Edited by Wing-Fu Lai

Materials Science and Engineering in Food Product Development

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Wing-Fu Lai
The Hong Kong Polytechnic University
Hong Kong

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This edition first published 2023

Registered Offices
John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

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Library of Congress Cataloging-in-Publication Data
Names: Lai, Wing-Fu, editor. | John Wiley & Sons, publisher.
Title: Materials science and engineering in food product development / edited by Wing Fu Lai.
Description: Hoboken, NJ : John Wiley & Sons, 2023. | Includes bibliographical references and index.
Identifiers: LCCN 2023000273 (print) | LCCN 2023000274 (ebook) | ISBN 9781119860358 (paperback) | ISBN 9781119860365 (pdf) | ISBN 9781119860587 (epub) | ISBN 9781119860594 (ebook)
Subjects: LCSH: Food industry and trade--Technological innovations | Food--Composition | Food--Analysis. | Food science.
Classification: LCC TP370 .M365 2023 (print) | LCC TP370 (ebook) | DDC 664/.07--dc23/eng/20230213
LC record available at https://lccn.loc.gov/2023000273
LC ebook record available at https://lccn.loc.gov/2023000274

Cover Image: © Sompong Sriphet/EyeEm/Getty Images
Cover Design: Wiley

Set in 9.5/12.5pt STIXTwoText by Integra Software Services Pvt. Ltd, Pondicherry, India

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About the Editor

Wing-Fu Lai

Department of Applied Biology and Chemical Technology, The Hong Kong Polytechnic University, Hong Kong

Wing-Fu Lai received his MSc degree in materials engineering and nanotechnology from the City University of Hong Kong, and earned his PhD in chemistry from the University of Hong Kong. He has been accredited as Shenzhen Municipal "Overseas High-caliber Personnel". Professionally, he is a registered nutritionist in the United Kingdom, and a Fellow of the UK Higher Education Academy. He has also received his certified food scientist credential from the International Food Science Certification Commission in the United States. His research focus is on the development and engineering of polymeric materials for food and pharmaceutical applications.

List of Contributors

Nahed A. Abd El-Ghany
Cairo University
Egypt

Youssef S. Abdelaziz
Cairo University
Egypt

Mariam Khaled Abdel-Latif
Cairo University
Egypt

Mohamed Abdel-Shafi Abdel-Samie
Arish University
Egypt

Abdulrahman M. Abdulrahman
Cairo University
Egypt

Sherif M. Abed
Arish University
Egypt

Mahmoud H. Abu Elella
Cairo University,
Egypt

Sukumar P. Aditya
ICAR-National Dairy Research Institute
India

José Manuel Aguilar
Universidad de Sevilla
Spain

Ghada A. Ahmed
Cairo University
Egypt

Nufile Uddin Ahmed
Rajshahi University of Engineering and Technology
Bangladesh

Omar A. Alaboudi
Cairo University
Egypt

Sara A. Al-Hafiry
Cairo University
Egypt

Estefanía Álvarez-Castillo
Universidad de Sevilla
Spain

Bissera Asenova-Pilicheva
Medical University of Plovdiv
Bulgaria

Liliam Becheran-Maron
University of Habana
Cuba

Carlos Bengoechea
Universidad de Sevilla
Spain

Martin Binks
Texas Tech University
USA

Gastón Bravo-Arrepol
Universidad de Concepción
Chile

Gustavo Cabrera-Barjas
Universidad de Concepción
Chile

Cecilio Carrera
Universidad de Sevilla
Spain

Johanna Castaño
Universidad San Sebastián
Chile

Cheryl Yingxue Chia
Agency for Science Technology and Research (A*STAR)
Singapore

Agnieszka S. Cholewa-Wójcik
Cracow University of Economics, Poland

Haiying Cui
Jiangsu University, China

Cédric Delattre
Université Clermont Auvergne
France

P. Devikrishna
ICAR-National Dairy Research Institute
India

Brendan Duffy
Technological University Dublin – City Campus
Ireland

Paul F. Egan
Texas Tech University
US

Ali Ekrami
University of Tehran
Iran

Mohammad Ekrami
University of Tehran
Iran

Zahra Emam-Djomeh
University of Tehran
Iran

Magdaline Eljeeva Emerald
ICAR-National Dairy Research Institute
India

Danilo Escobar-Avello
Universidad de Concepción
Chile

Heba Mohamed Fahmy
Badr University in Cairo
Egypt

Manuel Felix
Universidad de Sevilla
Spain

Lorenzo García
University of Havana
Cuba

Saji George
McGill University
Canada

Chandram Grover
ICAR-National Dairy Research Institute
India

Antonio Guerrero
Universidad de Sevilla
Spain

Sabit Hasan
Rajshahi University of Engineering and Technology
Bangladesh

Hasibul Hasan Himel
Rajshahi University of Engineering and Technology
Bangladesh

Habiba Mohamad Ibrahim
Cairo University
Egypt

Amit K. Jaiswal
Technological University Dublin-City Campus
Ireland

Swarna Jaiswal
Technological University Dublin-City Campus
Ireland

Plamen Dimitrov Katsarov
Medical University of Plovdiv
Bulgaria

Agnieszka K. Kawecka
Cracow University of Economics
Poland

Mariam Ashraf Fouad Khalil
Cairo University
Egypt

Maxim V. Kiryukhin
Singapore Institute of Food and Biotechnology Innovation
A*STAR
Singapore

Harshvardhan Kulkarni
ICAR-National Dairy Research Institute
India

Su Hui Lim
Agency for Science,
Technology and Research (A*STAR)
Singapore

Lin Lin
Jiangsu University
China

Maria Dolores Lopez
Universidad de Concepción
Chile

María Luisa López-Castejón
Universidad de Sevilla
Spain

Paolina Kancheva-Lukova
Medical University of Plovdiv
Bulgaria

Satwik Majumder
McGill University
Canada

Mahadi Hasan Masud
Rajshahi University of Engineering & Technology
Bangladesh

Philippe Michaud
Université Clermont Auvergne
France

Radwa Magdy Mohamed
Cairo University
Egypt

Salma Hossam Mohamed
Cairo University
Egypt

Omaima Ali Mostafa Mohammed
Cairo University
Egypt

Filopateer Nasser
Cairo University
Egypt

Aleksandra Nesic
Universidad de Concepción
Chile

Hazel Peniche
University of Havana
Cuba

Carlos Peniche-Covas
University of Havana
Cuba

Kalpani Y. Perera
Technological University Dublin-City Campus
Ireland

Víctor Manuel Pizones
Universidad de Sevilla
Spain

Dileswar Pradhan
Technological University Dublin-City Campus
Ireland

Heartwin A. Pushpadass
ICAR-National Dairy Research Institute
India

Sohaila Mohammed Salah Saleh
Cairo University
Egypt

Stefania Chirico Scheele
Texas Tech University
US

B. G. Seethu
ICAR-National Dairy Research Institute
India

Shubham Sharma
Technological University Dublin-City Campus
Ireland

Rana Tarek
Cairo University
Egypt

Oscar Valdes
Universidad Católica del Maule
Chile

Donia G. Youssef
Cairo University
Egypt

Preface

Food materials science is a discipline focusing on the development, characterization, processing, and engineering of materials used in food. Although it has practical significance in the food industry, it is an emerging area in the larger field of food science and little scholarly works are available in this field. Among those available works, most of them only focus on the characterization and properties of food materials *per se*. Efforts paid to explore how related advances can be translated into the development and improvement of a functional food product are almost absent. The objective of this book is to fill this gap by exploring and illustrating the roles played by materials science and engineering in the process of food production, particularly food microencapsulation and food packaging.

This book covers a wide range of topics in food materials science and engineering. Chapters 1–6 will present major concepts related to material properties in food science. An overview of different types of materials used in food applications will be provided. Concepts of bulk rheology and interfacial rheology in food emulsions will also be presented. This section lays a theoretical foundation for subsequent sections in this book. In Chapters 7–10, detailed discussions about the design and use of lipid-based and polymer-based materials in enrichment and protection of food components will be provided. Apart from chemical means, various engineering techniques (including 3D printing and electrospinning) can be applied to manipulate the properties of food materials or those used for food microencapsulation. Some of the major engineering techniques relevant to the process of food production will be discussed in Chapters 11–15. Chapters 16–19 will focus mainly on the design, characterization, and use of materials for food packaging. Various determinants of the quality and safety of food packaging, as well as concepts for the design of food packages, will be covered.

Contrary to existing books that largely focus on the chemical and physical principles of food materials science and hence are sometimes too theoretical to be directly adopted by food manufacturers in their professional practice, this book will approach the subject of food materials science with practical and industrial perspectives. Real-life examples will be provided to demonstrate how food products, especially functional foods, can benefit from the incorporation of materials science technologies. In addition, to benefit scholars, students, and a broader audience of interested readers, the book includes helpful glossary sections in each chapter. Important notes and tips to food manufacturers to translate the contents of the chapter from theory to real-life practice will also be provided in each chapter. This is the first book of its kind. It is not only a valuable reference book to researchers in the field, but can also serve as a guide for food manufacturers during the development of the food product.

Here I would like to express my gratitude to the contributors of different chapters of this book. Their support and efforts have made publication of this book possible. Thanks are extended to the staff in Wiley. The quality of this book, and its value to its readers, depends largely on the promptness with which submitted manuscripts are reviewed. I would like to thank the reviewers for putting their efforts to evaluate and select the best manuscripts for inclusion in this book, and for providing constructive suggestions to the contributors of those selected chapters. Haotian Zhang from the Chinese University of Hong Kong is also acknowledged for his editorial assistance throughout the process of this book's publication. I would like to express my appreciation in advance for every observation and suggestion toward further improvement of this material.

Wing-Fu Lai

List of Abbreviations

AFM	Atomic force microscopy
AMA	Antimicrobial agents
AMR	Antimicrobial resistance
AN	Anthocyanin nanoliposomes
AOA	Antioxidant agents
BSA	Bovine serum albumin
CAD	Computer-aided design
CEO	Clove essential oil
DD	Degree of deacetylation
DLS	Dynamic light scattering
DoE	Design of experiment
DP	Degree of polymerization
DQM	Design quality management
DS	Degree of substitution
DSC	Differential scanning calorimetry
DSD	Droplet size distribution
DWR	Double-wall ring
EAMPS	Edible antimicrobial packaging systems
EB	Elongation at break
EM	Electron microscopy
EMA	European Medicines Agency
EO	Essential oil
EVA	Ethylene vinyl acetate
F&D	Food and Drugs
FD&C	Food Drug and Cosmetic
FDA	Food and Drug Administration
FESEM	Field emission gun scanning electron microscope
FOS	Fructo-oligosaccharides
GA	Gum arabic
GK	Garcinia kola
GMP	Good manufacturing practice
GOS	Galacto-oligosaccharides
GRAS	Generally recognized as safe
GTE	Green tea extract

HIU	High-intensity ultrasound
HOSO	High-oleic sunflower oil
HSH	High-shear homogenization
HU	*Hunteria umbellata*
LA	Lactic acid
LH	Latent heat
LHS	Latent heat storage
LMWE	Low molecular weight emulsifiers
M&N	Micronutrients and nutraceuticals
MW	Molecular weight
NLC	Nanostructured lipid carrier
NMR	Nuclear magnetic resonance
OEO	Oregano essential oil
OP	Oxygen permeability
OSD	Open sun-drying
OTR	Oxygen transmission rate
PBAT	Polyadipate butylene terephthalate
PCM	Phase change materials
PPE	Pineapple peel extract
PV	Peak viscosity
QFD	Quality function deployment
RA	Rosmarinic acid
RB	Relative breakdown
RS	Resistant starch
SAOS	Small amplitude oscillatory shear
SDS	Sodium dodecyl sulfate
SEM	Scanning electron microscopy
SH	Sensible heat
SLN	Solid lipid nanoparticle
SPI	Soy protein isolate
SPM	Scanning probe microscopy
TC	Thermal conductivity
TEM	Transmission electron microscopy
TES	Thermal energy storage
TGA	Thermogravimetric analysis
TP	Tea polyphenol
TS	Tapioca starch
WPI	Whey protein isolate
WVP	Water vapor permeability
ZLO	*Zanthoxylum limonella* oil

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Overview of Different Materials Used in Food Production

Nahed A. Abd El-Ghany and Mahmoud H. Abu Elella*

Chemistry Department, Faculty of Science, Cairo University, Giza, Egypt
** Corresponding author*

Highlights

- Materials science and engineering can be applied to different aspects of food science, ranging from encapsulation of food ingredients to food packaging.
- Materials engineering, depending on biopolymers, has gained extensive interest because polymers have shown outstanding properties, such as nontoxicity, ease of availability, biocompatibility, biodegradability, and low cost.
- Materials engineering can enhance food product quality, which is all about sensory features, such as taste, flavor, palatability, and semblance.
- Advances in materials science and engineering are expected to bring new opportunities to the food industry.

1.1 Introduction

Rapid growth of materials engineering science has provided a lot of functionalized materials for food product development application in the recent years. Three advanced types of functional materials that have been widely applied in food industry are nanostructured and microstructured materials, and three-dimensional hydrogels [1]. In general, materials engineering science normally represents a solid state of matter and is an integrated field comprising chemistry, physical attributes, and processing. Additionally, it involves the maintenance of the materials' properties, for example, chemical (structure and composition), physical (thermal and optical), dimensional (shape and size), and mechanical (toughness and strength). On the other hand, food product development has been gaining more interest among many industrial and academic researchers around the world to improve the quality of food products. Notably, the major components of food are carbohydrates, and proteins that are called biopolymers [2]. In general, nowadays, polymeric materials are considered as an important class of materials in a wide range of applications, thanks to their physicochemical properties [3]. They are macromolecules composed of repeating units that are known as monomers joined by covalent bonds. According to their origin, they are classified as either natural (if produced from natural sources, such as plants, animals, and

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microorganisms) or synthetic [4]. Recently, biopolymers have gained more attention from global researchers in food development applications since they have fabulous properties, such as biodegradability, biocompatibility, low cost, nontoxicity, and ease of availability [4a, 5]. They include naturally extracted polymers from animal and plant origins, for example, polysaccharides and proteins. Their repeated units include sugar or protein chains [6].

Polysaccharides are an example of natural biopolymers that are composed of carbohydrate chains with a large polymeric oligosaccharide formed through glycosidic linkages between multiple monosaccharides as repeating units [7]. Polysaccharides are the most abundant natural organic compounds. Additionally, they can be extracted from natural renewable resources, including plants (e.g. cellulose), animals (e.g. chitosan and alginate), and microorganisms (e.g. xanthan gum) [5a, 7a, 8]. Also, they are classified into two categories, for instance, homopolysaccharides and heteropolysaccharides. Homopolysaccharides are composed of the same monosaccharide-repeating unit as cellulose, whereas, heteropolysaccharides are composed of various repeating units including alginate [9]. Furthermore, polysaccharides have been used in various applications owing to their sustainable properties, such as ease of availability at less cost, ease of modifications and manufacturing, biocompatibility, biodegradability, nontoxicity, and bioactivity [5a, 7a, 10]. Conversely, proteins have polyamide chains, and they are one of the main constituents of the human body because they play both dynamic and diverse roles, such as catalyzing reactions, building cellular structures, and controlling cell fates. They have fabulous physicochemical properties, including isoelectric point (pI), chemical compositions, denaturation thermal temperature (Tm), and solubility [11].

Nanotechnology has revolutionized several scientific and industrial fields, including the food business. Food processing, food packaging, functional food development, food safety, detection of foodborne pathogens, and shelf-life extension of food and/or food products have emerged because of the growing need for nanoparticles in various fields of food science and food microbiology. On the other hand, hydrogels in the food science sector are efficient materials in the field of food quality improvement, nutrient-modification, sensory perception optimization, targeted nutrient delivery and protection, calorie control, risk monitoring for food safety, and food packaging. Although applications of hydrogels in the food industry are still limited, there are large areas to promote their use in food science. As a result, it is expected that the hydrogel structure's reasonable design will lead to more useful applications in order to keep up with the development of new foods [12]. In this chapter, we focus on shaping up the biopolymer-based nanostructured, microstructured, and hydrogel materials as shown

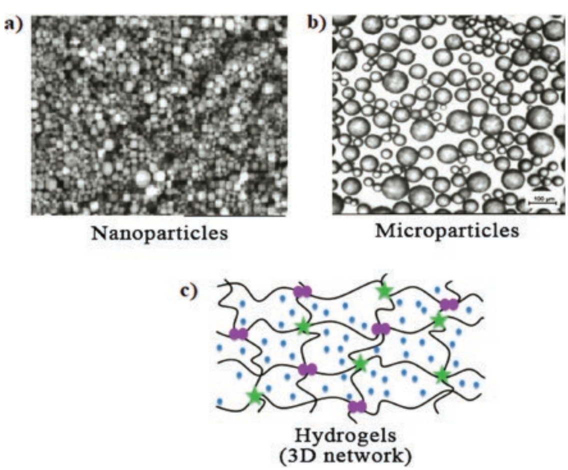

Figure 1.1 Different advanced material engineering formulations: (a) nanoparticles [13] / from ELSEVIER, (b) microparticles [14] / from ELSEVIER, and (c) hydrogel, formulations for food industry [15] / with permission of Elsevier.

in Figure 1.1, for encapsulation of different vital food ingredients in the food packaging field and explore their effect on food safety and quality that are essential for food development.

1.2 Advanced Materials Engineering for Food Product Development

1.2.1 Microstructured and Nanostructured Materials

Microstructured materials refer to the formulation of particle-sized compounds in the range of 1–1000 μm in diameter for different purposes, such as controlling and sustained bioactive compounds delivery, in addition to protecting the bioactive compounds from harsh environmental conditions. They have outstanding properties including a micro-size diameter and have the ability to encapsulate macromolecules with a high molecular weight [16]. For example, microcapsules based on the biopolymer mixture of chitosan and alginate have been reported in the literature [17], for encapsulating biologically active compounds, such as *Garcinia kola* (GK) and *Hunteria umbellata* (HU) seeds. The results showed that the extracted seeds have selective release patterns based on the pH of the medium. Also, a slower release of GK and HU from microcapsules was observed in an acidic medium (pH 1.2), but rose in a slightly neutral medium (pH 6.8). Nanostructured materials can be described as chemically and morphologically deposited matters in the range of 1–300 nm in diameter. All sorted materials used form the nanoscale and are classified from atoms to polymers. Moreover, nanostructured biopolymers are functional materials and controlling their architecture leads to achieved materials with amazing properties. For example, due to their nanometric dimension, which is less than the wavelength of light, they can display optical properties such as anti-reflectivity and structural colors [18].

1.2.2 Preparation Methods

1.2.2.1 Spray-Drying Technique

Spray-drying technique has been one of most widely used methods to design microparticle materials in the past decades due to its fabulous features, such as simplicity, speed, low cost, ease of scaling up, and flexibility [19]. It is also used to prepare microcapsule formulations for drug delivery applications in which the core material is dispersed in the solution of the shell material, such as water, after which, it is fed into the drying chamber while atomized under hot air coming from a pressure nozzle. Subsequently, the solvent is evaporated under the hot air stream, leaving a microparticle of solid. Additionally, this approach is a simple and flexible one to yield consistently distributed particle size in the range of 10–40 μm in diameter (Figure 1.2a) [20]. The spray-drying method allows a large-scale yield and high encapsulation efficiency in pharmaceutical applications, as well as excellent stability of the prepared product and ease of handling and maintenance of their properties [21].

1.2.2.2 Electrospinning Technique

Electrospinning technique is an effective method of fabricating micro- and nanoscale fibrous materials based on different biopolymers owing to their sustainable properties,

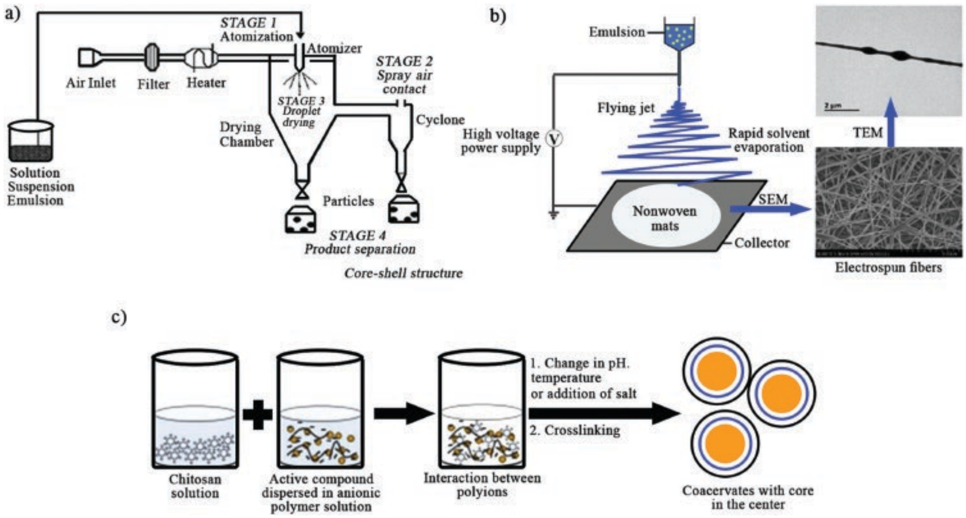

Figure 1.2 Schematic illustration of the (a) spray-drying technique Adapted from [20b], (b) electrospinning technique [22b] / with permission of Elsevier, and (c) coacervation technique [25b] / with permission of ScienceAsia.

including effectivity, low cost, and versatile technique. Also, it has been widely applied in recent years since it has many valuable advantages, such as high surface-to-volume ratio, high porosity, and ultrafine structures of the prepared fibers (Figure 1.2b). Figure 1.2b shows that it is non-mechanical technique and includes a high-voltage electrostatic field to charge droplets on a polymer solution surface, and then, induce the ejection of a liquid jet via a spinneret [22].

In this route, different natural polymers, such as biopolymers (proteins and polysaccharides), and biocompatible synthetic polymers, including polyvinyl alcohol and polycaprolactone, may be used individually or by mixing according to the specific type of usage of the food ingredients. Because these polymers are biodegradable, biocompatible, and nontoxic compounds, their micro- and nano-electrospun fibers have been applied for food and biomedical applications [22b, 23].

1.2.2.3 Coacervation Technique

Coacervation technique is widely used in food applications to prepare micro- and nanoparticle formulation. It involves the phase separation between the hydrocolloids phase from its starting solution using the change of ionic strength, temperature, solvent type, and pH. And then, subsequent deposition of the separated coacervate on the droplet core surface in the solution is noticed [24]. Generally, the coacervation technique involves many steps as shown in Figure 1.2c. The first step includes the dispersion of oil phase in the hydrocolloid solution to form oil/water emulsion. After that, the precipitation of hydrocolloid is put through different conditions, such as pH, temperature, ionic strength, and solvent polarity, to form a polyelectrolyte complex using the salting out method in the presence of salts, such as sodium sulfate, or the desolvation method in simple coacervation using a water miscible non-solvent [25]. However, in the complex coacervation method, there are polymer/polymer electrostatic interactions between two different and opposite charges that hydrocolloid. In addition, it contains other weak interaction bonds such as H-bonding and hydrophobic interactions. The obtained complex is stabilized through crosslinking interaction using tripolyphosphate, calcium chloride, and glutaraldehyde as crosslinkers. It is advantageous, thanks to high-encapsulated bioactive ingredients, up to 99% [25a, 26]. This technique is vastly applied in food industry, particularly, for encapsulating lipophilic ingredients, for example, essential oil, vegetable oil, and palm oil [27].

1.2.2.4 Emulsion Technique

Emulsion method based on the polymer hydrocolloid-delivery system is vastly applied in food and pharmaceutical applications to encapsulate, protect, and deliver bioactive ingredients. Based on the droplet size diameter, the emulsion product can be classified into three forms as shown in Figure 1.3a: nanoemulsion, miniemulsion, and macroemulsion formulations [28]. This technique basically depends on the mixing of two totally or partially immiscible liquids. Additionally, it involves amphiphilic surface-active surfactants that decrease the interfacial tension among both the liquids used to achieve good stability (Figure 1.3b). Generally, emulsion method can be found in two forms: oil-in-water (o/w) and water-in-oil (w/o) types that depend on oil dispersed as droplets in water or vice versa [28a, 29].

1.2.2.5 Ionic Gelation Technique

Ionic gelation method includes the reaction between polycation polymer as chitosan and polyanions, such as proteins, alginate, hyaluronic acid, etc., in the presence of crosslinking agents, including tripolyphosphate, aluminum chloride, calcium chloride, etc. (Figure 1.3c), to produce the desired nanoparticle formulation in different ranges of 84–600 nm. Ionic gelation technique has several outstanding advantages such as (i) a simple, easy, non-toxic, and mild technique, (ii) an organic solvent-free method; and (iii) prepared nanoparticles with excellent encapsulation efficiency. Additionally, it has main drawbacks as the prepared nanoparticles often appear with a broad size distribution and non-uniform composition [25b, 30].

1.2.2.6 Liposome Formulations

Liposome formulations are bilayer phospholipid vesicles with a definite diameter of 25 nm–10 μm. They could encapsulate polar materials inside their core and the hydrophobic materials through their lipid bilayer. They fabricate by the film hydration method (Figure 1.3d) with lipid and cholesterol and solvent as well. However, it has many instability issues referred to as aggregation, hydrolysis, and oxidation. So, to decrease its oxidation, an appropriate buffer is used, and the freeze-drying technique is also used to overcome the effect of temperature on liposomes [31]. Gomez et al. [32] reported the encapsulation efficiency of any liposome preparation based on the encapsulated active ingredient.

The aforementioned techniques of design or engineering of the materials science for food product development is governed by some factors summarized in Box 1.1.

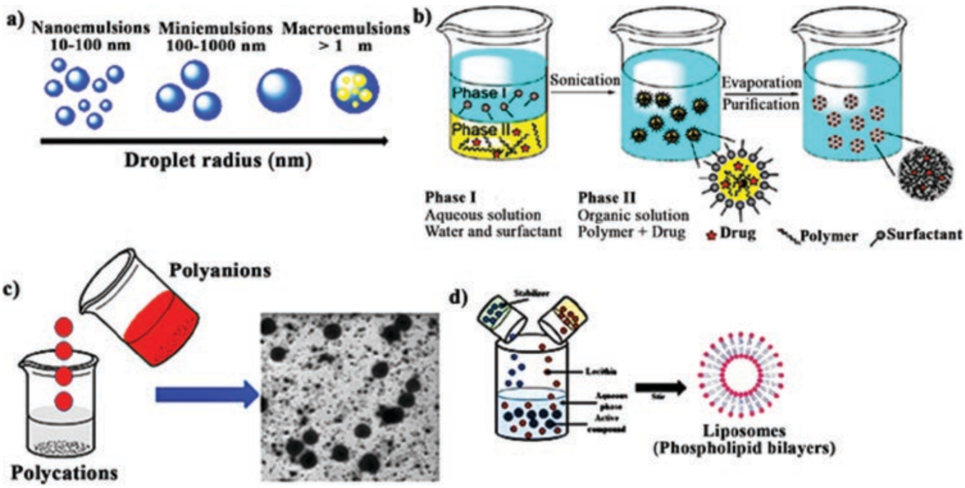

Figure 1.3 Schematic illustration of (a) emulsion fabricated products: nanoemulsion, miniemulsion, and macroemulsion formulations, (b) emulsion technique [28b] / with permission of Elsevier, (c) ionic gelation technique; and (d) liposomes formulation [25b] / with permission of ScienceAsia.

Box 1.1 Developing the product's concept

- A product is an amalgamation of hard values, or basic attributes, and soft values, or distinguishing qualities, such as aesthetic appearance and environmental friendliness that the consumer expects.
- Product design, or the process of creating a product, is a synthesis of consumer and market research and technological and engineering studies.
- The areas of engineering the product include: (i) determining what consumers want; (ii) creating a product brief for the target market; (iii) comparing with similar items; (iv) generating new ideas.

1.3 Encapsulation of Food Ingredients for Food Product Development

Encapsulation is a common technology in the food business for creating engineered products, especially in functional and specialized food industrialization, food processing, and product invention. Encasing a functionally active core material into an inert substance is what is required (Figure 1.4). The material that will be encapsulated is referred to as the core or active material. It is also known as the payload state, the fill state, or the internal state. The substance used to encapsulate the active component is known as the coating material, shell, matrix, membrane, wall, capsule, or carrier material [33]. As

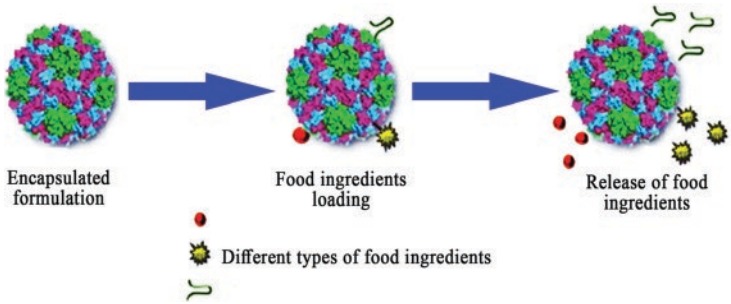

Figure 1.4 Schematic illustration of encapsulation of food ingredients.

the first to uncover the concept of cell encapsulation [34], pressure-sensitive coatings for carbonless copying paper were created using encapsulation technology for the first time in industry about two decades ago [35]. The main branches of nanotechnology, nanoencapsulation, and microencapsulation have been widely used in the food industry to protect bioactive food ingredients from processing and environmental stresses [36], as well as for controlled-release applications to solve the major problem of food ingredients that food industries face. They have received a lot of attention in the industrial world because of their capacity to safeguard unstable bioactive components, add new functional features into sophisticated food products, and release active material at a controlled rate. As a result, abundant encapsulation approaches have been studied for a long time.

The process selection is influenced by the nature of the active ingredient, the qualities of the shell material, and the wanted attributes of the final product based on the intended use. To improve shelf life and/or hide a disagreeable flavor or taste, food-grade proteins and polysaccharides are used to encapsulate sensitive and bioactive food constituents, such as highly unsaturated edible oils (e.g. fish oils), enzymes, vitamins, or diverse flavors [37]. However, recent research works have focused on enhancing the functionality and health benefits of processed foods, as well as enhancing the efficacy of probiotics and transportation of various enzymes or coenzymes, bioactive peptides, and so on [38]. Controlled and prolonged release and targeted delivery have been achieved by encapsulating artificial sweeteners, therapeutic proteins, and other bioactive ingredients [39]. Although the primary objectives of encapsulation research are to control the release of active ingredients with a desired rate, in the appropriate place at the appropriate time, and to protect bioactive food species from environmental factors (radiation, oxygen, light, moisture, and different pH states), recent developments have been made to improve product handling in terms of reduced toxicity, lowered cost, and reinforced nutrient bioavailability. The ultimate goal is to extend the shelf life of the designed product and promote its overall acceptability [40]. The physical and chemical properties of the resulting encapsulation are determined by the wall material chosen [33b]. As a result, the module that forms the wall is chosen based on the following criteria: (i) compatibility and degree of reactivity or inertness with the core and