OPEN ACCESS

Scholars Bulletin

Abbreviated Key Title: Sch Bull
ISSN 2412-9771 (Print) |ISSN 2412-897X (Online)
Scholars Middle East Publishers, Dubai, United Arab Emirates
Journal homepage: https://saudijournals.com

Subject Category: Biotechnology

Advancements in Nanoencapsulation Strategies for Enhancing Functionality and Quality of Food

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DOI: https://doi.org/10.36348/sb.2026.v12i01.002 | **Received:** 02.11.2025 | **Accepted:** 07.01.2026 | **Published:** 16.01.2026

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Abstract

Consumers around the world are turning to natural ingredients to enhance flavor and promote health and well-being, as food industry around the globe has seen a surge. The innovative technologies are brought in to ensure that food is available but safe and beneficial to all. Therefore, Nanoencapsulation is gaining much importance in nutraceuticals and encapsulation of food components. Considering the global food security and food safety we must move forward the ultimate sustainable food production, processing, preservation, bioavailability and food packaging techniques, which will assist and gives more economical as well environment friendly results. The main objective of this review is to create understanding for different nano encapsulating techniques, being used by producer to attain more profit and more sustainable products. On the other hand, Encapsulation technique can be used for the protection and controlled release of bioactive compounds towards targeted sides. These encapsulation processes include emulsification, coacervation, freeze drying, super critical fluid techniques, emulsification-solvent evaporation techniques and spray drying. All these processes have somehow limited utilization and exemplification in food industry. The Producer who has capacity to generate more advanced or extra ordinary approach in food industry should not lemmatized to conventional techniques of encapsulation. We cover some advances in encapsulation procedures which are not applicable to food but being utilized in pharmaceutical industry as well. Furthermore, we have given some suggestions to both producers as well as consumer aspect to make better understanding of cooperation in future.

Keywords: Nano technology, encapsulation, emulsification, trends in nanotechnology.

INTRODUCTION

Nanomaterial had been designed by human for the improvement and success of humanity. In 1959, Richard Feynman proposed the concept of nanostructures, while Nario Taniguchi proposed the term Nanotechnology for its control or process use of the nanoparticle in 1974, the one dimension of 10−9 meter being called a minimum size (Sun *et al.,* 2020). Nanotechnology can perhaps restructure farming and food structures, supply nourishments influencing the privilege, adequacy, dietary execution properties just as the subatomic blend of new items fixing and bioavailability (Joshi *et al.,* 2024). Small particles of building materials stuffed into a divider material for instance. An embodiment technique was used in a previous study to ensure bioactive mixes (polyphenols, micronutrients, and nutraceuticals, compound, anticancer agents,) and achieved submission to shield them from unfavorable condition or for the controlled delivery to exogenous locales (Tan & McClements, 2021).

They have been observed as colloidal fragments of dimension from 10 to 1000nano meters, which will transmit as nano sphere or nano capsules (Lamch *et al.,* 2018). It is accepted that nanocarriers (<1000 nm by and

huge) may have higher bioavailability because of greater broadness to volume proportion and in this way, higher mucoadhesive potential inside the little digestive framework, along these lines, the likelihood of taking a shot at proteins and metabolic chemicals; be that as it may, these little units could effortlessly infiltrate those cell dividers and interface the objective cells to discharge its charge (Katouzian, *et al.,* 2017; Jafari and McClements, 2017). Various methods are employed to construct the cases, for example, splash drying, splash cooling or spray chilling, fluidized bed covering, liposome entrapment, coacervation, incorporation complexation, radial expulsion and rotational suspension division (Tabassum *et al.,* 2023). Encapsulation techniques in food innovation protect bioactive compounds from environmental factors like heat and moisture, enhance their stability, and allow controlled release at desired times and concentrations (Saifullah *et al.,* 2019).

The macroscale highlights of food are developed by the utilization of nanotechnology including, taste, surface, other tactile characteristics, shading quality, process capacity, and strength during timeframe of realistic usability, prompting an inordinate number of new items. Moreover, nanotechnology other than increment the water solvency, oral bioavailability of bioactive compound and warm steadiness (Safarzaei *et al.,* 2024). Utilizations of this technology in food enterprises are presently Nano composites wise food bundling material to governing dissemination and bacterial, assurance, pathogen, discover, Nano biosensors for recognition of tainting and quality diminishing, and Nano exemplification or Nano transporter for exact conveyance to Nutraceuticals and food bioactive compounds (Pudake *et al.,* 2024; de Sousa 2023). On the other hand, flavor and antimicrobials conveyance to enhanced time span of usability, prolamin, available in corn protein work as a nano carries to transfer flavor mixes (Safarzaei *et al.,* 2024). The utilization of palatable meager film made with Nano covers to shield the foods grown from the ground from loss of gases like oxygen or ethylene, which abuse the food content (Pirozzi *et al.,* 2021). Numerous audits and investigations have been distributed for the utilization of nanotechnology in nourishments. Notwithstanding, just hardly any works were centered around nanoencapsulation of food fixings.

Nano Carriers

We can arrange the food Nano bearers into 5 sorts dependent on the center fixings/gear for readiness of these epitome frameworks lipid-based nanocarriers, nanoemulsions, Nanoliposomes, nano-lipid transporters (Akhavan *et al.,* 2018; Jafari *et al.,* 2017;). Nature-motivated nanocarriers including various types of caseins protein which is present in milk and cyclodextrins, and amylose nanostructures created by uncommon hardware electro-turning/splashing, nano spray dryer (Haratifar & Guri, 2017) and smaller nano-fluidics frameworks, biopolymer nanoparticles defined through particular biopolymer nanoparticles produced by precipitation of carbohydrates or desolation of proteins (Sadeghi *et al.,* 2017). Complexation of double diversely surface charged biopolymers (Hosseini *et al.,* 2017) nano-gels of biopolymers, for example soy proteins whey, alginates, or chitosan (Mokhtari *et al.,* 2018) whereas nanotubes and nanofibrils of whey proteins various nanocarriers they incorporate nanoparticles produced using synthetic polymers; nano-organized surfactants, for example nanocrystals, cubosomes, noisome, inorganic nanoparticles, microemulsions.

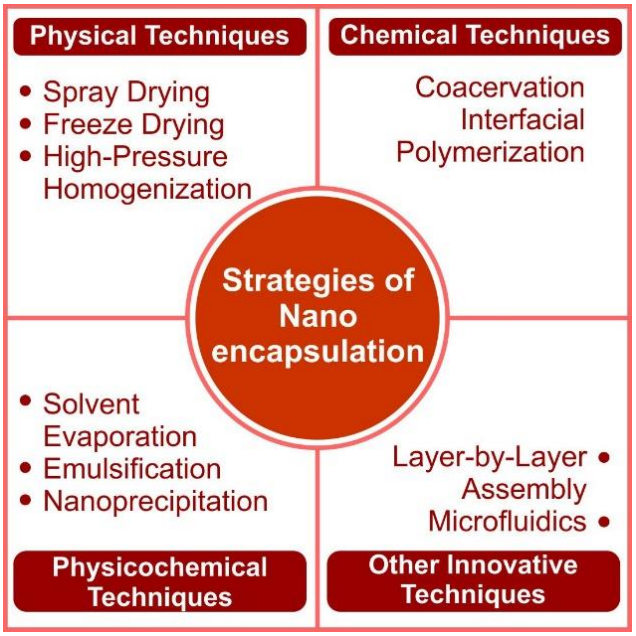

Figure: Simplified breakdown of nanoencapsulation strategies

NANO ENCAPSULATION TECHNIQUES

The physicochemical properties of a molecule, such as size, size distribution, surface region, shape, solubility, and encapsulation properties and encapsulating agents were taken to account nanoencapsulation techniques including incorporation, emulsification, coacervation, emulsification, or dissolvable dissolution and supercritical liquid, nanoprecipitation, and procedure (Prajapati *et al.,* 2023).

Table: Key advancements of nanoencapsulation strategies

Technique	Food Item/Outcome	Reference
Spray Drying	Encapsulation of bioactive peptides for improved solubility and stability.	Berraquero-García *et al.,* 2023
Freeze Drying	Preservation of probiotics with enhanced stability and shelf life.	Shavronskaya *et al.,* 2023
Emulsification	Development of stable double emulsions for vitamin encapsulation in dairy products.	Doost *et al.,* 2020
Solvent Evaporation	Encapsulation of hydrophobic bioactive in nano emulsions for food applications.	Sneha & Kumar, 2022
Microfluidics	Encapsulation of probiotics with precise control over particle size and uniformity.	Songca, 2024
Spray-Freezing Drying	Creation of nano emulsions for encapsulating bioactive compounds like curcumin in foods.	Khoshnoudi-Nia *et al.,* 2022
Electro spraying	Production of nonencapsulated bioactive ingredients for functional beverages.	Berraquero-García *et al.,* 2023

Emulsification Technique

Bioactive compounds generally mixed with fluids which is arrange by creating nano emulsions and this colloidal scattering contains more than one immiscible fluid. These two immiscible solutions in which one is dispersing while other one is bead sized ranging from 50 to 1000 nm (Negi *et al.,* 2024). It would provide extraordinary ability to embody or embody relatively high centralization of dissolvable oil, bioactive components, food supplementation or nutraceutical with huge scope of lipophilic exceptional substance specialists such as, β-carotene, vegetable sterol, nutritional fat, and carotenoids would be epitomized or convey by oil in water emulsion but would have utilized water in support emulsion for food dynamics or waste solvent operations for instance, polyphenols (Aktaş *et al.,* 2024). These emulsions both in fluids phase or dried phase to powder structure may utilize effectively for example freeze drying and spray drying before and after emulsion process have very high dynamic strength since of their amazing little emulsion bead size (Cao *et al.,* 2020). Elevated motor strength of this emulsion has genuine advantages to embodiment process which assume to basic job in maintenance for oil substance (Rezvankhah *et al.,* 2020).

Coacervation

The coacervation method includes the stage detachment of a solitary or a blend of polyelectrolyte from an answer and the resulting affidavit of the recently framed coacervate stage around the dynamic fixing. Further, a hydrocolloid shell can be cross-connected utilizing a proper compound or enzymatic cross-linker, for example, glutaraldehyde or transglutaminase, for the most part to expand the strength of the coacervate (Maqsoudlou *et al.,* 2020). We divide along the lines of straight forward (one polymer) or complex coacervation (more than one polymer) in terms of the quantity used while creating polymer. The intensity and communication between these polymers is influenced by numerous variables, for example, biopolymer classification relying upon molar mass, charge, or flexibility, ionic quality, pH, focus and weight by biopolymer (Xiao *et al.,* 2017). Wang et al. (2018) expressed that this is a particular and promising exemplification innovation in view of the high payloads reachable (near to 98 %) so that potential outcomes of managed discharge dependent on mechanical pressure, temperature, or supported discharge. Anandharamakrishnan (2014) embodied capsaicin utilizing this straightforward coacervation procedure in gelatin to cross-connecting with glutaraldehyde while drying in the vacuum broiler.

Emulsification–Solvent Evaporation Technique

This technique involves the dissipation of process by adjusted dissolvable strategy where the polymer creates a fluid stage and the actual polymer precipitation as nanosphere (Yan *et al.,* 2021). Their size can be changed in the frame arrangement considering the mix rate consistency, fluid stages, type and area of scattering operator (Operti *et al.,* 2019). There are a lot of different polymers utilized namely PLGA, PLA, acetate phthalate, PCL, ethyl cellulose, and others may use by ultra-sonification or homogenization basis. Alongside the freeze-drying procedure different emulsion or dissolvable strategy may use to produce better results (Rezvankhah *et al.,* 2020). This process produces nano capsules being utilized as circular fit as fiddle and molecule size ranges from 255 to 420 nm and 20 to 95 % nanoencapsulation acquired likewise when curcumin was exemplified in utilizing dissolvable dissipation strategy followed by freeze drying procedure. (Walia *et al.,* 2019). The got nano capsules were round,

with epitome efficiency of around 75 %. Besides, the nano capsules discovered practically two times the restraint of unsafe cells when contrasted with utilizing curcumin alone. Similarly, utilizing the emulsification–dissolvable dissipation method, Rachmawati *et al.,* (2016) arranged curcumin-stacked PLGA by nanospheres.

The nanospheres were smooth, round, and displaying high return and medication ensnarement effectiveness, with a mean molecule distance across of 45 nm. Further, they announced higher intracellular take-up and effective activity in prostate malignant growth cell lines. Mehanny *et al.,* (2016) moreover epitomized curcumin in a kind of nanocarrier which use dissolvable or emulsion–dissipation technique. These are seen to have association with 110 nm in diameter of size, with a tough diffusion and epitome efficiency of 75 %. These efficient frame works is also subjected to another method we called as freeze drying.

Supercritical Fluid Technique

Any fluid or a gas which being utilized by its thermodynamic properties to create super critical liquids which attain definite characteristics by its specific nature depends on temperature and weight (Kanbur *et al.,* 2024). These liquids have characteristics properties of path provision to liquids and gas interfaces, when there is low thickness on the other hands high diffusivities and high solvating power while high mass exchange rate to basic units so a lot of various mixture being used for treatment like propane, water and nitrogen (Duarte *et al.,* 2022). When fast extension founded from supercritical arrangement, we use different strategy to covers, like gas antisolvent, airborne dissolvable extraction, fast extension from supercritical fluids packed precipitation of antisolvent (Liang *et al.,* 2023; Saadati Ardestani *et al.,* 2022). When a bioactive compound or a polymer whenever is mixed by these fluids the arrangements extended using splash drying at that point, these fluids vanished while remaining particles settle for long time accelerated (Ha *et al.,* 2023). This procedure has been generally utilized considering its low basic temperature and least utilization of natural dissolvable.

Drying Techniques for Producing Nanoparticles

One must consider the very serious issue when we collect irreversible nano capsules, it has brittleness which comes by hydrolysis procedure of polymeric substances, and this brings dynamic fixings may be very easy to get spoil (Stoica *et al.,* 2024). Whereas its useful to create the nano capsule suspension by dried structure because a hard composition be maintaining by drying of such things in encapsulation (Saifullah et al. 2019). With the help of some these encapsulating techniques some suspensions of nano solutions which are covered by some coating material may deliver by dried substance to stabilize the structure. we generally divided these techniques into two main categories namely splash drying and freeze drying (da Fonseca Machado *et al.,* 2018). Dried powder form of nano capsules has better control over total discharge of bioactive compounds (Shishir *et al.,* 2018). Whenever we are creating these probes, the extra weight of coated material causes handling issues, so it's important to examine before this procedure of connection among the encapsulating material as well as the coated or inner material to accomplished better results (Singh *et al.,* 2023).

Spray Drying

Spray drying comprises with a process of change of the very low-level material feed (the arrangement of inside portion) into a very sophisticated dried particulate matter which structure by spraying the feed which has limitation, into a very hot drying medium. This produces a very fine and minute particle, and these has size small with less making time and likewise a gradually efficiently done and unit activity has marked (Piñón-Balderrama *et al.,* 2020). Since of its constant creation in which limit of dry powders with a very low value of the dampness content, this commonly utilized the whole for the modern or advanced procedure (Fedorowicz & Bartkowiak, 2024). Also, that point where the settled system in food the industry lines a very limited and generally utilized for exemplification since recent 10 years. This is the procedure that has very much common steps likewise when used to epitomize an extensive scope of food fixings, for example, minerals, nutrients, flavors, , fats, hues, and ,some common testing oils such that as to protection of them from their predicted in general situations or enlarge timeframe of realistic utilization of the basic strength during capacity (Delshadi *et al.,* 2020), and in this way it has a general understanding where a very well may be measured as a decent nanoencapsulation technique. Be that as it may, on account of nanoencapsulation, it is one of the only sophisticated methods which is trained for shifting over a suspension of colloidal nanoparticles which has some putting into a nanostructured a very fine powder structure (Singh *et al.,* 2023).

Freeze Drying

When fragrances and delicate materials fully dry out by utilizing the low temperature strategy, we coined the term freeze drying. Freeze drying was a multi-stage movement comparing materials all through the four principal stages: the first one is freezing, the second one is sublimation (essential the drying), third one is desorption stage, and, the last one is stockpiling. Freeze drying takes common quality elements, which are efficiently reconstituted, but having a furthermore drawn-out time span of utilization (Bhatta *et al.,* 2020). All things considered, freeze drying is normally utilized for the separation of nanoparticles (i.e., by expulsion of the water and from the other substances) this delivered is by other the nanoencapsulation strategies. Throughout freeze drying, small pores must shaped since of the core ice sublimation procedure. Thus, this method isn't so

simply exemplification as energetic food fixings have to offered to the air since of these pores are in the very top and so on the molecule surface. Thus, it is difficult to develop any of the minute discharge system like in which the dissemination or disintegration strategy are helpful. Presently, freeze drying method is approximately utilized policy by which one has to expel the inner water from nano capsules without the altering those shape and structure (Rezvankhah *et al.,* 2020).

Application

The global market for nanotechnology was estimated at USD 54.2 billion in 2020 and is anticipated to show a demand of 13.9% CAGR from 2021 to 2028. Current trends of increased nanotechnology use in the food and beverage sector are packaging, delivery systems and food safety (Chinnasami Sivaji *et al.,* 2024). Nanotechnology covers all of the main processes like bioavailability, nano sensors, food safety, food security and food packaging systems detection of pathogens (Singhal & Rana, 2019).

CONCLUSION

Nanotechnology now has more ability in developing the efficiency bioavailability of food products to fulfill consumer demands. Presently, several nanoencapsulation techniques are emerging with their own merits and demerits including, supercritical fluid technique, coacervation, emulsification, and inclusion complexation, nanoprecipitation solvent evaporation, are procedures for nanoencapsulation of food ingredients. Furthermore, coacervation, and emulsification continuously distinctive techniques for encapsulation of lipophilic compounds. Nevertheless, sum of all the encapsulation techniques finally depend on appropriate freezing techniques to create nano encapsulates in freeze form. Presently, drying and freezing methods are extensively utilized techniques engaged in the nano encapsulation process. However, spray drying is costly or require additional processing period. Moreover, all these techniques have some different processes factors which will affects the final product, these factors may be optimized and control. many of them depicts excellent bioavailability and some of them have inhibitory results against diseases.

Conflict of Interest

There is no conflict of interest among all authors.

Acknowledgment

All authors contributed equally for this review article.

REFERENCES

- Akhavan, S., Assadpour, E., Katouzian, I., & Jafari, S. M. (2018). Lipid nano scale cargos for the protection and delivery of food bioactive ingredients and nutraceuticals. Trends in Food Science & Technology, 74, 132-146.
- Aktaş, H., Napiórkowska, A., Szpicer, A., Custodio-Mendoza, J. A., Paraskevopoulou, A., Pavlidou, E., & Kurek, M. A. (2024). Microencapsulation of green tea polyphenols: Utilizing oat oil and starch-based double emulsions for improved delivery. International Journal of Biological Macromolecules, 274, 133295.
- Anandharamakrishnan, C. (2014). Techniques for nanoencapsulation of food ingredients (Vol. 8, pp. 65-67). New York: Springer.
- Berraquero-García, C., Pérez-Gálvez, R., Espejo-Carpio, F. J., Guadix, A., Guadix, E. M., & García-Moreno, P. J. (2023). Encapsulation of bioactive peptides by spray-drying and electrospraying. Foods, 12(10), 2005.
- Bhatta, S., Stevanovic Janezic, T., & Ratti, C. (2020). Freeze-drying of plant-based foods. Foods, 9(1), 87.
- Cao, L., Xu, Q., Xing, Y., Guo, X., Li, W., & Cai, Y. (2020). Effect of skimmed milk powder concentrations on the biological characteristics of microencapsulated Saccharomyces cerevisiae by vacuum-spray-freeze-drying. Drying Technology, 38(4), 476-494.
- Chinnasami Sivaji, M. R., Saravanan, V., & Kumaravel, M. (2024). The applications of nanotechnologies in food science using the ARAS method. Journal on Applied and Advanced Research, 12(4), 389–400.
- da Fonseca Machado, A. P., Rezende, C. A., Rodrigues, R. A., Barbero, G. F., e Rosa, P. D. T. V., & Martínez, J. (2018). Encapsulation of anthocyanin-rich extract from blackberry residues by spray-drying, freeze-drying and supercritical antisolvent. Powder Technology, 340, 553-562.
- de Sousa, M. S., Schlogl, A. E., Estanislau, F. R., Souza, V. G. L., dos Reis Coimbra, J. S., & Santos, I. J. B. (2023). Nanotechnology in packaging for food industry: Past, present, and future. Coatings, 13(8), Article 1411.
- Delshadi, R., Bahrami, A., Tafti, A. G., Barba, F. J., & Williams, L. L. (2020). Micro and nano-encapsulation of vegetable and essential oils to develop functional food products with improved nutritional profiles. Trends in Food Science & Technology, 104, 72-83.
- Doost, A. S., Nasrabadi, M. N., Kassozi, V., Nakisozi, H., & Van der Meeren, P. (2020). Recent advances in food colloidal delivery systems for essential oils and their main components. Trends in Food Science & Technology, 99, 474-486.
- Duarte, M. M., Silva, I. V., Eisenhut, A. R., Bionda, N., Duarte, A. R. C., & Oliveira, A. L. (2022). Contributions of supercritical fluid technology for advancing decellularization and postprocessing of viable biological materials. Materials Horizons, 9(3), 864-891.
- Fedorowicz, A., & Bartkowiak, A. (2024). The Influence of Different Butter Type, Their Fatty Acid

Composition and Melting Enthalpy on the Viability Rate of Lacticaseibacillus rhamnosus GG Directly After the Spray-Drying Process and During Storage of Powders. Foods, 13(23), 3803.

- Ha, E. S., Kang, H. T., Park, H., Kim, S., & Kim, M. S. (2023). Advanced technology using supercritical fluid for particle production in pharmaceutical continuous manufacturing. Journal of Pharmaceutical Research, 5(4), 123–135.
- Haratifar, S., & Guri, A. (2017). Nanocapsule formation by caseins. In Nanoencapsulation technologies for the food and nutraceutical industries (pp. 140-164). Academic Press.
- Hosseini, S. M., Ghiasi, F., & Jahromi, M. (2017). Nanocapsule formation by complexation of biopolymers. In Nanoencapsulation technologies for the food and nutraceutical industries (pp. 447-492). Academic Press.
- Jafari, S. M., Paximada, P., Mandala, I., Assadpour, E., & Mehrnia, M. A. (2017). Encapsulation by nanoemulsions. In Nanoencapsulation technologies for the food and nutraceutical industries (pp. 36-73). Academic Press.
- Joshi, N., Nawaz, T., Rahman, T. U., & Khan, M. N. R. (2024). Application of nanotechnology in biofortification. In Applications of Agri-Nanotechnology (pp. 85–102). Springer.
- Kanbur, B. B., Busch, A., & Kriezi, E. E. (2024). Computational multiphase mixture simulations of a two-phase R-744 ejector geometry in transcritical R-744 heat pump applications. International Journal for Heat & Fluid Flow, 15(1), 100-115.
- Khoshnoudi-Nia, S., Forghani, Z., & Jafari, S. M. (2022). A systematic review and meta-analysis of fish oil encapsulation within different micro/nanocarriers. Critical Reviews in Food Science and Nutrition, 62(8), 2061-2082.
- Lamch, Ł., Pucek, A., Kulbacka, J., Chudy, M., Jastrzębska, A., Szuwarzyński, M., & Świerczek, J. (2018). Recent progress in the engineering of multifunctional colloidal nanoparticles for enhanced photodynamic therapy and bioimaging. Advances in Colloid and Interface Science, 261, 62–81.
- Liang, D., Zhang, W. M., Liang, X., Tian, H. Y., Zhang, X. M., Li, X., & Gao, W. Y. (2023). A review on the extraction and separation of andrographolide from Andrographis paniculata: Extraction selectivity, current challenges and strategies. Trad. Med. Res., 8(7), 37-42.
- Maqsoudlou, A., Assadpour, E., Mohebodini, H., & Jafari, S. M. (2020). Improving the efficiency of natural antioxidant compounds via different nanocarriers. Advances in Colloid and Interface Science, 278, 102122.
- Mehanny, M., Hathout, R. M., Geneidi, A. S., & Mansour, S. (2016). Exploring the use of nanocarrier systems to deliver the magical molecule; curcumin and its derivatives. Journal of controlled release, 225, 1-30.
- Mokhtari, H., Ghasemi, Z., Kharaziha, M., Karimzadeh, F., & Alihosseini, F. (2018). Chitosan-58S bioactive glass nanocomposite coatings on TiO2 nanotube: Structural and biological properties. Applied Surface Science, 441, 138-149.
- Negi, A., Vanmathi Mugasundari, A., & Singh, A. (2024). Nanoemulsion: A potential strategy toward edible coatings. Food Coatings and Encapsulation Technology, 10, 175–190
- Operti, M. C., Dölen, Y., Keulen, J., van Dinther, E. A., Figdor, C. G., & Tagit, O. (2019). Microfluidics-assisted size tuning and biological evaluation of PLGA particles. Pharmaceutics, 11(11), 590.
- Pirozzi, A., Ferrari, G., & Donsì, F. (2021). The use of nanocellulose in edible coatings for the preservation of perishable fruits and vegetables. Coatings, 11(8), 990.
- Prajapati, B. G., Basu, B., & Kendre, P. N. (2023). Methods for nanoencapsulation: Emulsification, coacervation, nanoprecipitation, and supercritical fluid technologies. Sustainable Process for Advanced Applications, 30(1), 55–70.
- Pudake, R. N., Mohanta, T. K., & Mahato, N. (2024). Opportunities and challenges for nanotechnology in sustainable agri-food production. Frontiers in Nanotechnology, 6, 1420192
- Rachmawati, H., Yanda, Y. L., & Rahma, A. (2016). Curcumin-loaded PLA nanoparticles: Formulation and physical evaluation. Scientia Pharmaceutica, 84(2), 191–202.
- Rezvankhah, A., Emam-Djomeh, Z., & Askari, G. (2020). Encapsulation and delivery of bioactive compounds using spray and freeze-drying techniques: A review. Drying Technology, 38(1-2), 235-258.
- Rezvankhah, A., Emam-Djomeh, Z., & Askari, G. (2020). Encapsulation and delivery of bioactive compounds using spray and freeze-drying techniques: A review. Drying Technology, 38(1-2), 235-258.
- Rezvankhah, A., Emam-Djomeh, Z., & Askari, G. (2020). Encapsulation and delivery of bioactive compounds using spray and freeze-drying techniques: A review. Drying Technology, 38(1-2), 235-258.
- Saadati Ardestani, N., Rojas, A., Esfandiari, N., & Galotto, M. J. (2022). Supercritical fluid extraction from Zataria multiflora Boiss and impregnation of bioactive compounds in PLA for developing materials with antibacterial properties. Processes, 10(9), 1787–1795.
- Sadeghi, R., Rodriguez, R. J., Yao, Y., & Kokini, J. L. (2017). Advances in nanotechnology as they pertain to food and agriculture: benefits and risks. Annual Review of Food Science and Technology, 8(1), 467-492.
- Safarzaei, A., Farahmandfar, R., Mehravaran, A., & Fanaei, H. (2024). Application of antisolvent precipitation method for encapsulation of date seed

extracts of Rabbi variety in zein ptotein biopolymer. Journal of food science and technology (Iran), 20(145), 188-207.

- Saifullah, M., Shishir, M. R. I., Ferdowsi, R., & Rahman, M. R. T. (2019). Micro and nano encapsulation, retention, and controlled release of flavor and aroma compounds: A critical review. Trends in Food Science & Technology, 86, 34–48.
- Saifullah, M., Shishir, M. R. I., Ferdowsi, R., Rahman, M. R. T., & Van Vuong, Q. (2019). Micro and nano encapsulation, retention and controlled release of flavor and aroma compounds: A critical review. Trends in Food Science & Technology, 86, 230-251.
- Shavronskaya, D. O., Noskova, A. O., Skvortsova, N. N., Adadi, P., & Nazarova, E. A. (2023). Encapsulation of Hydrophobic Bioactive Substances for Food Applications: Carriers, Techniques, and Biosafety. Journal of Food Processing and Preservation, 2023(1), 5578382.
- Shishir, M. R. I., Xie, L., Sun, C., Zheng, X., & Chen, W. (2018). Advances in micro and nano-encapsulation of bioactive compounds using biopolymer and lipid-based transporters. Trends in Food Science & Technology, 78, 34-60.
- Singh, A. K., Pal, P., Pandey, B., Goksen, G., Sahoo, U. K., Lorenzo, J. M., & Sarangi, P. K. (2023). Development of "Smart Foods" for health by nanoencapsulation: Novel technologies and challenges. Food Chemistry: X, 100910.
- Singh, R., Dutt, S., Sharma, P., Sundramoorthy, A. K., Dubey, A., Singh, A., & Arya, S. (2023). Future of nanotechnology in food industry: Challenges in processing, packaging, and food safety. Global Challenges, 7(4), 2200209. Piñón-Balderrama, C. I., Leyva-Porras, C., & Martínez-Torres, P. (2020). Encapsulation of active ingredients in the food industry by spray-drying and nano spray-drying technologies. Processes, 8(8), 889.
- Singhal, B., & Rana, S. (2019). Nanosensors in Food Safety: Current Status, Role, and Future Perspectives. In Nanotechnology and Nanomaterial Applications in Food, Health, and Biomedical Sciences (pp. 249-292). Apple Academic Press.
- Sneha, K., & Kumar, A. (2022). Nanoemulsions: Techniques for the preparation and the recent advances in their food applications. Innovative Food Science & Emerging Technologies, 76, 102914.
- Songca, S. P. (2024). Sol-Gel, Phase Inversion Precipitation, Supercritical Fluid, and Microfluidic Systems for Controlled Delivery of Bioactive Compounds in Nutraceuticals and Nano-Nutraceuticals. In Handbook of Nutraceuticals: Science, Technology and Engineering (pp. 1-31). Cham: Springer International Publishing.
- Stoica, M., Bichescu, C. I., Crețu, C. M., Dragomir, M., Ivan, A. S., Podaru, G. M., & Stuparu-Crețu, M. (2024). Review of Bio-Based Biodegradable Polymers: Smart Solutions for Sustainable Food Packaging. Foods, 13(19), 3027.
- Sun, X., Chen, S., Liu, J., Zhao, S., & Yoon, J. Y. (2020). Hydrodynamic cavitation: A promising technology for industrial-scale synthesis of nanomaterials. *Frontiers in Chemistry, 8*, 259.
- Tabassum, N., Joshi, S., Anjum, V., & Azad, Z. (2023). Encapsulation technologies: Principles and applications in the food industry. In Emerging Processing Methods for Food Materials (pp. 85–102). CRC Press.
- Tan, Y., & McClements, D. J. (2021). Plant-based colloidal delivery systems for bioactives. Molecules, 26(22), 6895.
- Walia, N., Dasgupta, N., Ranjan, S., Ramalingam, C., & Gandhi, M. (2019). Methods for nanoemulsion and nanoencapsulation of food bioactives. Environmental Chemistry Letters, 17, 1471-1483.
- Wang, B., Akanbi, T. O., Agyei, D., Holland, B. J., & Barrow, C. J. (2018). Coacervation technique as an encapsulation and delivery tool for hydrophobic biofunctional compounds. In Role of materials science in food bioengineering (pp. 235-261). Academic Press.
- Xiao, J., Li, Y., & Huang, Q. (2017). Application of Monte Carlo simulation in addressing key issues of complex coacervation formed by polyelectrolytes and oppositely charged colloids. Advances in colloid and interface science, 239, 31-45.
- Yan, X., Bernard, J., & Ganachaud, F. (2021). Nanoprecipitation as a simple and straightforward process to create complex polymeric colloidal morphologies. Advances in Colloid and Interface Science, 294, 102474.