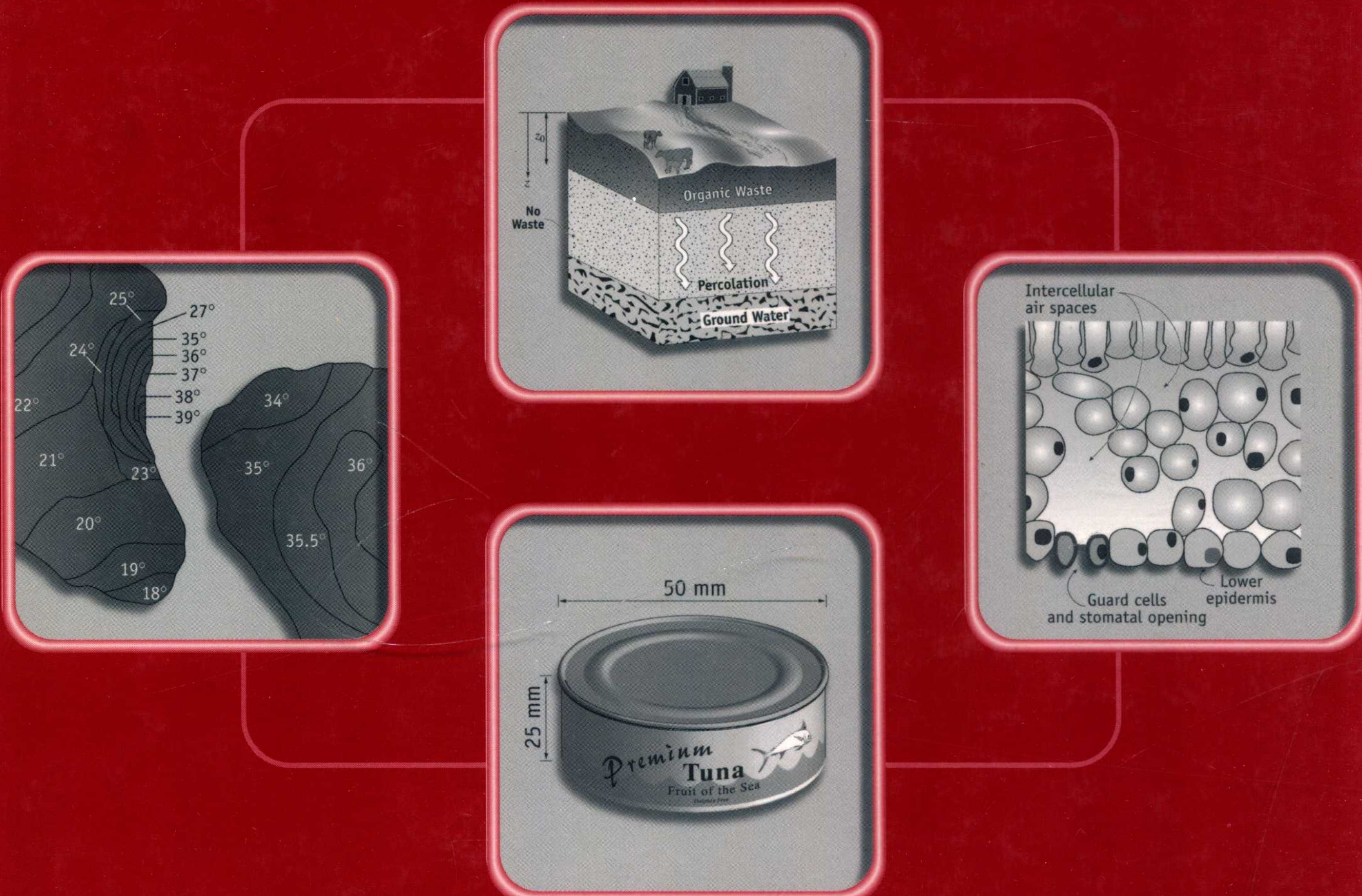
Biological and Bioenvironmental Heat and Mass Transfer



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Biological and Bioenvironmental Heat and Mass Transfer

To my parents

Atindra Nath Dutta
and
Bela Rani Dutta

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PREFACE

It is very important to give the undergraduate engineer a fundamental education in the context of his/her likely application areas. Transport of energy and mass is fundamental to many biological and environmental processes (see pages xi to xx). Areas, from food processing to thermal design of buildings to biomedical devices to pollution control and global warming, require knowledge of how energy and mass can be transported through materials. These wide-ranging applications have become part of emerging curricula in biological engineering, and societies such as the Institute of Biological Engineering and the American Society of Agricultural Engineers have recognized the need for a course (and a text) that presents fundamentals while integrating the diverse subject matter.

The basic transport mechanisms of many of these processes are diffusion (or diffusion-like, such as capillary and dispersion) and bulk flow. Additionally, there is radiative heat transfer. It is crucial for the student to see these concepts as comprehensive and unified subject matter (much like fluid mechanics); they are the building blocks for lifelong learning in many of their interest areas. Such fundamentals-based approach will replace the more empirical and ad-hoc teaching that sometimes exists.

Although the concept of teaching transport processes as a unified subject has existed for over forty years in some engineering disciplines, only in recent years have we seen adequate quantitative studies to make such teaching possible in biological and bioenvironmental processes. This book attempts to bring together under one umbrella the unique content, contexts and parameter regimes of biologically related processes and to emphasize principles and not just mathematical analysis. *Content*, such as bioheat transfer, thermoregulation, freezing, global warming, capillary flow, and dispersion, are some of the topics not typically included in the undergraduate-level teaching of transport phenomena. *Context*, such as plants, animals, water, soil, and air is important at this level, because without this information students have an unnecessarily hard time relating to real physical processes. Context also helps students learn about the physical processes themselves in a quantitative way. For example, studying convective transfer of water vapor over a leaf includes a quantitative introduction to transpiration. (The present text was created by distilling the content of hundreds of research papers and textbooks on similar biological and environmental applications.) The *parameter regimes* of biological processes are also different from those of typical mechanical and chemical processes. For example, biological processes often involve a source term of heat generation or oxygen consumption. Presence of the source or sink term changes the nature of the solution and is emphasized in this text.

How This Book Fits in a Biological Engineering Curriculum

This text is intended for a junior-level engineering science course in curricula that emphasize biology and the environment. The course would build on the prerequisites of partial differential equations and fluid mechanics. Prior knowledge of biological and environmental science, although not required, would be useful. For example, this course can readily build on a course such as Thermodynamics of Biological Systems that has been discussed in the context of a biological engineering curriculum. Mass and heat transfer, much like fluid flow, are just as much building blocks for many of the upper-level courses. Thus, specialized design courses and advanced courses such as bioprocessing, biomedical engineering, food process engineering, environmental processes and their control, and waste management can build on a course that uses this text, greatly reducing the need to teach basic engineering science of mass and heat transfer in these upper-level courses. This text was developed at Cornell University for a junior-level engineering science course.

Approach and Organization of the Book

The overall organization of the book follows the well-tested transport phenomena approach. The chapters and their content on heat and mass transfer are made to follow an almost exact parallel, as shown in the table below. The first two chapters in each part (Part I, "Energy Transfer" and Part II, "Mass Transfer") develop the two building blocks of conservation laws and rate laws, and the next chapter (Chapters 3 and 11) combines them to build the general governing equations and boundary conditions. The next two chapters in each part (as shown in the table above) cover steady-state or transient diffusion, without any flow, while the last one adds the effect of flow. Chapter 7 covers heat transfer with change of phase, and Chapter 8 covers radiative energy transfer. Porous media flow and simple kinetics of zero and first order are included for completeness as they relate to transport. Effort has been made to clarify important processes such as dispersion. Different application areas in biology and environment are included within this framework of chapters, when they are relevant.

	Chapter numbers	
	Energy	Mass
Conservation	1	9
Rate laws	2	10
Governing equation	3	11
Diffusion, steady-state	4	12
Diffusion, transient	5	13
Diffusion (and dispersion) with bulk flow	6	14

How to use This Book

Students frequently follow individual topics well but have difficulty seeing their relatedness, i.e., the big picture. Thus, major effort has been made to distill the concepts presented here and to show the connections among chapters. Each chapter begins with a small list of major concepts to be covered, together with important terminologies introduced in that chapter, and each chapter has a map showing how all chapters are interconnected in terms of the topic under consideration. Each chapter has a summary at the end that puts every major concept and equation at the reader's fingertips, providing page numbers for easy access, and a set of descriptive questions checks the reader's understanding of concepts and facts. Summary maps in Appendix A (pages 316-318) show the integration of all the scenarios covered in the text. The first-time reader of the subject is strongly encouraged to use these features.

As curricula in biological and related engineering programs evolve, the core of such curricula will include mass and heat transfer as essential building blocks in students' instruction in a natural and obvious way. The author sincerely hopes that this text will serve the needs of these curricula. He also believes that the text must evolve with the curricula. Additional materials helpful for teaching this subject matter can be seen on the Internet at www.ashimdatta.net. Please do not hesitate to contact the author if you have comments on any aspect of the book.

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INTRODUCTION

Problem Formulation in the Transport Processes

This book centers around problem formulation, shown schematically in Figure 1—taking a biological problem and, after making sufficient assumptions, formulating it as a mathematical problem that one can solve using standard undergraduate calculus. The mathematical model thus built provides a more quantitative insight into the biological process by seeing how the various parameters of the process influence it. Having started from a general and fundamental description (e.g., mass and energy balances) of the process, it will be easier for students to formulate more complex processes.

The various application areas in biological engineering can be grouped as follows: plant systems, mammalian systems, the bioenvironment, and the industrial processing

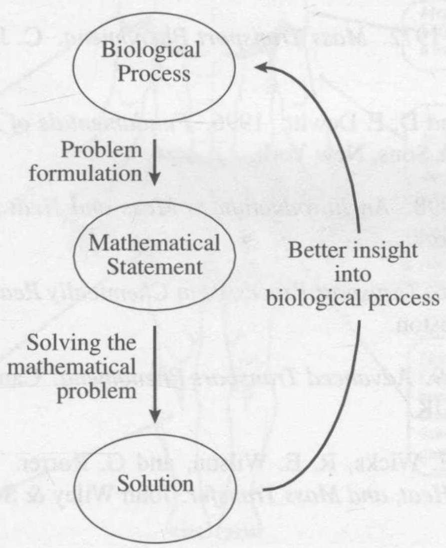

Figure 1: Schematic showing the steps of problem formulation and solution.

of biomaterials and foods. Schematics of examples and problems in each of these four areas are shown on the following pages, together with a brief description of transport processes in each application area and a list of reading materials covering specialized transport in that area. These pages will provide the reader with a glimpse of the biological processes that are discussed in this book.

In addition to the specialized texts covering transport processes in various application areas mentioned in the following pages, several well-known books on general transport phenomena can provide the reader with information on governing equations and solutions for various situations. Some of these general texts are:

Bird, R. B., W. E. Stewart, and E. N. Lightfoot. 1960. *Transport Phenomena*. John Wiley & Sons, New York.

Cussler, E. L. 1997. *Diffusion Mass Transfer in Fluid Systems*. Cambridge University Press, Cambridge, UK.

Deen, W. M. 1998. *Analysis of Transport Phenomena*. Oxford University Press, New York.

Eckert, E. R. G. and R. M. Drake. 1987. *Analysis of Heat and Mass Transfer*. Hemisphere Publishing Corporation, New York.

Fahien, R. W. 1983. *Fundamentals of Transport Phenomena*. McGraw-Hill, New York.

Geankoplis, C. J. 1993. *Transport Processes and Unit Operations*. P T R Prentice Hall, Inc., Englewood Cliffs, New Jersey.

Geankoplis, C. J. 1972. *Mass Transport Phenomena*. C. J. Geankoplis, Columbus, OH.

Incropera, F. P. and D. P. Dewitt. 1996. *Fundamentals of Heat and Mass Transfer*. John Wiley & Sons, New York.

Middleman, S. 1998. *An Introduction to Mass and Heat Transfer*. John Wiley & Sons, New York.

Rosner, D. E. 1986. *Transport Processes in Chemically Reacting Flow Systems*. Butterworths, Boston.

Slattery, J. C. 1999. *Advanced Transport Phenomena*. Cambridge University Press, Cambridge, UK.

Welty, J. R., C. E. Wicks, R. E. Wilson, and G. Rorrer. 2001. *Fundamentals of Momentum, Heat, and Mass Transfer*. John Wiley & Sons, New York.

Transport in the Mammalian System

In mammalian systems, transport processes occur at the cellular, tissue, organ, and whole-body levels (Figure 2). At the cellular level, transport across the cell membrane is driven by passive diffusion of solutes and water, hydraulic and osmotic transport of water, carrier-mediated transport, passive ion transport and active transport. This text includes diffusion, as well as hydraulic and osmotic transport, but not the other important but complex transport mechanisms just mentioned. An extensive treatise of cellular transport is provided in Weiss (1996). At the tissue or organ level, diffusion of oxygen is an important transport process. One of many examples of such transport being the oxygen diffusion from air to the blood stream in alveoli of the lungs. At the whole body level, there is thermoregulation, whereby heat production in the body and heat dissipation through behavioral changes (movements of the whole body) or autonomic, reflex-like changes (such as sweating or shivering) are modified. Thermal therapy, either the use of heat (hyperthermia) or the use of freezing temperatures (cryosurgery) to destroy tissue, demonstrates heat transfer in clinical applications. Transport in artificial organs such as the dialyzer is another important group of problems. The reader can consult several specialized books on transport in biomedical systems for further

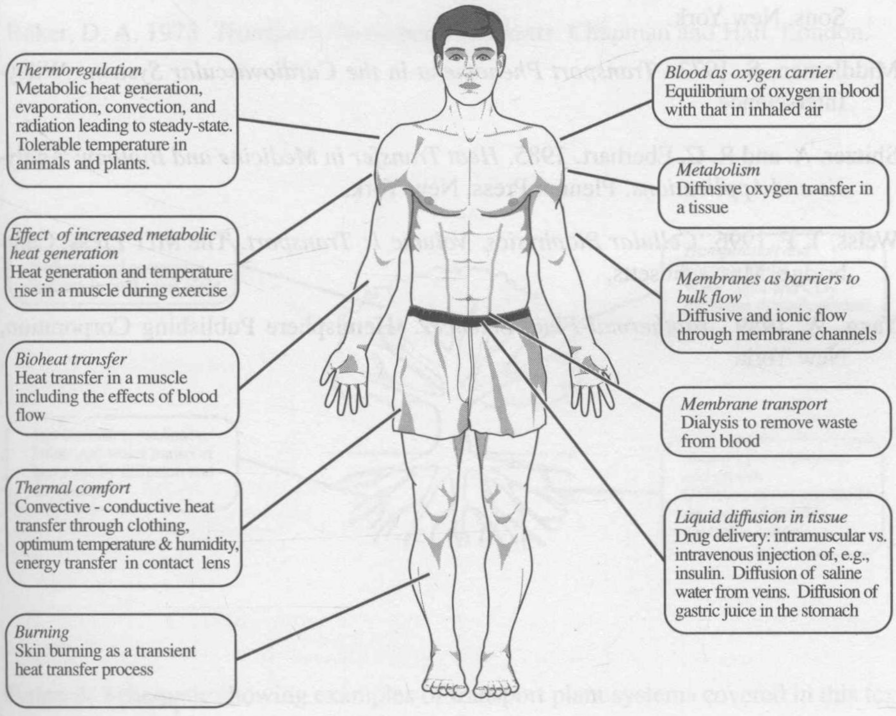

Figure 2: Schematic showing examples of transport in mammalian systems covered in this text.

details. Some titles follow:

Berger, S. A., W. Goldsmith, and E. R. Lewis. 1996. *Introduction to Bioengineering*. Oxford University Press, Oxford, UK.

Charny, C. K. 1992. Mathematical models of bioheat transfer. Advances in Heat Transfer 22:19-153.

Cooney, D. O. 1976. *Biomedical Engineering Principles. An Introduction to Fluid, Heat and Mass Transport Processes*. Marcel Dekker, Inc., New York.

Evans, D. H. 1998. *The Physiology of Fishes*. CRC Press, Boca Raton, Florida.

Fanger, P. O. 1972. *Thermal Comfort: Analysis and Applications in Environmental Engineering*. McGraw-Hill, New York, NY.

Fournier, R. L. 1998. *Basic Transport Phenomena in Biomedical Engineering*. Taylor & Francis, Philadelphia, Pennsylvania.

Lightfoot, E. N. 1974. *Transport Phenomena in Living Systems*. John Wiley & Sons, New York.

Lih, M. M. 1975. *Transport Phenomena in Medicine and Biology*. John Wiley & Sons, New York.

Middleman, S. 1972. *Transport Phenomena in the Cardiovascular System*. Wiley-Interscience.

Shitzer, A. and R. C. Eberhart. 1985. *Heat Transfer in Medicine and Biology: Analysis and Applications*. Plenum Press, New York.

Weiss, T. F. 1996. *Cellular Biophysics. Volume 1: Transport*. The MIT Press, Cambridge, Massachusetts.

Yang, W. 1989. *Biothermal-Fluid Sciences*. Hemisphere Publishing Corporation, New York.

Transport in Plant Systems

From an engineering standpoint,[1] an annual crop plant may be regarded as a self-replicating structure. The first structures produced, leaves and roots, function primarily in transport and energy acquisition. The leaves intercept solar energy for the fixation of carbon dioxide in photosynthesis, acquiring the carbon dioxide by diffusion through the boundary layer over the leaf and through the stomatal pores, while inevitably losing water by evaporation from the cell surfaces of the wet leaf. The roots extract water from the soil, replacing that lost by the leaves and providing the water that constitutes the bulk of growing plant tissue. For many mineral nutrients essential for plant growth, roots are also the initial site of transport into the plant. The properties of soil-root interface also determine whether pollutants in the soil enter the food chain. Within the plant, transport across the cell membranes involves both diffusion, for water and solutes, and carrier-mediated processes, for ions and organic molecules but not water. Bulk flow of water, ions, and some nitrogen compounds from the roots to the shoot occurs in the specialized vascular tissue called the xylem. Some of the examples of transport in plant systems covered in this text are shown in Figure 3. (The topic of carrier-mediated transport is outside the scope of this text, and the reader is referred to specialized texts such as Marschner, 1995). Some texts and reference books covering transport in plant systems are noted below:

Baker, D. A. 1978. *Transport Phenomena in Plants*. Chapman and Hall, London.

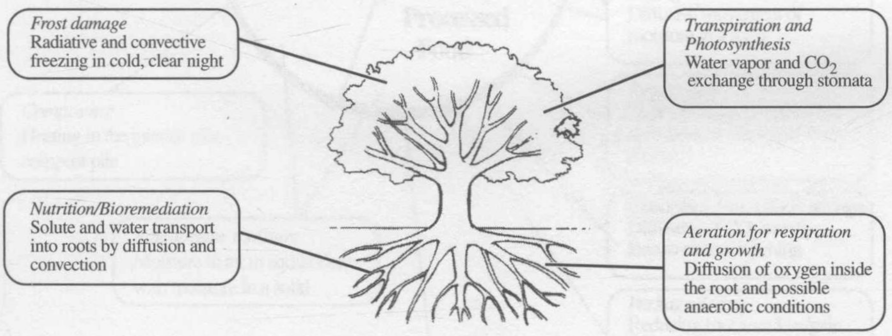

Figure 3: Schematic showing examples of transport plant systems covered in this text.

[1] Paragraph based on contribution from Prof. Roger Spanswick, Dept. of Biological and Environmental Engineering, Cornell University.

Buchanan, B., W. Gruissem, and R. L. Jones. 2000. *Biochemistry and Molecular Biology of Plants* (Chapters 3, 15 and 23). American Society of Plant Biologists, Rockville, MD.

Cundiff, J. S. 1999. Simulation of biological systems. Coursenotes for BSE 4144, Virginia Polytechnic and State University, Blacksburg, Virginia.

Flowers, T. J. and A. R. Yeo. 1992. *Solute Transport in Plants*. Blackie Academic & Professional, London.

Marschner, H. 1995. *Mineral Nutrition of Higher Plants*. Academic Press, San Diego.

Merva, G. E. 1995. *Physical Principles of the Plant Biosystem*. American Society of Agricultural Engineers, St. Joseph, MI.

Nobel, P. S. 1999. *Physiochemical and Environmental Plant Physiology*. Academic Press, San Diego.

Siau, J. F. 1984. *Transport Processes in Wood*. Springer-Verlag, New York.

Transport in Industrial Food and Biological Processing

Transport is at the core of industrial (and domestic) processing of food and biomaterials (see examples in Figure 4). In most food processes heat and moisture transport influ-

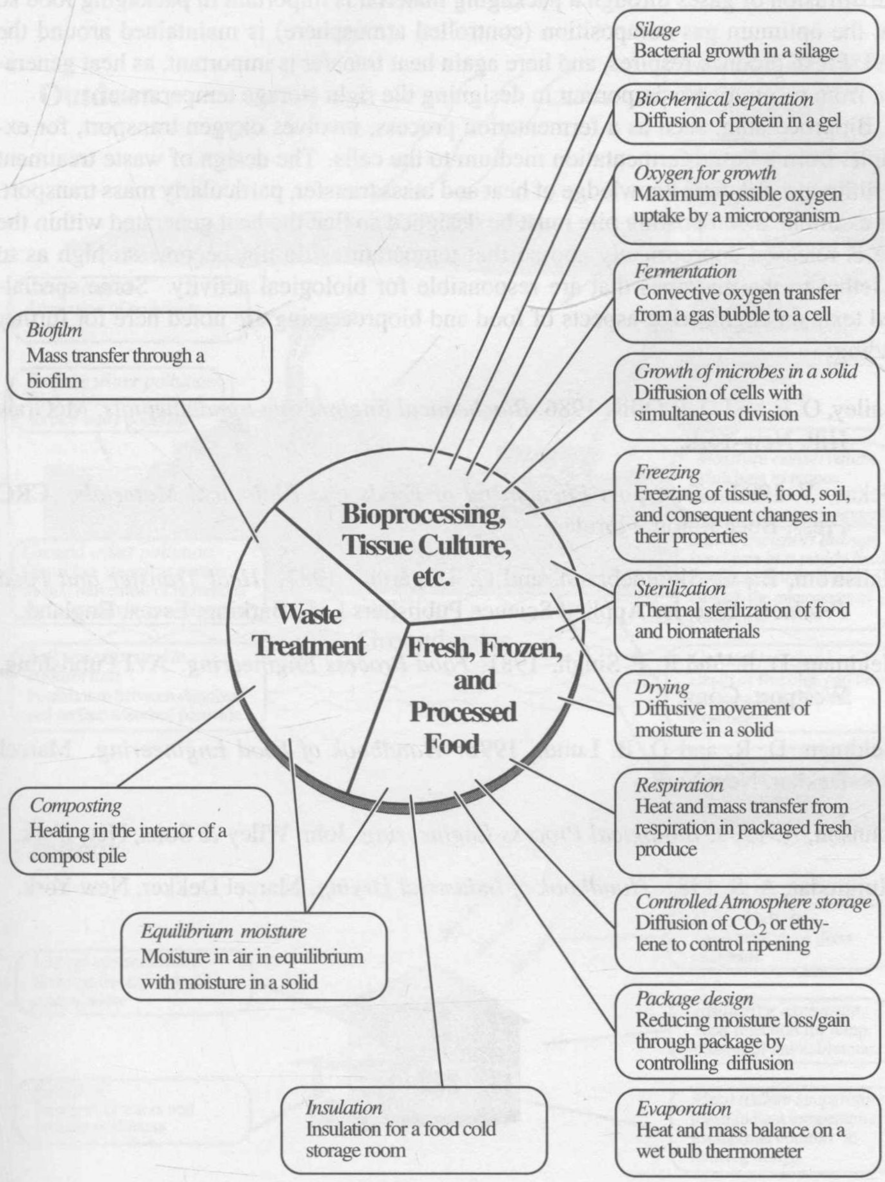

Figure 4: Schematic showing examples of transport in industrial food and biological processing that are covered in this text.

ences chemical and microbiological changes. Sterilization of food to extend its storage life is done primarily using heat, making heat transfer an extremely important transport process. Freezing of food involves heat transfer with a change of phase. Drying, and related processes such as baking and frying, are also important and involve the phase change of water to vapor and the transport of water and vapor through the food matrix. The diffusion of gases through a packaging material is important in packaging food so that the optimum gas composition (controlled atmosphere) is maintained around the food. Fresh produce respires, and here again heat transfer is important, as heat generation from respiration is important in designing the right storage temperature.

Bioprocessing, such as a fermentation process, involves oxygen transport, for example, from a liquid fermentation medium to the cells. The design of waste treatment facilities also requires knowledge of heat and mass transfer, particularly mass transport. For example, a composting pile must be designed so that the heat generated within the pile is released appropriately and so that temperatures do not become so high as to be lethal to the microbes that are responsible for biological activity. Some specialized texts on engineering aspects of food and bioprocessing are noted here for further reading:

Bailey, O. E. and D. F. Ollis. 1986. *Biochemical Engineering Fundamentals*. McGraw-Hill, New York.

Gekas, V. 1992. *Transport Phenomena of Foods and Biological Materials*. CRC Press, Boca Raton, Florida.

Hallström, B., C. Skjöldebrand, and C. Trägårdh. 1987. *Heat Transfer and Food Products*. Elsevier Applied Science Publishers Ltd., Barking, Essex, England.

Heldman, D. R. and R. P. Singh. 1981. *Food Process Engineering*. AVI Publishing, Westport, Conn.

Heldman, D. R. and D. B. Lund. 1992. *Handbook of Food Engineering*. Marcel Dekker, New York.

Johnson, A. 1999. *Biological Process Engineering*. John Wiley & Sons, New York.

Mujumdar, A. S. 1987. *Handbook of Industrial Drying*. Marcel Dekker, New York.