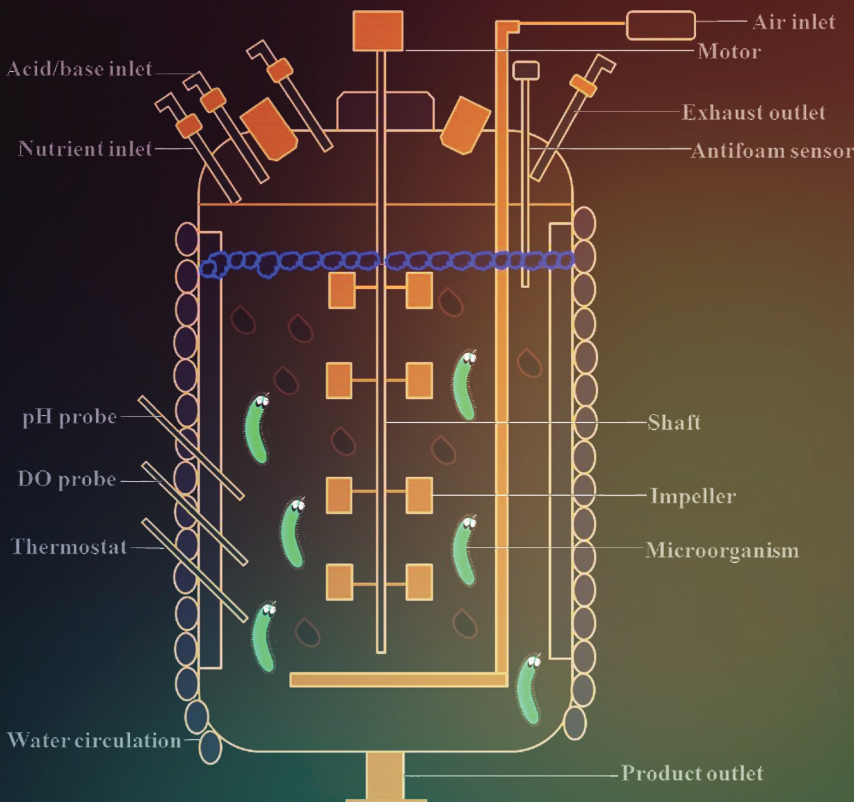
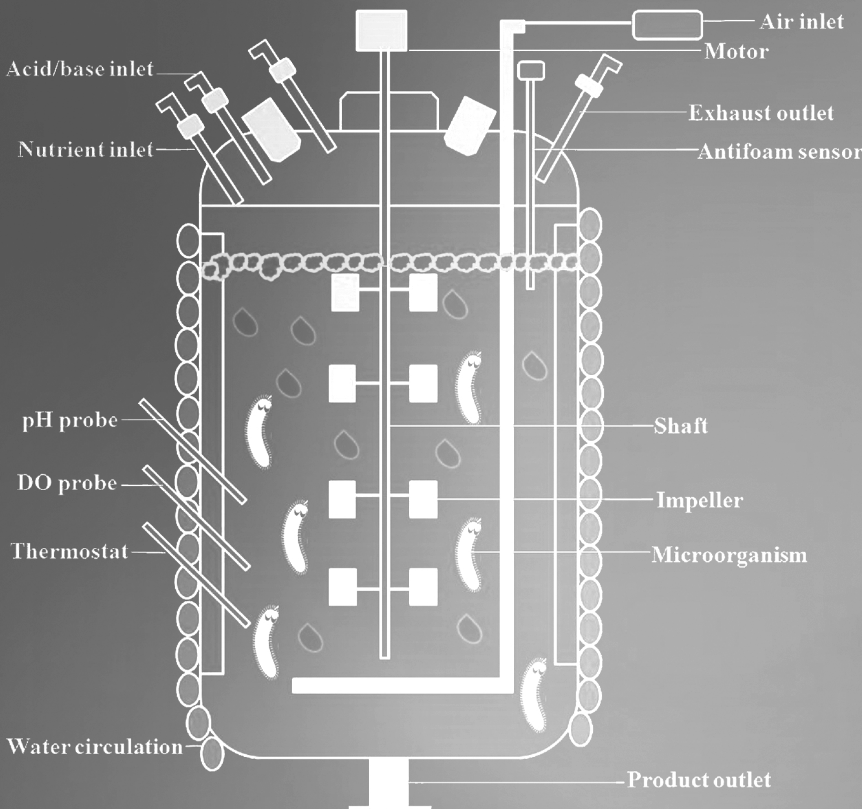


Biochemical Engineering

An Introductory Textbook

Debabrata Das | Debayan Das



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Foreword

The importance of biotechnology has been increasing due to the manipulation of DNA for the production of several new bioproducts that are useful in chemical, pharmaceutical, agricultural, and environmental management. Through research work, it is possible to produce new products useful for mankind.

A book on biochemical engineering would certainly help not only the undergraduate and postgraduate students but also researchers and process engineers involved in developing and applying bioprocesses to get all the necessary information for designing and operating bioreactors, which are the heart of any biochemical process. I congratulate the authors, Prof. Debabrata Das and Dr. Debayan Das, for seeing the need for such a book and bringing it out in a timely manner. The present book titled *Biochemical Engineering: An Introductory Textbook* comprehensively covers all aspects of the applications of bioprocesses. The objective of this book is to carry out the mathematical analysis of the processes in simplified forms in order to be understandable and utilizable by most of the biologists. Derivation of mathematical equations is explained in details so that the majority of the students can understand the meaning of the equations.

I strongly recommend this excellent book to the undergraduate and postgraduate students in biotechnology, biochemical engineering, chemical engineering, food technology, biochemistry, and related fields and also to the researchers and process engineers involved in the production of bioproducts so that they can enrich their knowledge in the area of application of biosciences and benefit mankind.

Prof. Roberto De Philippis

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Preface

Education is not the learning of the facts,
but training of the mind to think.

—Albert Einstein

All engineering disciplines have been developed from basic sciences. Science gives us the knowledge to develop new products whereas engineering applies science to scale up production for commercial purposes. Biological processes involve different biomolecules, which come from living sources. It is now possible to modify DNA to get desired changes in biochemical processes. Developments in gene expression, protein engineering, and cell fusion have significantly affected product development in biotechnology industries. Chemical processes deal with different reactions to get desired products. Biochemical reactions in nature are mostly reversible and chain reactions. To understand biochemical engineering, it is necessary to know the principles of chemical engineering, which involves not only mathematical modeling but also scaling up of processes for commercial applications. Any biochemical industry can be divided into three major steps. The first step is upstream processing, which involves medium preparation, medium and air sterilization, etc. The second step involves the bioreactor where biochemical reactions lead to the desired products. The third and crucial step is purification of the products, known as downstream processing.

This book begins with the identification of the differences between conventional chemical reaction engineering and biochemical reaction engineering. It gradually makes readers conversant with the rate laws and their applications to help them understand reaction engineering behavior and give them the expertise to apply the acquired knowledge in designing bioreactors. It discusses the stoichiometry of bioprocesses for materials and energy analysis and the transport phenomena that are important for the operation of bioprocesses. The book also enables students to contribute their knowledge in various professional fields like bioprocess development, modeling and simulation, environmental engineering, etc.

The chapters are organized in broad engineering sub-disciplines such as mass and energy balances, reaction theory using chemical and enzymatic reactions, microbial cell growth kinetics, and transport phenomena. Other chapters such as different control systems used in the fermentation industry, case studies of some industrial fermentation processes, different downstream processes, and effluent treatment are also included. Each chapter begins with a fundamental explanation for general readers and ends with in-depth scientific details suitable for expert readers. The book also includes solutions of more than 100 problems. It is written in a manner so that it can be useful to senior and graduate students of biotechnology and those studying courses in food and environmental engineering. It is also appropriate for chemical engineering graduates, undergraduates, and industrial practitioners.

We would like to acknowledge help of Ms. Jhansi L. Varanasi and Mr. Chandan Mahata at various stages of manuscript preparation. We are also thankful to Mr. Tapas Mohanty for his help in creating most of the book's illustrations using computer graphics.

We hope this book will be useful to our readers!

Debabrata Das

Debayan Das

Summer 2019

List of Symbols

Symbols

a	Constant
A	Area
A_b	Frontal area of the float
A_p	Area of the particle
a_m, a_v	Surface area per unit volume
b	Constant
C	Heat capacity; Concentration, Concentration ratio, Cunningham's correction factors for slip flow
C_A*	Equilibrium concentration of solute in fluid phase
C_{AS}*	Equilibrium concentration of solute on the solid surface
C_{ASm}	Maximum solute adsorption capacity of the solid
C_{Dm}, C_D	Drag coefficient
C_E	Equilibrium solute concentration in extracting solvent
C_P	Product concentration; Heat capacity at constant pressure
C_R	Equilibrium solute concentration in raffinate
C_S	Substrate concentration
C_V	Heat capacity at constant volume
D	Dilution rate, Decimal reduction time
D_a	Damköhler number
D_{es}, D_{BM}, D_{AB}	Effective diffusivity of substrate, Diffusivity of the particle, Diffusivity A into B
d_P, d_f, d_S	Particle diameter, Fiber diameter, Sauter mean diameter
D_z	Axial dispersion coefficient

E, E_a, E_o or e_o	Activation energy, Total enzyme concentration, Potential difference
E_{IME}	Overall activity of immobilized enzyme
F	Force, Volumetric flow rate, Faraday constant, Flow rate
f	Friction factor
F_d	Drag force
F_b	Buoyancy force
G	Free energy, Substrate feed rate
g_c, g	Conversion factor, Acceleration due to gravity
G_r	Grashof number
h	Heat transfer coefficient
H	Enthalpy
H_f	Enthalpy of formation
H_{comb}	Enthalpy of combustion
I	Inhibitor concentration
K, k	Constant, Thermal death rate constant, Rate constant
k_a	Mass transfer coefficient
K_A	Adsorption constant
k_G	Gas side mass transfer coefficient
K_i	Inhibition constant
k_L	Mass transfer coefficient in the liquid phase
k_La	Volumetric mass-transfer coefficient
k_f	Rate constant of forward reaction
K_{eq}	Equilibrium constant
K_m	Michaelis–Menten constant
k_p	Product inhibition constant
K_S	Saturation constant
k_r	Rate constant of backward reaction
l	Length
m, m_S	Mass, Maintenance coefficient, Empirical constant

M	Amount of biomass
N	Number of moles, Concentration of the cells, Number of discs in the stack
n	Order of reaction, Constant
N_{P}	Power number
N_{r}	Reaction number
N_{S}	Rate of mass transfer
N_{u}	Nusselt number
P	Pressure, Product concentration
P_{e}	Peclet number
P_{o}	Power number
P_{r}	Prandtl number
q, Q	Thermal energy, Rate of uptake of oxygen, Heat flux, Volumetric flow rate
q_{P}	Specific product formation rate
q_{S}	Specific substrate consumption rate
r	Rate of reaction, Radius
R	Gas constant, Radius, Pellet radius
R_{a}	Rayleigh number
Re, N_{Re}	Reynolds number
r_{O2}	Rate of oxygen consumption
r_{x}	Specific oxygen uptake rate
T	Temperature
t, t_{gn}, t_{d}, t_{b}, t_{hd}	Time, Generation time, Doubling time, Batch time, Holding time
S, S_0, S_{SS}	Entropy, Substrate concentration, Initial substrate concentration, Steady state substrate concentration
Sc	Scmidth number
Sh	Sherwood number
u, U	Internal Energy, Overall heat transfer coefficient
V, v	Volume, Air velocity, Rate of reaction

v_{max}	Maximum velocity of reaction
V_P, $V_{R,}$ V_C, V_g	Volume of the particle, Volume of the reactor, Critical air velocity, Settling velocity
W, w	Work done
X	Fraction of the substrate converted
x_{90}	90 % removal of cell mass
Y	Mole fraction
Y_C	g C-atom biomass/g C-atom substrate
$Y_{X/S}$, Y	Cell mass yield coefficient
$Y_{P/S}$	Product yield coefficient
$Y_{X/O}$	g biomass/g oxygen as O_2 consumed
Z	Height of the column

Greek Letters

m	Micron, Specific growth rate of the cell
μ_{max}	Maximum specific growth rate
μ_d	Specific death rate of the cell
η	Energetic growth yield, Efficiency
ξ_p	Energetic product yield
σ_b	Weight fraction of carbon in biomass
σ_P	Weight fraction of carbon in product
σ_S	Weight fraction of carbon in substrate
γ_b	Degree of reduction of biomass
γ_p	Degree of reduction of product
γ_s	Degree of reduction of substrate
τ, τ_{CSTR}, τ_{PFR}	Space time, Space time in CSTR, Space time in PFR
ε	Voidage, Void fraction
η	Effectiveness factor
β	Saturation parameter, Non-growth associated coefficient
φ	Thiele modulus, Inertial parameter
ρ	Density

α	Growth associated coefficient, Recycle ratio, Volume fraction of the filter
$\alpha_{g,m}$	Fraction of carbon utilized for cell growth and maintenance
α_G	Fraction of carbon converted to gaseous form
∇_{total}	Sterilization criterion
ε_M	Eddy diffusivity of momentum
τ	Stress
ω	Angular velocity
λ	Extraction factor
θ	Hydraulic retention time
θ_C	Mean cell residence time

Abbreviations

A	Arrhenius constant
AC	Activated charcoal
Acetyl-CoA	Acetyl co-enzyme A
AD	Anaerobic digestion
ADP	Adenosine diphosphate
AMP	Adenosine monophosphate
6-APA	6-aminopenicillanic acid
ASP	Activated sludge process
ATP	Adenosine triphosphate
BOD	Biochemical oxygen demand
CA	Citric acid
CAA	Citric acid anhydrous
CAM	Citric acid monohydrate
CMC	Carboxymethylcellulose
CoA	Coenzyme A
COD	Chemical oxygen demand
CSTR	Continuous stirred tank reactor
DEAE	Diethylaminoethyl

DHAP	Dihydroxy acetone phosphate
DNA	Deoxyribonucleic acid
DO	Dissolved oxygen
EMP	Embden–Meyerhof–Parnas
FAD	Flavin adenine dinucleotide (oxidized form)
FADH	Flavin adenine dinucleotide (reduced form)
FDA	Food and Drug Administration
F6P	Fructose-6-phosphate
F1,6 P	Fructose 1,6 diphosphate
FTU	Formazin turbidity unit
GC	Gas chromatograph
HAc	Acetic acid
HEPA	High efficiency particulate air
HFCS	High fructose corn syrup
HLac	Lactic acid
HMP	Hexose monophosphate
IE	Immobilized enzyme
IR	Infrared
KE	Kinetic energy
LAB	Lactic acid bacteria
LC	Liquid chromatograph
MLSS	Mixed liquor suspended solids
MLVSS	Mixed liquor volatile suspended solids
NAD^+	Nicotinamide adenine dinucleotide (oxidized form)
NADH	Nicotinamide adenine dinucleotide (reduced form)
$NADP^+$	Nicotinamide adenine dinucleotide phosphate (oxidized form)
NADPH	Nicotinamide adenine dinucleotide phosphate (reduced form)
NTU	Nephelometric turbidity unit
PE	Potential energy

PEP	Phosphoenolpyruvate
PFFP	Plate and frame filter press
PFR	Plug flow reactor
RBC	Rotating disc biological contactor
RNA	Ribonucleic acid
RQ	Respiratory quotient
RVF	Rotary vacuum filter
SCP	Single cell protein
SVI	Sludge volume index
TCA	Tricarboxylic acid
TA	Total acid
UQ	Ubiquinone
UV	Ultraviolet
VFA	Volatile fatty acid