Nanotechnology for Sustainable Food Packaging

Edited by

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Preface

The packaging component holds a prominent space in the food industry. Over the years, several innovations and advances have been made, and recent endeavors focus on developing sustainable packaging solutions. Among the various approaches to achieving this target, copious research focus and commercial interest have been diverted to nanotechnology-driven concepts, which is the motivation for this book. To achieve this, the book has excellent contributions and expert insights from leading voices in the field, from across different countries.

The introductory chapters present an overview of nanotechnology and its applications in the food industry, the emerging trends in food packaging, and the scope of nanotechnology. This is followed by chapters highlighting different material compositions such as polymer-based nanocomposites and Inorganic and metal oxide nanomaterials. The next set of chapters present interesting applications such as edible coatings, multilayer flexible films for bio-based food packaging, nanoencapsulation and nanodelivery through packaging, active packaging, and intelligent packaging. With information on concepts, approaches, and advances, this section is followed by chapters showcasing the integration of quality detection and sensing applications, and emerging application fields such as the significance of additive manufacturing technology and nanoscale surface modification. The last application-focused chapter is on how nanotechnology is expanding in the packaging space for special/space foods. The concluding chapters explain concepts of life cycle analysis, migratory effects, safety, and concerns of nanofood packaging, global regulatory frameworks for nanomaterials in food packaging, and a strong focus on sustainability and the approaches thereof.

We are confident that this book will be a valuable resource for researchers and industry, who aim to develop sustainable food packaging solutions in the fascinating field of nanotechnology. This will be of significance as the shift to sustainable packaging technologies gains momentum.

1

Nanotechnology in the Food Industry

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1.1 Introduction

In the broadest sense, nanotechnology deals with the manipulation of matter on a near-atomic scale, aiming to develop new structures, materials, or devices. Given its uniqueness in terms of material functionalities to beneficial properties and capabilities, nano-based concepts have gained enormous applications across different sectors, ranging from medicine to energy to environment to agriculture to electronics to drug delivery to material sciences (Anandharamakrishnan, 2021; Maria et al., 2019). This also explains that nano-based concepts were in use centuries before and these are documented in different other literature sources. Irrespective of the application, one concept that is unarguably considered as the deciding factor for the level of changes a material can undergo when present in nanoscale vs. bulk counterpart is the significant variation in surface-to-volume ratio (Perumal et al., 2022). Now this can have prominent effects on a range of properties, spanning from thermal to physical to electrical to absorption to reaction to several others. In addition, for many applications, the impact of quantum confinement on the properties thereof has been well documented.

Particularly in the past couple of decades, copious works have been taken up and the field has gained considerable research and commercial interest. Just as every other technology, nanotechnology has also been associated with both merits and limitations (Maria et al., 2019). This explains the need for a judicious evaluation of the technology in a broad perspective, alongside both near and long-term impact. On a different note, nano-based concepts have been recognized with several Noble Prizes for discoveries ranging from characterization techniques to applications. Nano-based materials have been classified under various categories and scientists have used different scales to explain their classification. For a simple understanding, such classifications are done based on the number of dimensions (e.g., 0D, 1D, 2D, or 3D materials), shapes (e.g., spheres, shells, rods, etc.), and even based on composition or source (e.g., nature-derived, nature-identical, engineered, etc.) (Anandharamakrishnan, 2021).

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Several technologies have emerged in the food industry and some of them have transformed our existing approaches in handling, manufacturing, sensing, quality evaluation, processing, and other aspects (Anandharamakrishnan, 2021). Similarly, nanotechnology has also found diverse applications in the food sector and the focus of this chapter is to present such applications, highlighting examples of research work done during the recent past. Having said this, it is important to note that the following approach is logical and valid for all such applications:

1) Material fabrication/synthesis/preparation
2) Material characterization
3) In-depth assessment of the functionalities and identification of the application range
4) Application
5) Assessment of merits and limits
6) Iterations for technology modification/improvement
7) Final optimized process
8) Detailed impact assessments, validation, and documentation
9) Commercialization

Here, typically, (1) involves either physical, chemical, biological, or hybrid approaches for the production of nanomaterials or for structuring at the nanoscale or for allied applications. Then, in (2) different techniques and instrumental approaches are used to characterize the developed material (Preethi et al., 2019). This could be in terms of surface morphology and topography assessments, particle size, surface composition, or other measurements. Following suitable studies as in (3), the application range can be assessed. In the lab scale, once an application (4) is made, the pros and cons are identified (5), and any further improvement required is done (6). A final optimized process with a set process and product variables is then developed (7) and this is subjected to a detailed assessment in terms of various aspects (8), before being commercialized (9). A popular example is the synthesis and characterization of metal nanoparticles, and the assessment of functionalities to meet different applications (Lakshmanan et al., 2021). It is important to note that for specific requirements and applications, the order listed here may have minor variations.

1.2 Nanotechnology in the Food Industry

Along the food supply chain, nano-based concepts can be used at any or multiple points (Figure 1.1) (Anandharamakrishnan, 2021). Typical applications are detained in this section. In a broad sense, when nano-based approaches are involved, the product is categorized as “nanofood.”

1.2.1 Food Production

Nanotechnology has found several applications at the production site. Popularly, several innovations have come forth in aspects of seed quality improvement, fertilizers, pesticides, soil quality improvement, growth stimulators, and an array of sensing

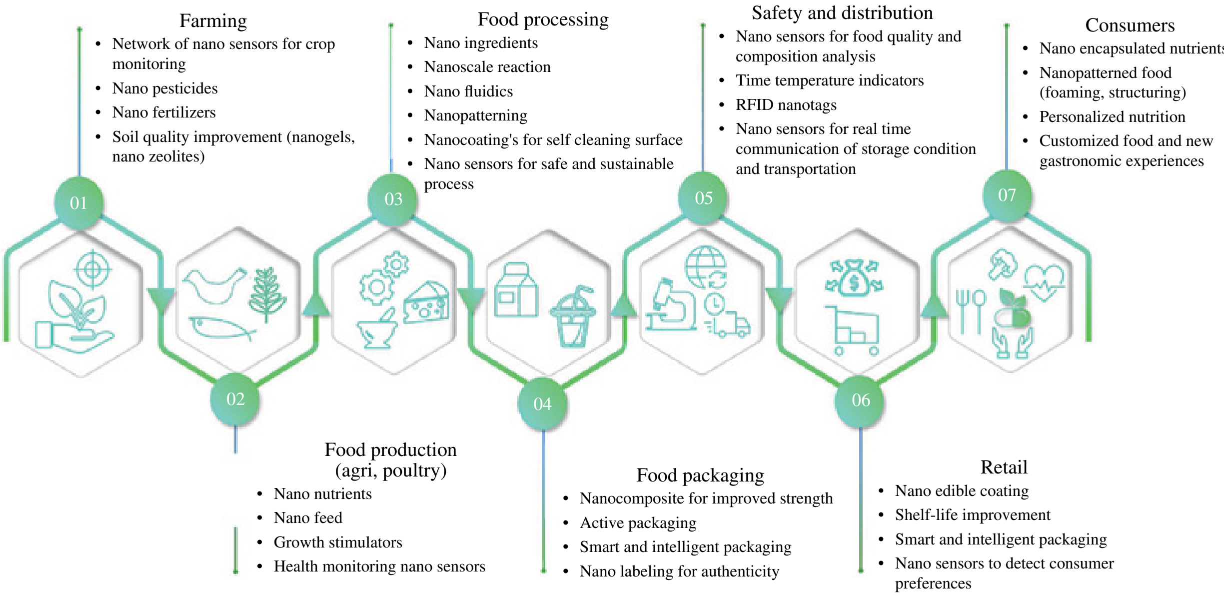

Figure 1.1 Potential applications of nanotechnology in Agro-Food Sector (*Source:* Anandharamakrishnan (2021)/with permission of Elsevier)

devices to monitor soil and water quality. There has been a keen focus on crop yield improvement and targeted destruction of weeds or insect pests. Also, nanosensing devices are valued for their speed, specificity, and accuracy. Nano-based concepts are also being explored to improve feed quality; nutrient-dense feeds can prove beneficial for fish, poultry, and animals. Overall, such aspects are better reviewed by other researchers.

1.2.2 Food Processing

Taking roots from applications in different other sectors such as chemical engineering, biomedical engineering, mechanical engineering, etc., the food industry has also benefitted from nano-based concepts. There are also nature-based nanostructures that researchers have taken ideas from. A classic example is the beautifully structured milk casein micelles. Accordingly, engineered nanostructures have been fabricated for different applications (Preethi et al., 2019), including the delivery of nutraceutical ingredients (Choudhary et al., 2021; Jayan et al., 2019; Leena et al., 2022; Mahalakshmi et al., 2020; Selvakumar et al., 2019). Certainly, a vast majority of such applications are still at the lab level. Some of them are being explored currently in pilot-scale trials and a couple of them have been commercialized. Some interesting applications include the improvement of reaction rates and kinetics, nanofluidics for different applications, nanopatterning and nanostructuring of foods and beverages, even for improved sensorial perception, and self-cleaning equipment, including nanocoatings, and machine parts (Deotale et al., 2020; Joseph et al., 2024; Logesh et al., 2021). In such examples, either the food or the equipment used or the process uses nanotechnology concepts. One recent example is the usage of an electrospun nanomembrane for the filtration of coconut neera, wherein the authors reported a substantial improvement in the product's quality (Leena et al., 2021). Electrospun nanomembrane are potential material for ensuring quality and safety of beverages (Leena et al., 2020b) and delivery of nutraceutical ingredients (Kavimughil et al., 2023). Similarly, nanomaterials can be used for disinfection applications in the food and water sector (Murugesan et al., 2019). Innovations in the past and recent advances have been reviewed and reported by different research groups (Anandharamakrishnan and Parthasarathi, 2019).

1.2.3 Food Additives

Closely linked to food processing, several works have demonstrated the capabilities of using nanoscale ingredients and additives in foods for improved characteristics and specific functionalities. For instance, nano additives can provide intense flavors, stable colors, improved efficiencies against microorganisms, better water dispersibility of targeted compounds, and improved functional characteristics. Another interesting application is the scope of using nano-sized salt to lower dietary intake of sodium (Figure 1.2) (Vinitha et al., 2021). Researchers used an electrospraying approach and demonstrated its scope in a study conducted in comparison with conventional and spray-dried micron-sized salts (Vinitha et al., 2021). Such applications have been reviewed, consolidated, and reported