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Applying Material Science to Caffeine Delivery in Functional Drinks: Targeted Release and Improved Bioaccessibility with Nano-/Microcarriers

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(I) Introduction: Background on caffeine

Caffeine (1,3,7-trimethylxanthine), a purine alkaloid, is a white crystalline powder with a molar mass of **194.19 g/mol** and a log P of about **−0.07**. It is moderately **soluble** in H_2O and classified as **hydrophilic**. It occurs naturally in **coffee beans** (*Coffea arabica*) and **tea leaves** (*Camellia sinensis*).

Mechanism of action (Figure 1):

- **Non-selective adenosine receptor antagonist** (A1, A2A, A2B).
- It **boosts the secretion of dopamine** and **norepinephrine**, amplifying the stimulation of the **CNS.**
- It acts as a phosphodiesterase (PDE) inhibitor, elevating intracellular cAMP and **promoting lipolysis** and **thermogenesis.**
- It **modulates** intracellular Ca^{2+} via the inositol triphosphate receptor (IP_3R), thereby **influencing** neurotransmission.
- **Biological activity:**
  - → Stimulatory and cognitive-enhancing effects
  - → Metabolic support
  - → Antioxidant effects
  - → Neuroprotective effects via metabolites

Limitations of conventional caffeine delivery

- **Pharmacokinetics:** rapid gastrointestinal absorption, metabolized in
- the liver via the isoenzyme **CYP1A2**, half-life **≈ 3–7 h.**
- **Bioavailability:** short-lived plasma levels, rapid peaks and **declines** → **inconsistent energy effects.**
- **Adverse effects:** tachycardia, insomnia, anxiety, gastrointestinal discomfort.
- **Variability:** age, genetics, sex, body mass, habitual intake influence tolerance.

Materials science

Increase **bioavailability**, **stability**, and **controlled release** through encapsulation with **nano-/microcarriers.**

Nanomaterial-Based encapsulation

It **preserves** caffeine from acidic gastric breakdown, allows for **targeted intestinal release, stabilizes** plasma concentrations, **prolongs** the stimulatory effects, and **mitigates acute pharmacological spikes** and systemic side effects.

Influence of the liquid matrix

- **Macro-/micronutrients** in functional drinks influence:
  - → **Nanocarrier physicochemical stability**
  - → **Release kinetics** (diffusion, dissolution, degradation)
  - → **Caffeine bioaccessibility** (interaction with proteins, polysaccharides, lipids)
- Matrix–nanocarrier interactions are critical for **predictive formulation design**

Benefits and consumer implications

- **Pharmacological:** sustained **release**, improved **safety**, minimized **side effects.**
- **Sensory:** reduced bitterness and astringency via taste receptor modulation.
- **I+D+i:** promotes the **next generation** of functional drinks with optimized. **bioefficacy**, **sensory profile,** and **consumer appeal.**

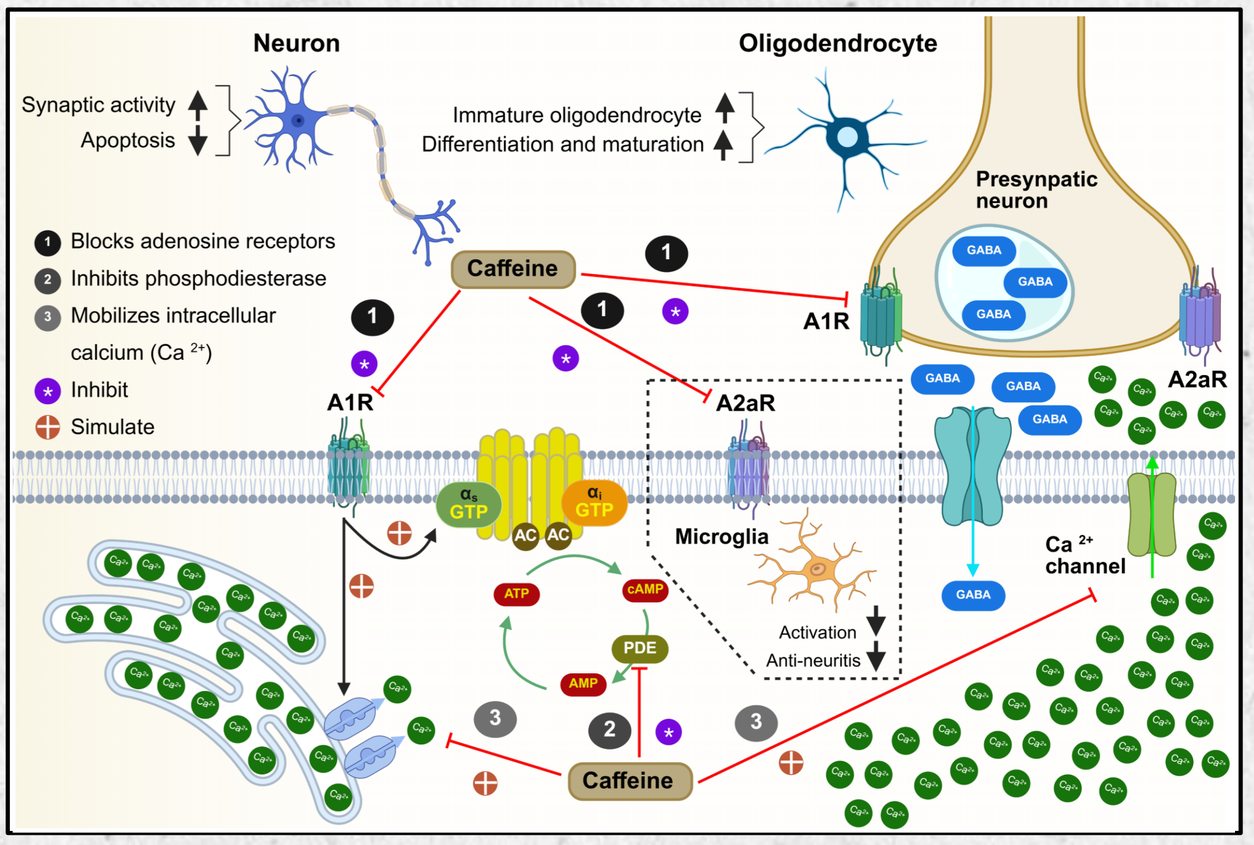
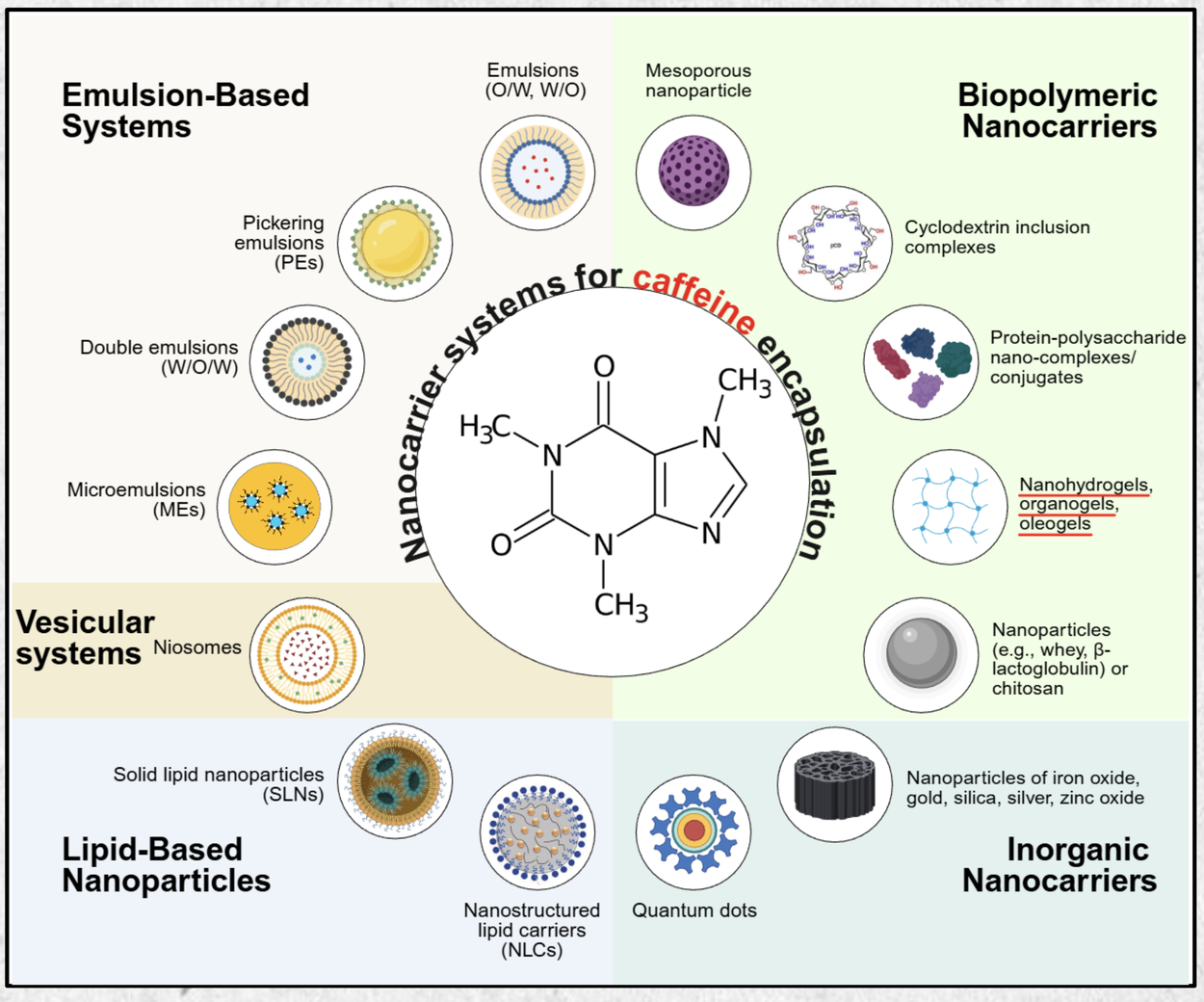
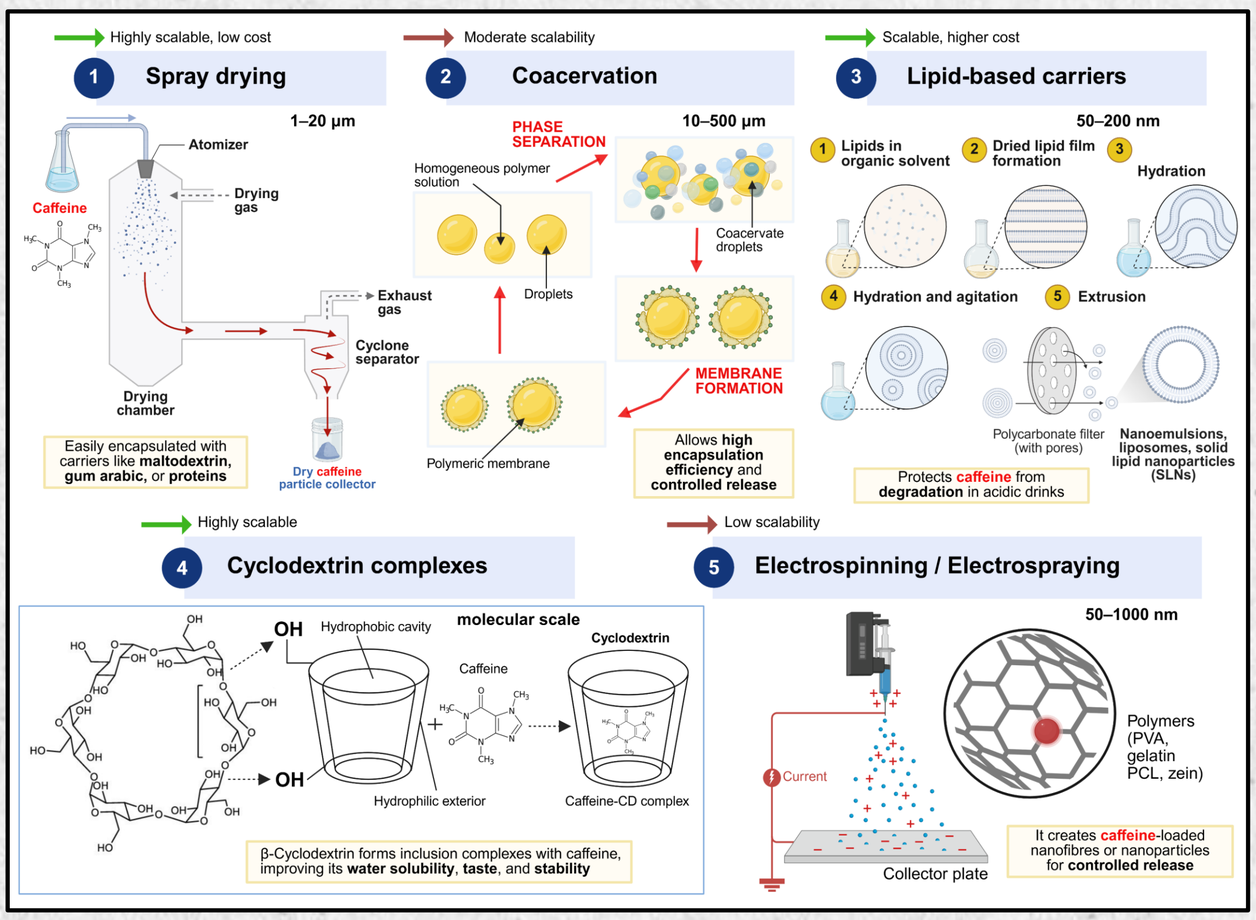


Figure 1 | Major mechanisms of caffeine within the central nervous system (CNS): adenosine receptor antagonism (mainly A1R and A2aR), phosphodiesterase inhibition, and intracellular calcium mobilization. Through these actions, caffeine influences neuronal activity, oligodendrocyte maturation, microglial activation, and neurotransmitter release. ***Abbreviations:*** A1R, A2aR, A2bR, A3R – adenosine receptors, AC – adenylate cyclase; AMP – adenosine monophosphate; cAMP – cyclic adenosine monophosphate; Ca^{2+} – calcium ion; GABA – γ-aminobutyric acid; GTP – guanosine triphosphate; PDE – phosphodiesterase. (Yang et al., 2021).

(II) Different carriers for the delivery of caffeine



(III) Techniques for encapsulation caffeine for delivery in functional drinks



(IV) Conclusions and future outlook

Nano- and microstructured encapsulation -based technologies, such as spray drying and electrospinning, may offer a versatile and efficient approach to **make safer, tastier,** and **more beneficial functional drinks**. When integrated into optimal liquid matrices, the pharmacokinetic behavior and bioavailability of caffeine can be boosted, paving the way **for enhanced physiological performance and greater commercial acceptance.** Overall, **cost, process control,** and **industrial upscaling** remain key bottlenecks for commercial applications.

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References

Fang, Z., & Bhandari, B. (2010). Encapsulation of polyphenols – A review. *Trends in Food Science & Technology, 21*(10), 510–523. https://doi.org/10.1016/j.tifs.2010.08.003

Mozafari, M. R., Johnson, C., Hatziantoniou, S., & Demetzos, C. (2008). Nanoliposomes and their applications in food nanotechnology. *Journal of Liposome Research, 18*(4), 309–327. https://doi.org/10.1080/08982100802465941

Shaddel, R., Akbari-Alavijeh, S., Cacciotti, I., Yousefi, S., Tomas, M., & Capanoglu, E. (2024). Caffeine-loaded nano/micro-carriers: Techniques, bioavailability, and applications. *Critical Reviews in Food Science and Nutrition, 64*(15), 4940–4965. https://doi.org/10.1080/10408398.2022.2147143

Yang, L., Yu, X., Zhang, Y., Liu, N., Xue, X., & Fu, J. (2021). Encephalopathy in preterm infants: Advances in neuroprotection with caffeine. Frontiers in Pediatrics, 9, 1–11. https://doi.org/10.3389/fped.2021.724161