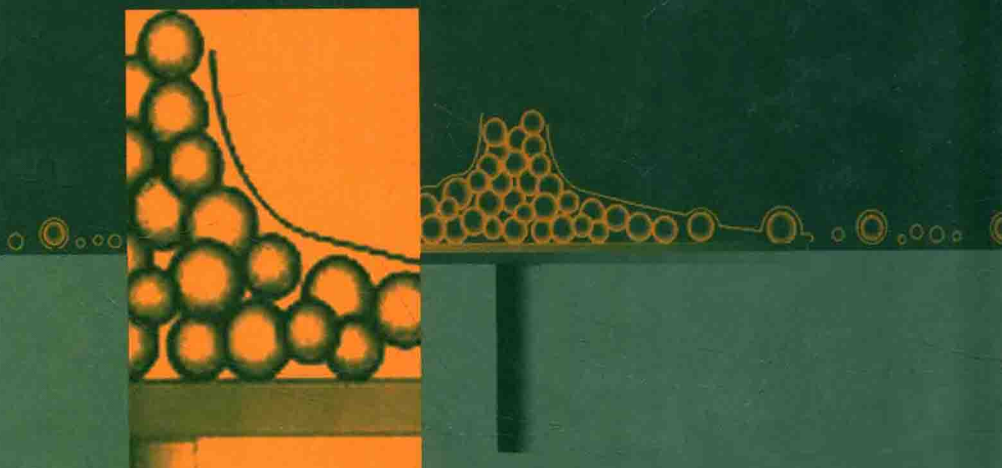
FOOD ENGINEERING SERIES

José Miguel Aguilera
Peter J. Lillford
Editors

Food Materials Science

Principles and Practice



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FOOD MATERIALS SCIENCE

Principles and Practice

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PREFACE

Most people do not think of foods as engineering materials, and specialized books make almost no reference to them. Somehow, foodstuffs have been set apart from other materials—textiles, wood, clay, metals—used by mankind since prehistoric times and more recently, ceramics and plastics. Perhaps, it is because for many old cultures foods were a gift of the gods and it would appear demeaning now to consider them as mere substances.

Why then should we compile a book about the science of food materials? Reasons abound. The Merriam-Webster Dictionary defines food as "*material* consisting essentially of protein, carbohydrate, and fat used in the body of an organism to sustain growth, repair, and vital processes and to furnish energy." People describe the process of eating in terms typical of the mechanics and flow of materials (e.g., tough, soft, thick, thin). Modern food processing can be defined as a controlled effort to transform and create microstructures that are palatable. Even the amateur scientist realizes that foods do not escape the principles of physics and chemistry. Rising bubbles in champagne, dunking biscuits and the sound emitted by potato chips during mastication are the result of physical phenomena, and the flavors delivered by many foods originate from both molecular reactions and the collapse of physical structure.

Often, foods must be treated as engineering materials. Heat has to be transported so that the components become "cooked" or harmful microorganisms and toxins become inactivated. Even in the kitchen, mixing involves the mass transfer of liquids and solids to form metastable structures, which are "fixed" by subsequent treatment by heat or cooling. Heat transfer properties are crucial in the formation of ice crystals in ice cream and fat crystals in chocolate products. Food materials have been used as a source of industrial components: soybean proteins to manufacture auto parts in the 1940s, casein to make buttons and knitting pins, and starches in adhesives and thickeners.

Foods are unique among materials of our daily life in that they are ingested and become part of our body. This immediately adds several extra dimensions to their intrinsic properties: foods have to be appealing, tasty, nutritious and safe. Unlike the case of engineering materials food properties have no single value but they depend largely on consumers' characteristics (e.g., age, physiological state, etc.) and judgment. The biological origin of foods makes them prone to degradation, adding a temporal dimension to their desirable attributes not found in ordinary materials. Moreover, because natural edible materials play a biological role in plants, animals and fish they have a structure (usually assembled hierarchically) imposed by the functional role. Typical of foods is the presence of multiple chemical components adding complexity to their study. Foods are such easily recognised materials that many reputable scientists, including Nobel laureates, chose them to illustrate their findings to the laymen. At the other extreme, innovative chefs are using the properties of food as materials to create dishes that astound their customers and provide exquisite sensations. This *mélange* of science and gastronomy is becoming an autonomous discipline: molecular gastronomy.

The body of scientific knowledge behind food fabrication started to accumulate less than 50 years ago. It has been in the last 20 years that the study of foods as materials has become a field in its own. It has been fostered by advances in related areas, most notably polymer science, mesoscopic physics, microscopy, and other advanced physical techniques. Progress in separations science has led to economically feasible processes that make available refined and functional food ingredients that replace or complement traditional raw materials. New technologies, most notably the use of membranes and microdevices, promise to bring the scale of fabrication closer to that of microstructural elements in dispersed phases (droplets, bubbles).

On the demand side, increasing evidence of links between diet and some non-transmissible diseases (obesity, cardiovascular diseases, and some cancers) has opened new opportunities to tailor-made products with reduced caloric content or increased levels of beneficial nutrients that may help prevent or ameliorate the effects of these diseases. In coming years, structuring foods for the brain (pleasure) and the gut (health) will become increasingly important as new knowledge emerges on neurophysiology and the fate of nutrients in the digestive tract, respectively. Discoveries in materials nanotechnology may be adapted to improve food quality and traceability. Lastly, the technology of genetic engineering provides the opportunity to harness cellular processes to fabricate the complex food molecules that we require. We can now alter the amount and properties of materials directly in the natural source. With this power to control the synthesis of biomolecules comes enormous responsibility, but the future seems bright and full of opportunities for food materials science.

This book describes the science and practice behind the materials in foods that impart their desirable properties. The first part of the book describes those physico-chemical aspects that intervene in the organization of food components from the molecular level to actual products and methods used to probe into foods at different length scales. The second part explains how food structures are assembled during processing in order to achieve desirable and recognizable properties. Processed foods are mostly metastable structures in which water, air, and lipids are immobilized as dispersed phases within a polymeric matrix of proteins, polysaccharides, or a fat crystal network. The last section of the book presents specific examples of how structures of familiar products are obtained by processing and describe some new developments.

Combining breadth and depth was our ambitious goal for this book. This was only possible by bringing together the talent and knowledge of many scientists. Our first thanks go to the authors for contributing chapters. We were fortunate to gather a highly authoritative group of scientists that have made major contributions to what is presently the science of food materials. It has been a pleasure to work with them. We appreciate the enthusiasm and support provided by the publisher, in particular, by Susan Safren. We owe many thanks to our graduate students and colleagues for their critical comments and suggestions. Any errors that remain are, of course, entirely our own.

In these times of dwindling funding for science, the support of the Nestlé Research Centre (Lausanne), the Alexander von Humboldt Foundation, and recently, the Marcel Loncin Fund of IFT is appreciated by JMA. PJL wishes to thank Heather McGown without whom no texts would ever have been completed. He acknowledges all his former colleagues in Unilever Research for their stimulating challenges, and thanks CSIRO for a recent series of Fellowships which has given access to new co-workers, and an opportunity to develop the practice of food materials science.

Our families also deserve our gratitude, once again, for their forbearance. However, we warn them that acting as editors of this book does not mean we have the answers to the secrets of the kitchen. Hopefully, our responses will provide insight into the operating principles encountered every day by millions of food providers.

Santiago, Chile — José Miguel Aguilera
Heslington, York, UK — Peter Lillford

Contents

FUNDAMENTALS

Chapter 1

Why Food Materials Science?

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1.1 Introduction

For centuries, mankind has hunted and farmed its food supply. For an equal amount of time, someone has had to convert these raw materials to an edible state, most of which required processing, since apart from fruits and nuts, most biological materials are not easily eaten and digested by *Homo sapiens*. In the hands of an expert, such as a the Cordon Bleu chef, this processing has been developed into an art form, using the intrinsic properties of the raw materials to create colours, textures and flavours for our delectation and nutrition. Furthermore, the methods and materials have been codified into millions of recipes, which are available to everyone.

So what more do we need to know about food materials and their processing?

Chefs, and indeed all cooks, operate batch processes on selected materials. Originally all food was prepared this way, and the resultant quality related to the individual's skill in selecting raw materials and operating subsequent processes. As civilization advanced and societies became urbanized, mass food preparation became necessary, with the concomitant problems of scaling up the operations and of sourcing raw materials of at least reasonable quality. By these criteria, the food manufacturing industry is highly successful. As a percentage of earned income, food is now cheaper in the developed world than it has ever been. However, it is still the case that product quality and utilisation of materials is inadequate because of:

1. *Irreproducibility*: Even in the hands of the best chefs results are variable, either because the raw materials are not completely specified or the processes are "interpretable" in terms of energy input and time. In a way, recipes are like patents: they tend to conceal "secrets" rather than reveal details.

2. *Cost*: The "best" materials are not always available. Agricultural products are conditioned by their biological source (genetics) and the action of abiotic stresses (the environment). All of the resultant raw materials should be used, to avoid waste and to maximise conversion efficiency, yet not all of them can be ideal for a given process or product type.
3. *Scale*: In our modern society most processing is not done locally by the producer but in large-scale factory conditions. The processes described in most recipes relate to a small scale, and are not directly transferable to large-scale, continuous processing.

The net effect is that food products are not easily standardised, and by the necessarily subjective measurement of quality by the consumer, not everyone is satisfied all of the time. Faults can occur for two major reasons. Either the product was not what was intended (problems in fabrication to an exact specification); or the product did not meet the performance expectation of the user (problems in performance and expectation).

The food industry is like any other manufacturing industry; Commercial practice is competitive, and the manufacturer who is best able to make the most acceptable product most often, from the most appropriate raw materials and at the right cost will be successful. The ability to innovate products, processes and interchange raw materials is necessary for financial survival, and so the science of food materials is necessary to deliver consistent quality and novelty of product to very demanding customers.

1.2 What is Quality?

Unlike other manufacturing industries, where the product can be accurately specified in terms of its performance, food is measured by individuals, and its qualities of appearance, texture and flavour are measured subjectively against a set of criteria established by experience. We know what we like, and it is very dependent on our own cultural background and lifestyle. As consumers, we detect some qualities instantly with our eyes, nose and mouth, all of which have multiple sensors with stimulus/response behaviour that is not completely understood. We have to recognise that these qualities are defined subjectively, and are described in words that have, as yet, no clear numerical definition. There are other qualities such as the effect of food on our longer-term health and well-being that as individuals we are not well equipped to measure. We cannot easily detect the effect of salt on our blood pressure or antioxidants on our cancer resistance. The development of biomarkers for health is outside the scope of this volume.

Returning to qualities that we *can* recognize during purchase and eating, we must understand that subjectively measured quality, and its relationship to perceived preference or liking, is the real criteria of success in food manufacture. Throughout this volume, reference will be made to how finished product structures relate to these subjective assessments. Fortunately, even though individual preferences change, there are certain textural parameters such as toughness, crispness, smoothness, and so on, that are universally recognised, and we can attempt to understand their origin. Also, despite the fact that there are an enormous number of food types available, they all have to be chewed and swallowed, and the equipment we have to deal with them (teeth, tongue, saliva) are common to most consumers. We must recognise therefore, that quality is measured throughout the mastication process and is not just a simple property of the manufactured structure.

Quality control or quality assurance tests are already common throughout the industry. Many of these tests are physical measurements that have been derived empirically. Rather than relating to the fundamental physical properties of foods, they are designed to detect deviation from a standard sample already defined to be of acceptable quality. While useful, they should not be confused with the measurements necessary to understand how components interact with each other to form the complex composite structure required in most foods.

Apart from producing convenient food that is pleasant to eat, the food manufacturing industries face a further major challenge. International supply chains now offer the developed world a surfeit of food calories, so that our natural tendency to enjoy eating means that obesity, not malnutrition, is a major health risk (even in the less-developed world). Now consumers would like to continue to enjoy eating, but without the risk to their health in terms of chronic ailments such as diabetes, cardiovascular disease and cancer. These qualities of long-term health benefit are not directly measurable by the consumer, but consumers and legislators now demand both information and delivery of foods that will protect, or at least not cause a decline in, long-term health.

The boundaries between food science, nutrition and medicine are beginning to blur, and molecular nutrition, or "Nutrigenomics," is in vogue. While these topics are in the area of biological rather than material sciences, the findings will have to be translated into edible foodstuffs. Even if we knew the exact genomic regulation of every individual on the planet, and even if nutritionists might specify their exact daily requirements of macro- and micronutrients, unless the food was available, attractive and pleasant to eat, there would be little impact on human health.

Someone will have to develop and make the new foods and deliver them to the right markets at the right time. This will require continuous innovation in ingredients and processes. A greater depth of understanding of the relation between components of food, the effect of processes upon them, the net effect on the "architecture" of the composite structure, and the subsequent appearance, organoleptic and nutritional performance, will be required. Neither is this science required solely to fulfill the demands of the idle rich. If we are to feed the increasing world population, the need to use agricultural produce as efficiently as possible is mandatory, so a growth in knowledge of food materials behaviour is equally necessary. This is further justification of the approach we call "food materials science."

Ideally, the science of food materials should approach and provide answers to two fundamental questions:

1. What are the causal relations between the structure of a food and its performance when assessed visually, organoleptically and in the delivery of its components to the human digestive tract?
2. How do we control (predictively) the effect of processes on components to form the required product structure?

When both questions are answered, we can begin to develop "design rules" for food products, comparable to those available in assembled products from bridges and buildings to machinery and composites. When phrased in this way, it is obvious that food can be related to these other manufacturing industries, such as construction, ceramics, polymer products, and so on, and wherever possible we should borrow approaches and methodologies from them.

1.3 What Are the Materials?

The words "materials," "components" and "structures" have been used thus far with little regard to their definition. Without being too pedantic, we need to be clear about their use, and to do this the scale of the observation needs to be considered. Food materials and structures are similar to other well-known objects in this regard. For example, taking the analogy of the construction industry, we can equate a finished food to a building. This is obviously a structure made from components such as doors, windows, roofs, and so on, and materials such as bricks, mortar, timber, plastic, and so on. While we can see that components such as windows and doors are obviously structures in their own right, a little help with a hand lens shows that brick, timber, and mortar are themselves structures comprised of particles, fibres, and crystals. Likewise, at a higher level of magnification, the particles, fibres and crystals are structures formed from molecular assemblies, the properties of which are determined not only by the molecular species present but also by the conditions under which they were formed. The structural (mechanical) requirements of a building are that it should not fall down and remain stable for as long as possible. This requires appropriate organization at all hierarchical levels.

We can perform a similar analysis on a loaf of bread, a sausage or a tomato. Our components are starch granules, gluten networks, muscle, plant cells, and so on. But our assembly processes simultaneously modify the structure of components, colloidal assemblies and molecular configurations. The structural requirements for the lifetime of products are a little different, but stability is required during transportation and storage. Food materials scientists have a further, even greater challenge: Under incompletely specified conditions in the mouth and gastrointestinal tract, the structure must collapse in a fashion recognizable to the consumer and appropriate to the unique processes of mouth action and digestion. No wonder we do not yet have a handbook of food design!

Fortunately, we are not entirely alone in studying the architecture of biological structures. Nature itself provides many sophisticated solutions to mechanical problems faced by living organisms, using the same materials and components found in foods. For those wishing to explore this topic of biomechanics further, the now classic texts of Wainwright et al. (1976) and Vincent and Currey (1980) are recommended reading; these sources can be followed by the inspirational works of Gordon (1976, 1978).

We note from all this prior work that structure at the macro, micro, nano and molecular levels of organisation will all be important. Secondly, the properties of the composite food product will not be related simply to a list of its components (the recipe), since different structural forms can be assembled from the same components by different processes. Emphasis on structure and its origin discriminates food materials science from the former descriptive approach of formulation/process empiricism embodied in most recipes.

There is enough published microscopy of foods (Aguilera and Stanley, 1999) to indicate that their structures are enormously variable and complex. The physical property of appearance is derived from the structure itself, and texture, flavour, taste, and subsequent bioavailability of nutrients are derived from the manner in which the structure collapses or breaks down. Simple theories of composite solids tell us that the spatial organisation of components and materials, their own physical properties and the interfacial interactions between them will determine overall properties. The components and materials themselves consist of molecular assemblies. This hierarchy of structure suggests we will need measurement at all length scales from molecular to macrostructure and over timescales relevant to processing (milliseconds to hours) and product stability (minutes to months).

1.3.1 Fundamentals

In the first section of this volume we examine the fundamentals of structure at the level of the overall composite, as well as the properties of its components. The starting materials of food derive from living biological systems, whose mechanical properties have been studied in their own right. Vincent explores the extent to which biological composites can be related to other natural and manmade composites, and emphasises the difference between the properties of components (fibres and matrix) and the structure itself. This engineering approach to biological structures, whether natural or fabricated, shows the fundamental difference in the materials science approach, compared with the former recipe approach to food manufacture.

In subsequent chapters we examine the physical forms and properties of products and components. These are shown schematically in Figure 1.1.

It is important to recognise the ubiquitous presence of water in all foods. Every chapter will mention the particular impact of water as a solute, diluent and plasticiser, often converting one physical state to another and also promoting mixing or segregation of one component molecular species from another.