Exploring traditional food at the nanoscale to harmonise sensation and nutrition

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Live to eat, eat to live

We were walking through a local market by the seaside of Pesaro, Italy, on a sunny Friday morning in October. The market is a simple and temporary setting and only occupies a short segment of a backstreet. A wide range of fresh fruits, vegetables, and spices awaited there, in the kind of vivid, glossy colours you don't usually see at Tesco. Next to them, fishmongers were showing off their scurrying crabs, bouncing mantis shrimp, sleepy flounders, and stealthy octopus. That is the freshness you can smell, and taste. Judging from my accent and enthusiasm for food, a tall and strong *Socio* shared his views on a cultural difference: we Italians live to eat, and the English eat to live.

Freshly home-cooked food has become a luxury to many people. Facing the grand challenge in building a healthy and sustainable food system, we look for solutions in science and technology—perhaps with confidence gained from modern medicine—to explore new sources of edible species, to create new ways of production, and to forge entirely new types of food. The plant-based meat alternatives have been in the spotlight and commercially available for a while now (although often limited to the high-income countries). These products were introduced about 12 years ago and enjoyed high popularity as the modern version of 'Nuttose', the first commercial meat alternative created by Dr. John Harvey Kellogg in 1896. However, they were soon criticised for their high sodium and carbohydrate content, placing them within the ultra-processed food category defined by the NOVA classification. The high exposure in social media didn't bring the same level of success. Besides the nutritional concerns, another factor withholding its popularity is the consumers' acceptance. They look the same, taste similar, and feel different. The 'meat-eaters' will probably never be truly satisfied by eating a beef burger reconstructed from legume protein isolates. A vegetarian would simply enjoy the legumes and vegetables as they are, not even a thought of trying the meat alternatives. A tasty tofu dish may bring them the same level of satisfaction as the wagyu steak to 'meat-eaters'.

We are what we eat. We are not only cultivated by the food we consume but also represented by the food culture we grow from. Food needs to be authentic to both taste and mind. One of the long-wanted qualities of healthy food is to be sensorially appealing and nutritionally balanced at the same time. People simply don't always make food choices based on rational thinking and nutrition knowledge, especially when the dietary recommendations go against the loud call of taste. Therefore, seeking solutions or inspirations in the traditional foods may save us a lot of effort, while providing an excellent excuse for the food maniacs like me to make my favourite food a study subject.

Bitter or mouth-watering, the art and nanoscience of tea making

One classic example of a well-educated taste and food choice is Chinese tea, the world's most widely manufactured drink. Chinese tea, made from the leaves of *Camellia sinensis*, is rich in phenolic compounds such as catechins, gallic acid, and theaflavins. These phenolic compounds are often bitter and astringent, which would have kept our hands off the teacups if we followed our instinct of avoiding the poisonous plants by steering clear of anything bitter or astringent. However, the processing of tea leaves, together with tea ceremony, has transformed both the leaves and us to harmony. Tea processing involves physical (heat, mechanical force), chemical (oxidation), and biological (enzyme catalysis, microbial fermentation) processes to prepare the cellular structure of leaves for proper water extraction and to transform the native components into something more palatable and less poison-like. The best way to enjoy the tea is through a tea ceremony, which typically involves several rounds of tea steeping and tasting using a fine porcelain tea set. The tea tastes far better than you might expect—no need to add milk or sugar. It is rich, well-balanced, refreshing and, most intriguingly, bitter in an enjoyable way.

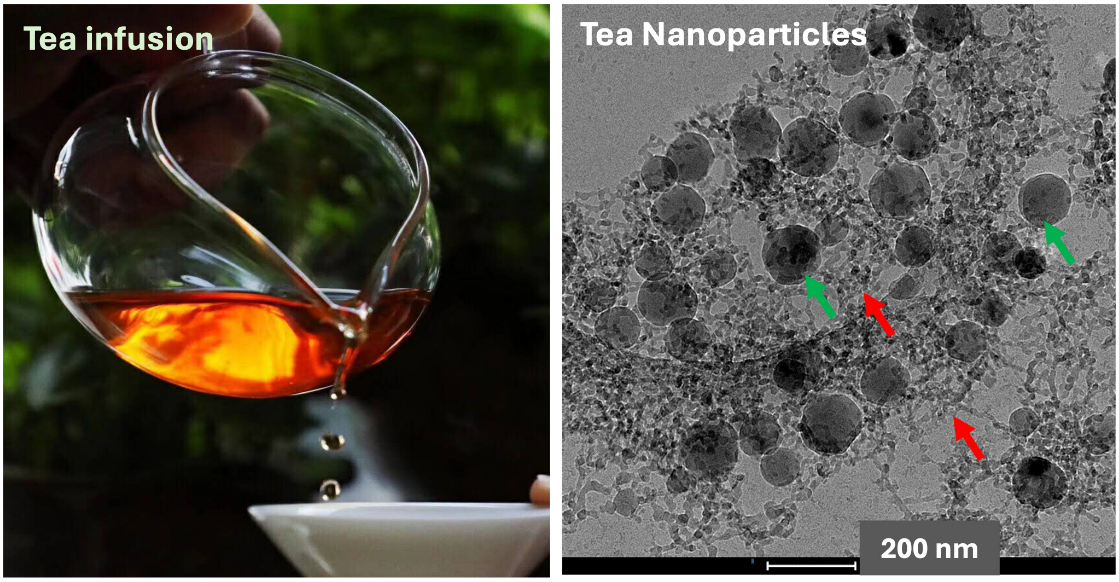

Figure 1. Black tea infusion and the nanoparticles (cryo-TEM image). Left: tea infusion (photography: Kangrong Sun). Right: green arrows, protein-based nanoparticles; red arrows, polysaccharide-based nanoparticles. The photo on the right is adapted from a figure published in https://doi.org/10.1039/D3FO00641G under a CC BY-NC 3.0 licence.

While you may be amazed by the professionalism of the tea master and the elegant porcelain cups, the secret to making a perfect cup of tea lies behind the gestures of the ceremony—in controlling the tea steeping. The tea infusion, prepared from whole leaves with freshly boiled hot water, is full of nano-sized colloidal particles (average diameter ~180 nm)(Figure 1). These nanoparticles are composed of proteins (particularly an enzyme called polyphenol oxidase), pectin, and polyphenols, and they are responsive to temperature changes ($20^{\circ}C$–$60^{\circ}C$) and pH (1–11). Most polyphenols in the tea infusion (70-80%) are carried by these particles. The formation of these native nanoparticles in tea infusion is due to the partially deformed cell wall, readily available proteins, polyphenols, and pectin in cytoplasm and in the extracellular matrix, as well as the generally intact cell–tissue structure of the leaves, which makes such selective and defined assembly possible.

Biomacromolecule–phenol complexes are a classic example of food-derived micro-/nano-scale structure affecting the overall sensory and digestive properties. For instance, protein conformational dynamics during food processing critically influence their functional properties, including solubility, emulsification, and gelation. Chemical modifications—such as glycation, disulphide bond rearrangement, and oxidation—play decisive roles in nanostructure formation, offering opportunities to tailor physicochemical, sensory, and nutritional properties using existing processing infrastructure. The protein scaffolds, often complexed with polysaccharides via hydrogen bonding or electrostatic interactions, serve as delivery vehicles for hydrophobic bioactives, micronutrients, and amphiphilic phytochemicals, enabling targeted release and, not to be underestimated, modulation of cell sensing(Figure 2).

The bitter-tasting tea catechins, a type of flavonoid, often contain hydrophobic residues and are entangled within the complexes of tea proteins and pectin. As a result, their bitter taste will be modulated while their bioactivities, like antioxidant and anti-inflammatory effects, are preserved during further processing and digestion. Other sensations, such as astringency and greasiness, are also affected in the presence of nanoparticles. Black tea infusion and its nanoparticles help saliva emulsify oil more effectively, thereby reducing the greasiness of eating oily food. This nicely explains why Pu-erh tea is served in every Chinese restaurant to accompany dim sum and roasted pork belly or duck.

Tea as medicine

Upon ingestion, tea nanoparticles directly interact with gastrointestinal mucus and mucosal cells, influencing taste transduction, nutrient sensing, and downstream cascade of physiological events. Besides harmonising the taste and mouthfeel, tea nanoparticles scavenge intracellular reactive oxygen species, modulate cellular redox and mitochondrial function, suppress mucosal inflammation, and alleviate inflammatory bowel disease (e.g., ulcerative colitis). These bioactivities echo nicely with the long history of using tea as a home therapeutic to help digestion and cease irritations in the gut. The tea nanoparticles were isolated with physical

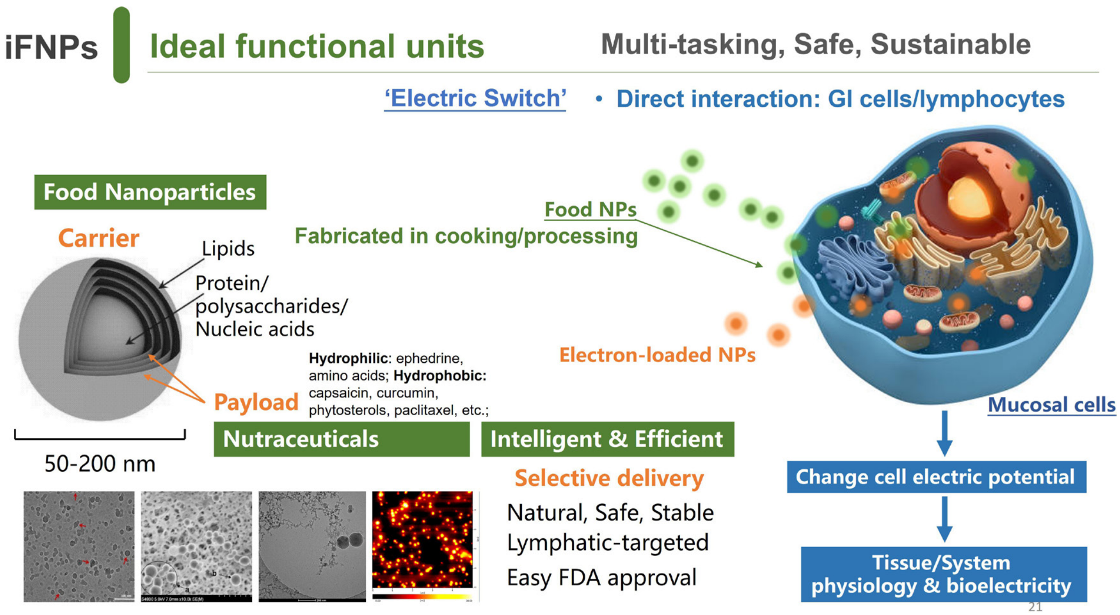

Figure 2. The multi-functional native nanoparticles derived from food. iFNPs, incidental food nanoparticles.

methods (ultrafiltration, gel filtration), which allow the preservation of native complexes formed during tea steeping. Unlike functional studies employing polyphenol extracts of tea, which typically require polyphenol concentrations one or two orders of magnitude higher than those found in a daily tea drink. Conversely, the isolated tea nanoparticles, which carry catechins from a normal tea drink, reproduced the effectiveness in *in vitro* cell models and *in vivo* animal models to the same extent as whole-body tea infusion, whereas a physical mixture of individual catechin compounds did not produce the same effects. The enhanced bioactivity of nanoparticles is attributed to the enrichment of tea catechins at the water/solid interface and their increased bioaccessibility and bioavailability to the intestinal mucosa. Furthermore, because protein–pectin–polyphenol complexes can be highly resistant to gastrointestinal enzymatic hydrolysis, some particle components—especially dietary fibre and polymerised polyphenols—will reach the lower intestine, modulate gut microbial homeostasis, and eventually degrade to short-chain fatty acids (SCFAs). The reabsorption of SCFAs, such as butyrate, can regulate enteroendocrine hormone secretion and cross the blood–brain barrier to influence brain function.

Future food: beyond being just a source of energy and nutrients?

Despite all our efforts and resources to transform the food system, we risk creating foods that meet scientific and nutritional standards—but fail to delight the senses. Sensory nutrition has traditionally centred on taste and smell, examining how these senses shape flavour and influence consumer choices. Yet food experiences involve far more than taste and smell—they include sensations like thirst, refreshment, appetite, fullness, bloating, mucosa irritation, ease of chewing and swallowing, warming and cooling, and even digestive responses such as constipation and drowsiness. A truly comprehensive understanding must also include somatic sensations—such as texture, temperature, pain, and oral kinesthetics—and visceral signals from the gut. Visceral afferent signals that control hunger, satiety, and energy balance often operate below conscious awareness, yet they strongly shape eating behaviour and metabolism. At the cell level, activating taste receptors (e.g., bitter, sweet)—both oral and extraoral—by the tastants (e.g., flavonoids, sugar and sweeteners) or nutrients (e.g., fatty acids, amino acids) released from the food complexes set off complex processes that orchestrate digestion, hormone, immunity, oxidative balance, and gut microbiome, highlighting their importance in future food design. Understanding the cross-talk between senses and the interplay of food microstructure and cell sensing may inform food engineering and dietary intervention strategies, paving the way for optimised nutrition and a healthier food system.

The sensory impairments caused by ageing and diseases such as COVID-19, diabetes, and multiple sclerosis—combined with emerging insights into taste receptors along the gut–immune–brain axis—underscore the need for novel foods designed with sensory nutrition in mind. One promising approach is to draw inspiration from nature, build on culinary traditions, and harness advanced technologies such as nanostructure fabrication to optimise cellular sensing. Ultimately, these innovations should aim not only for nutritional excellence but also for pleasurable human perception and experience.

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Further Reading

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