to lifestyle modification and, where appropriate, pharmacotherapy[57]. For example, meals fortified with nanoemulsified polyphenols and fibers that blunt postprandial glucose and triglyceride spikes might enhance the effectiveness of calorie-restricted diets or GLP-1 receptor agonists. In tertiary prevention, nanoengineered foods could help stabilize weight loss and support remission of type 2 diabetes or NAFLD by maintaining beneficial adipose, hepatic and microbiota configurations achieved through more intensive interventions[57].

To realize these roles, evidence needs to move beyond pharmacokinetics and surrogate markers to long-term, clinically relevant outcomes. Pragmatic trials embedding nanoengineered functional foods into real-world dietary patterns and monitoring changes in weight, waist circumference, incident diabetes and cardiovascular events will be crucial. Integration with digital health tools that track intake and metabolic responses could support adaptive, personalized use, while also generating the data needed for continual refinement.

From a systems perspective, nanoengineering can be seen as part of a broader shift toward "nutrition by design," where food structure and matrix are deliberately manipulated to optimize health outcomes. This aligns with emerging interests in reformulating ultra-processed foods to reduce harm and in upgrading traditional foods with health-promoting structures rather than merely adding isolated nutrients[57]. Nonetheless, caution is warranted. Over-enthusiastic promotion of nanonutraceuticals as "magic bullets" for weight control would be

counterproductive, potentially fostering unrealistic expectations and neglect of fundamental lifestyle determinants. Responsible messaging should emphasize that nanoengineered functional foods can facilitate healthier trajectories when combined with supportive environments, physical activity and evidence-based clinical care.

If developed and deployed thoughtfully, nanoengineered functional foods may become a valuable layer in multi-component obesity prevention strategies, offering scientifically grounded, user-friendly ways to deliver complex nutraceutical payloads within everyday diets.

CONCLUSION

Nanoengineering of functional foods represents a promising frontier in obesity prevention, aiming to unlock the full potential of nutraceuticals by overcoming long-standing challenges in solubility, stability and bioavailability. By embedding nanoencapsulated bioactives into familiar foods and beverages, it becomes possible to enhance their metabolic impact at lower doses, align release with physiological windows and target specific gastrointestinal or systemic pathways relevant to weight regulation. Advances in nanoencapsulation platforms, smart and hybrid delivery systems and early preclinical and human studies support the feasibility of this approach, while evolving regulatory frameworks and safety assessments provide a foundation for responsible use. Remaining challenges include demonstrating long-term efficacy in real-world settings, ensuring safety and transparency, maintaining sensory and cultural acceptability and avoiding exacerbation of health inequities. Addressed carefully, nanoengineered functional foods could complement lifestyle and pharmacologic interventions, contributing to more effective, scalable and sustainable strategies for reducing obesity burden.

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