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Nanoencapsulation as a Burgeoning Nanotechnology-Based Approach for Modern Industry

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Abstract
The role of nanotechnology, specifically nanoencapsulation, as an emerging technology in enhancing modern industries in the fields of agro-food, drug security and safety and energy storage has attracted the interest of researchers and investors worldwide. Nanoencapsulation is the process of encapsulating unstable hydrophobic chemicals (core materials) in a protective coating at the nanoscale. The coating can be in the form of films, layers, or even simple microdispersions. The goal of nanoencapsulation is to improve their stability and controlled release characteristics. It also minimizes unwanted chemical reactions among the core materials with other components. The uniformity of nanocapsules is one of their key advantages, which leads to improved efficacy. However, the appropriate and effective nanoencapsulation process depends on the core material and the required final application. However, in terms of application, the fabrication of nanoencapsulated materials has several challenges, which range from figuring out the optimal technique for obtaining the best to determining the most suitable form of nanostructure for a core material of interest. This paper addresses the concepts, recent advances in nanoencapsulation techniques, and current challenges of nanoencapsulation, with special reference to core materials for agro-food, drug, and energy storage applications. Dealing with food, drug, and energy materials also raises the quest for safety and regulatory norms. Thus a brief overview of the safety and regulatory aspects of nanoencapsulation is also presented.
Keywords: Nanoencapsulation; agro-food industry; drug delivery; pesticide delivery, energy storage

Introduction

Nanoencapsulation technology is an emerging area important for future industrial production and sustainability. This technology represents a significant advancement, especially in the fields of agro-food, pharmaceuticals and energy storage sector by contributing practical applications in conventional ways and practices (Muhamad *et al.*, 2020; Pardeshi *et al.*, 2023; Alehosseini & Jafari, 2020). Based on the market growth report, the year 2023, the Global Nanoencapsulation Market was valued at USD 687.94M and expected to increase to USD 1428.27M by the year 2030, with the growing at a Compounded Annual Growth Rate (CAGR) of 11% (www.reanin.com).

Nanoencapsulation technology may be the manipulation of active substances such as pesticides, fertilizers, nutrients, drugs, or phase change materials enclosed in nanometer-sized capsules to create novel and useful advanced materials and products. An inert material, usually polymer, is used for the nanoencapsulation of active substances. The sizes of nanocapsules materials range from 1 to 1000 nm, however they are typically between 100 and 500 nm (Shrivastava *et al.* 2021). Additionally, their large surface area has numerous advantages, such as high surface activity and aqueous solubility. Besides, the capsule wall can increase the stability of active substances, thus extending their service life. Another benefit of nanoencapsulation is homogeneity, resulting in better encapsulation efficiency, which offers better physical and chemical properties (Pateiro *et al.* 2021).

Comprehensive investigation has been done using various inert materials for nanoencapsulation of active substances. The capsule materials choose is depending on the application and can be grouped

Into two, polymer-based and inorganic framework-based. Many nanoencapsulation methods have been extensively developed for the nanoencapsulation of active substances, such as mini emulsion in-situ polymerization method, coacervation, and intercalation. Every inert material and nanoencapsulation technique has its advantages and disadvantages. Careful selection of them is the key factor for the successful nanoencapsulation of the active substances. Due to that, the purpose of this study is to review important advancements in the technology of nanoencapsulation of active substances, with an emphasis on concepts and practical applications in the agriculture, food, pharmaceuticals and energy storage sectors. Additionally, various methods for nanoencapsulation and their use in agriculture, food, pharmaceutical and energy storage will be highlighted. A brief overview of nanocapsules products' safety, regulatory aspects, and challenges is also discussed.

Materials and methods

Nanoencapsulation technology is beneficial to various industries. In this study, exploring the potential application of nanoencapsulation technology focuses on the agricultural, food, pharmaceutical, and energy storage sectors since these four areas are more relevant and have recently become more important for sustainable life. The source of references was obtained from various journal platforms such as Elsevier, Tailor & Francis, and many more, including Google. The data obtained from references were carefully analyzed and summarized, and some of them were tabulated in table form and visualized through a mind map system. **Table 1** summarizes the method used for conducting a literature review to gather the data and information.

Table 1: Method used for conducting a literature review.

Type of literature review	Action taken
Narrative review	Carried out overviews to find out the reason for conducting a review on the importance of nanoencapsulation technology topic for agriculture, food, pharmaceutical and energy storage sectors.
Systematic review	Carried out a comparison study on the potential application of nanoencapsulation technology in agricultural, food, pharmaceutical and energy storage sectors.

Findings

Nanoencapsulation technology in the agricultural industry

Modern agricultural practices have triggered environmental pollution and degradation of ecosystems and land. The current scenario of the agricultural sector shows that this industry will become unsustainable in the near future. One of the major issues in the agricultural industry is the overuse and mismanagement of pesticides and fertilizers, which lead to nutrient pollution, greenhouse gas emissions, and soil degradation. The adaptation of nanoencapsulation technology in the conventional agricultural industry shows promise in improving the agricultural sector by enhancing food productivity and security.

Nanoencapsulation technology can be applied to develop nanoscale agrochemicals such as nanopesticides and nanofertilizers. This technology involved enclosing pesticides or fertilizer within the nanoscale carrier. Benefits of using nanoscale agrochemicals include improved delivery, controlled release, enhanced solubility and stability, reduced toxicity, and targeted delivery of pesticides or fertilizers. The effective delivery of pesticides and fertilizer will improve crop productivity, yield, and quality. In addition, nanoencapsulation is vital in protecting active substances from environmental degradation, such as UV radiation and hydrolysis, which can otherwise reduce their effectiveness. This protection not only prolongs the life of the pesticides and fertilizers but also minimizes environmental pollution by preventing harmful active substances from leaching and evaporating (Nuruzzaman *et al.*, 2016).

The control release properties of nanoencapsulated pesticides and nanoencapsulated fertilizers offer many advantages. Unlike traditional pesticides and fertilizer systems that might dissipate rapidly or require frequent reapplication, nano-encapsulated pesticides and nano-encapsulated fertilizer can be tailor-made to release the active substances more gradually and controlled. Additionally, targeted delivery of pesticides and fertilizers released in specific areas or conditions reduces unintended exposure to non-target species and minimizes environmental contamination. Nanoencapsulation technology is also applied in developing nanosensors for controlling crop diseases and pathogens and for pesticide and herbicide detection. It is also applied in nanocoating for agro product shelf-life enhancement. **Table 2** and **Figure 1** show the nanoencapsulation system encapsulating pesticides and fertilizer.

Table 2: Nanoencapsulation system used to encapsulate pesticides.

Active substances	Nanoencapsulation technique; capsule system	References
Essential oil	Ion gelation; chitosan	Mohammadi *et al.*, 2015
Dill essential oil	Copper nanoparticles	Weisany *et al.*, 2019
Tebuconazole	Cryogel	El-Naggar *et al.*, 2020
Captan; pyraclostrobin	Miniemulsion; cellulose	Machado *et al.* 2021
Acaricide; clofentenzine	Polyethylene glycol	Ahmadi *et al.*, 2020

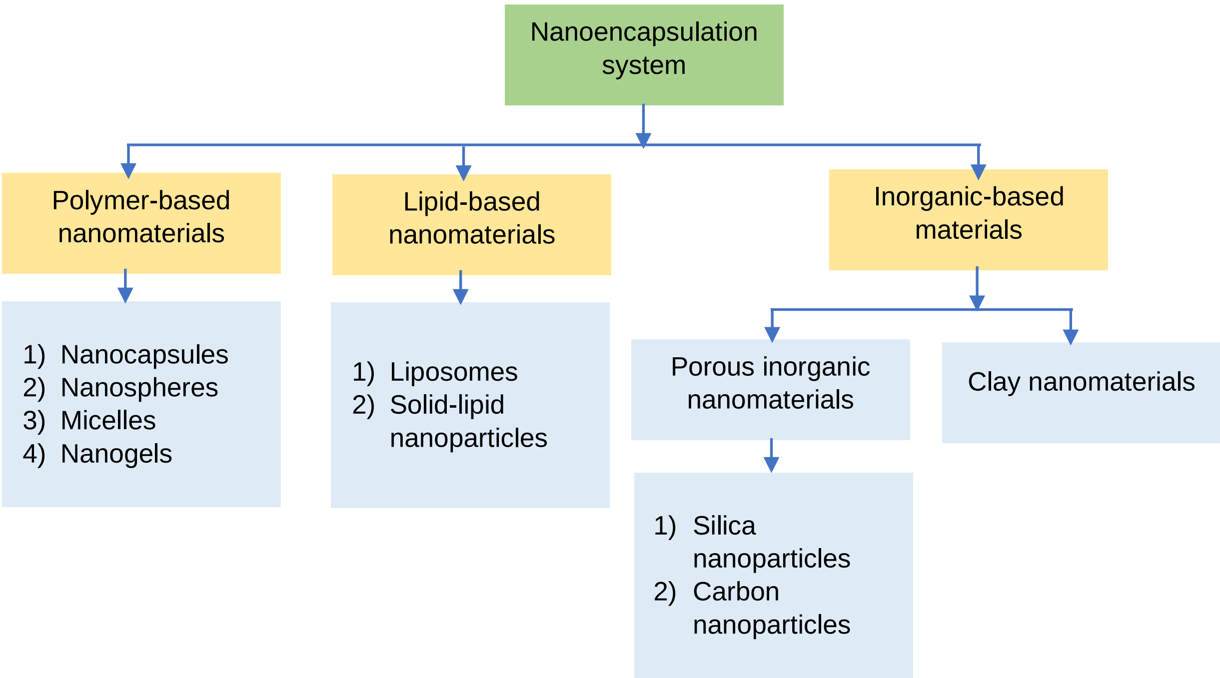

Figure 1 Nanoencapsulation system used to nanoencapsulate fertilizer.

Nanoencapsulation technology in the food industry

Consumer awareness of the sustainability of food supply and the relationship between nutrition and health has led to a growth in functional food and nutraceutical products. Nanotechnology-based nanoencapsulation is applied to ensure those products function well and benefit the food industries, particularly regarding their ability to maintain the availability of active substances (e.g., vitamins and minerals) over a longer period. According to Katouzian *et al.* (2017), applying nanoencapsulation technology in food products offers several benefits, such as taste and flavour enrichment, protection against moisture, oxidative, microbial and degradation effect, and enhancement of bioavailability and bioaccessibility. **Figure 2** illustrates one of the potential applications of nanoencapsulation technology in the food industry. **Table 3** summarizes nanoencapsulation techniques utilized in the food processing industry. Incorporating nanoencapsulated active substances such as vitamins and minerals in food products has attracted significant attention due to their functional properties. Current research on the evolution of the many food industries containing nanoencapsulated active substances is listed in **Table 4**.

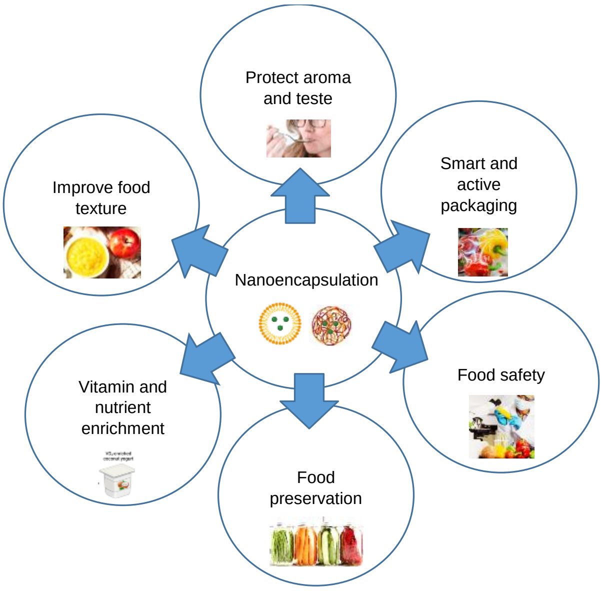

Figure 2 Potential application of nanoencapsulation technology in the food industry.

Table 3: Nanoencapsulation techniques used by food processing industry

Nanoencapsulation technique	Characteristics	Advantages	Disadvantages	References
Nanoemulsion	1) Size typically between 20 to 500 nm 2) In the form of colloidal dispersions of two immiscible liquids 3) Homogeneous dispersions 4) Ultrafines and thermodynamically stable,	1) Protection against oxygen, light, and temperature fluctuation 2) Protection against processing methods used such as pH variation, pasteurization, enzymes. 3) Enhance solubility, dispensability and retention 4) Controlled-release 5) Enhance bioavailability, adsorption and biocompatibility	1) Limited solubilizing capacity 2) The surfactant use must be non-toxic if want to use for pharmaceutical application	Tapia-Hernandez *et al.*, 2017; Harwansh *et al.*, 2019; Sauto *et al.*, 2022
Nanoliposome	1) Size typically between 2 nm to 2 µm 2) Size smaller than 50 nm tend to instable and vulnerable to	1) Good biocompatibility, biodegradability, low toxicity and has ability to encapsulate chemicals	1) Inadequate stability 2) Tendency to aggregation 3) Poor encapsulation efficiency	Lombardo & Kiselev, 2022; Wang *et al.*, 2022; Tripathy & Srivastav, 2023

	intermingling with other nanoliposome due to elevated surface tension 3) Saiz 50-200 nm more stable 4) Colloidal with vesicular structures 5) Made up of one or more phospholipid bilayers which enclosing an equal number of aqueous compartments	2) Can be used to encapsulate hydrophilic, hydrophobic, and amphiphilic active substances 3) Enhance bioavailability 4) Enhance solubility 5) Enhance targeting 6) Able to modulate release kinetic of active substances	4) Tendency to burst release (rapidly release)	
Nanoprecipitation	1) Nanocapsules obtained in a capsular structure	1) Suitable to encapsulate active substances that are hydrophobic in nature 2) Easy nanoencapsulation method, more facile, relatively inexpensive, less energy usage and easy to scale-up. 3) High encapsulation efficiency 4) Good stability	-	Jammes *et al.* 2020
Electrospraying/ Electrospinning	1) Hollow, uniaxial, core-shell and porous configuration structure	1) Cost-effective and scalable 2) Can be prepared at room temperature and atmospheric pressure	1) Use of toxic solvent 2) Inhomogeneous encapsulation	He *et al.*, 2018, Moreira *et al.*, 2021; Niamah *et al.*, 2021;
Nanogel	1) 3D nanonetwork 2) Produced via physical or chemical cross-linking of hydrophilic synthetic of natural polymers 3) Size 10 to 100 nm in diameter	1) Excellent capacity to swell if place in the suitable solvents	1) Long processing time 2) Use of organic solutions that can be toxic	Leena *et al.*, 2020; Rahmanian *et al.*, 2022

Table 4: Nanoencapsulated active substances incorporated in food.

Food industry	Active substances	Nanoencapsulation technique; capsule system	Food product	References
Cereal and bakery	Vitamin D	Nanoemulsion; egg white proteins	Bread	Zhu *et al.*, 2021

	Oregano	Nanoprecipitation; Zein	Bread	da Rosa *et al.*, 2020
	Orange peel	Nanoemulsion; sodium alginate	Cake	Hussein *et al.*, 2019
Dairy-based food	Iron	Nanoemulsion; olive oil, Tween 80 and polyricinoleate	Cream	Koohenjani & Lashkari, 2022
	Vitamin B12	Nanoemulsion; sunflower oil	Skim milk	Zaqhian & Goli, 2020
Fruit and vegetable	Pomegranate flavedo	Freeze drying; maltodextrin	Mango pulp-based beverage	Thakur & Thakur, 2020
	Steppogenin, butylated hydroxytoluene, Vitamin C (ascorbic acid) and vitamin E	Nanoemulsion: Ethyl butyrate, Tween 80, and PEG 400	Fresh apple juice	Tao *et al.*, 2017
Meat-based food	Fish oil	Nanoemulsion; Carrageenan and gum tragacanth	Chicken nugget	Pourashouri et al., 2021
	Fish oil	Freeze drying: soy protein isolates and inulin	Beef and pork burger	Rios-Mera *et al.*, 2021

Nanoencapsulation technology in the pharmaceutical industry

The continuous usage of medicine products has given rise to the broad evolution of drug resistance. Drug resistance is the phenomenon in which a significant portion of pathogens (bacteria, fungi, and parasites) develop resistance to drugs such as antibiotics, making them unresponsive to medication, causing complicated treatment, which finally increases the risk of disease transmission, severe illness and mortality (Mittal *et al.*, 2020; Catalano *et al.*, 2022).

Nanoencapsulation of drugs is revolutionizing the pharmaceutical industry by improving drug delivery systems and therapeutic outcomes. By doing nanoencapsulation, the drug is protected from degradation, enhanced solubility, and increased bioavailability. The controlled release and sustained release ability of nano-encapsulated drug products help maintain therapeutic drug levels over extended periods, simultaneously reducing the need for frequent dosing. Besides, the noencapsulation drugs can delivered more effectively to the targeted areas in the body. This smart approach minimizes side effects of healthy cells or tissues, which is particularly valuable in treating diseases like cancer.

Various nanocarrier systems for drug delivery have developed, including liposomes, polymeric nanoparticles, and micelles. The selection of nanocarrier systems depends on the drug's specific requirements and its intended application. Each nanocarrier system has advantages and limitations, such as size, release profile and stability. For example, nanocarrier system-based liposomes are particularly effective for hydrophilic drugs (Thirumalai *et al.* 2024).

Nanoencapsulation technology in the energy storage industry

One of the applications of nanoencapsulation technology in the energy storage sector is to encapsulate phase change materials (PCMs). This technology can eliminate the leakage problem of PCMs (Sheikh *et al.* 2023). Various methods to overcome the drawbacks of PCMs have been extensively developed, including solvent evaporation, emulsion polymerization, layer-by-layer assembly, and miniemulsion. This technique enables the creation of nanocapsules PCMs with sizes typically less than 1000 nm. Among potential capsules, synthetic polymers, such as polystyrene, poly (methyl methacrylate), and polyvinyl alcohol, have been studied as rigid and leakage-proof core-shell structures for PCMs (Agresti et al., 2023). For instance, nanocapsules PCMs can integrated into building walls, roofs and floors to provide passive temperature regulation, thereby reducing energy consumption for heating and cooling. Nanocapsules PCMs are also reported to be used as waste heat recovery and thermal regulation in electronic devices. Besides, nanoencapsulated PCM have also shown great potential for improving the efficiency of air conditioning systems.

Challenges and future prospects

Despite the benefits offered, some challenges need consideration associated with the nanoencapsulation of active substances for the agricultural, food, pharmaceutical, and energy storage sectors. The production and formulation of nanoencapsulated active substances can be complex and costly. Moreover, nanocapsule-based products' potential environmental and health impacts are still studied, as their behaviour and interactions at the nanoscale can differ significantly from bulk materials. Additionally, concerns about nanomaterials' long-term safety and biocompatibility, especially for food and pharmaceutical applications, must be carefully addressed through rigorous testing and regulatory oversight. Therefore, ongoing research and regulation are essential for its safe and effective implementation.

Conclusion

Nanoencapsulation technology has emerged as an innovation across various sectors, especially agriculture, food, pharmaceuticals, and energy storage. In the agricultural industry, nanoencapsulation of pesticides and fertilizers can help in terms of controlled release, thus reducing pollution issues. The food industry enhances the stability and bioavailability of nutrients and active ingredients, leading to improved product quality and extended shelf life. In pharmaceuticals, nanoencapsulation enables targeted drug delivery, controlled release, and enhanced solubility, optimizing therapeutic efficacy and reducing side effects. This technology improves the performance of energy storage based on phase change materials. It also functions as waste heat recovery and thermal regulation for electrical appliances. Collectively, these advancements illustrate the broad impact of nanoencapsulation in optimizing efficiency, efficacy, and sustainability across multiple industries.

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