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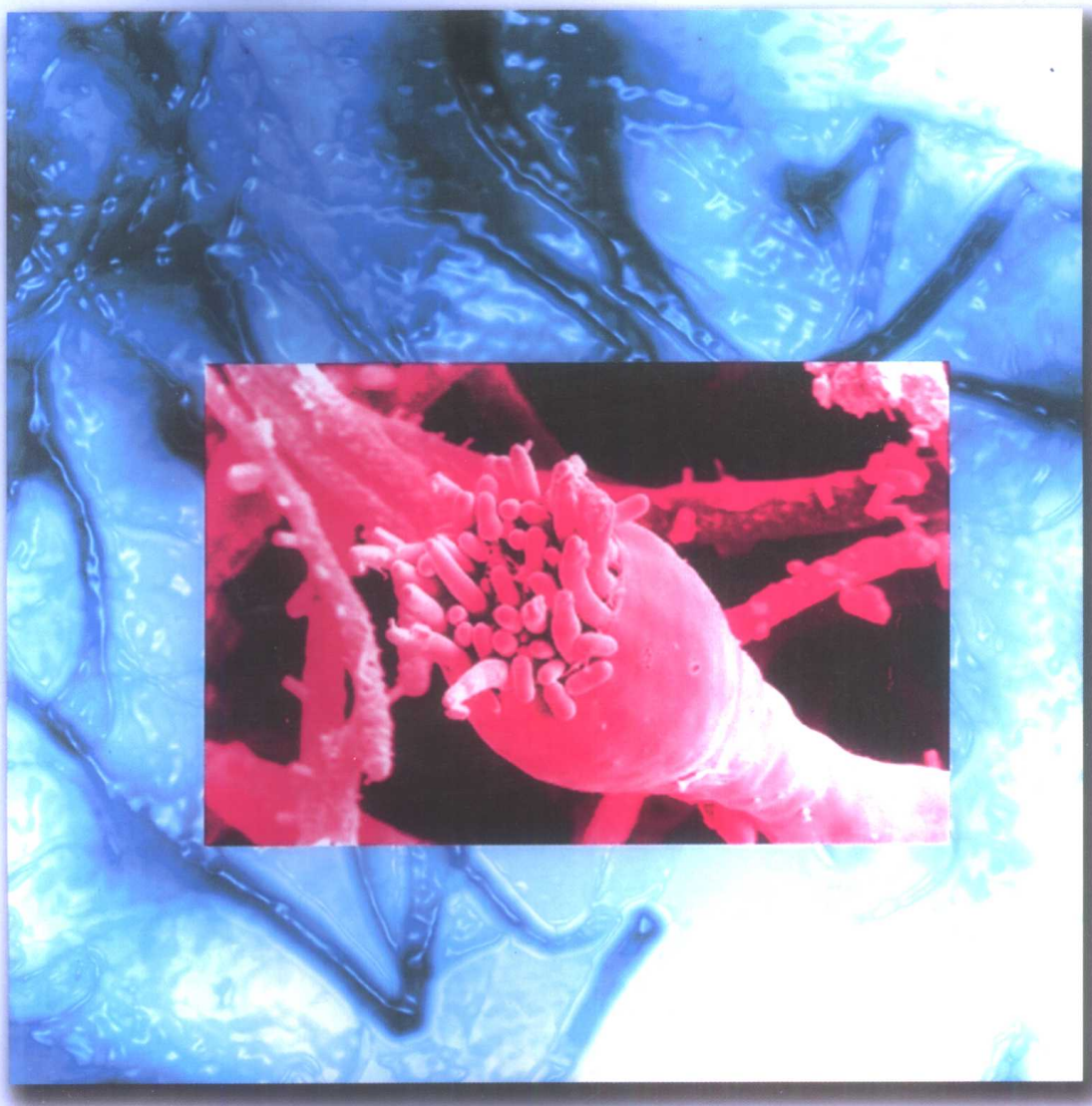
J. Nicklin, K. Graeme-Cook & R. Killington

Microbiology

微生物学

（第二版）
影印本



科学出版社
www.sciencep.com

图字:01-2002-5305

内 容 简 介

"精要速览系列(*Instant Notes Series*)"是国外教材"Best Seller"榜的上榜教材。该系列结构新颖,视角独特;重点明确,脉络分明;图表简明清晰;英文自然易懂,被国内多所重点院校选用作为双语教材。先锋版是继"现代生物学精要速览"之后推出的跨学科的升级版本。

本书是该系列中的《微生物学(第二版)》分册,全书共10章。新版在内容上进行了全面调整、更新和扩充,加强了学科间的渗透与交叉,如分子生物学和免疫学技术在微生物学研究中的应用,并对该领域的发展进行了总结与展望。

本书是指导大学生快速掌握微生物学基础知识的优秀教材,也是辅助教师授课的极佳教学参考书,同时可供生命科学相关专业的研究生参考。

J. Nicklin, K. Graeme-Cook & R. Killington

Instant Notes in Microbiology (Second Edition)

Original edition published in the United Kingdom under the title of Instant Notes in Microbiology (Second Edition)

图书在版编目(CIP)数据

微生物学:第2版/(英)尼科利(Nicklin,J.),格雷米-库克(Graeme-Cook,K.),基林顿(Killington,R.)著.—影印本.—北京:科学出版社,2003.4
(精要速览系列——先锋版)

ISBN 7-03-010960-0

Ⅰ.微… Ⅱ.①尼… ②格… ③基… Ⅲ.微生物学-英文 Ⅳ.Q93

中国版本图书馆CIP数据核字(2002)第093754号

责任编辑:周 辉 黄 方
责任印制:刘士平/封面设计:王 浩

科学出版社 出版
北京东黄城根北街16号
邮政编码:100717
http://www.sciencep.com
双青印刷厂 印刷
科学出版社发行 各地新华书店经销
*
1999年3月第 一 版 开本:B5(720×1000)
2003年4月第 二 版 印张:21 1/4
2003年4月第五次印刷 字数:415 800
印数:10 001—12 000

定价:40.00元

(如有印装质量问题,我社负责调换〈环伟〉)

ABBREVIATIONS

A	adenine
ABC	ATP-binding cassette
ACP	acyl carrier protein
ADP	adenosine 5′-diphosphate
Ala	alanine
AMP	adenosine 5′-monophosphate
A-site	amino-acyl site (ribosome)
ATP	adenosine 5′-triphosphate
ATPase	ATP synthase
BHK	baby hamster kidney
Bp	base pair
C	cytosine
C-phase	Chromosome replication phase (bacterial cell cycle)
cAMP	cyclic adenosine 5′-monophosphate
CAP	catabolite activator protein
CAT	chloramphenicol acetyl transferase
CFU	colony-forming unit
CMV	cytomegalovirus
CNS	central nervous system
CoA	coenzyme A
CPE	cytopathic effect
CRP	cAMP receptor protein
CTL	cytotoxic T lymphocyte
Da	Dalton
D-Ala	D-alanine
DAP	*meso*-diaminopimelic acid
D-Glu	D-glutamic acid
DHA	dihydroxyacetone
DNA	deoxyribonucleic acid
dNTP	deoxyribonucleoside triphosphate
DOM	dissolved organic matter
D-phase	division phase (bacterial cell cycle)
Ds	double-stranded
EF	elongation factor
EM	electron microscopy
ER	endoplasmic reticulum
FAD	flavin adenine dinucleotide (oxidized)
$FADH_2$	flavin adenine dinucleotide (reduced)
FMN	flavin mononucleolides
G	guanine
G-phase	gap phase (bacterial cell cycle)
GTP	guanosine 5′-triphosphate
HA	hemagglutination
Hfr	high frequency recombination
HMP	hexose monophosphate pathway
HSV	herpes simplex virus
I	inosine
ICNV	International Committee on Nomenclature of Viruses
Ig	immunoglobulin
IHF	integration host factor
Inc group	incompatible group (of plasmids)
IS	insertion sequence
Kb	kilobase
KDO	2-keto-2-deoxyoctonate
KDPE	2-keto-2-deoxy-6-phosphogluconate
Lac	lactose
LBP	luciferin-binding protein
LPS	lipopolysaccharide
MAC	membrane-attack complex
MCP	methyl-accepting chemotaxis protein
MEM	minimal essential medium
MHC	major histocompatibility complex
m.o.i.	multiplicity of infection
mRNA	messenger ribonucleic acid
MTOC	microtubule organizing centre
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)
NAG	*N*-acetyl glucosamine
NAM	*N*-acetyl muramic acid
NB	nutrient broth
NTP	ribonucleoside triphosphate
O	operator
OD	optical density
Omp	outer membrane protein
P	promoter

PCBs	polychlorinated biphenyls	RNA	ribonucleic acid
PCR	polymerase chain reaction	rRNA	ribosomal RNA
PEP	phosphoenol pyruvate	rubisco	ribulose bisphosphate carboxylase
Pfu	plaque-forming unit		
PHB	poly-β-hydroxybutyrate	S	Svedberg coefficient
Phe	phenylalanine	snRNA	small nuclear ribonucleic acid
P_i	inorganic phosphate	SPB	spindle pole bodies
PMF	proton motive force	ss	single-stranded
PMN	polymorphonucleocyte	T	thymine
PP_i	inorganic pyrophosphate	TCA	tricarboxylic acid
PPP	pentose phosphate pathway	TCID	tissue culture infective dose
PS	photosystem	tRNA	transfer RNA
PSI and II	photosystems I and II	Trp	tryptophan
P-site	peptidyl site (ribosome)	TSB	tryptone soya broth
R	resistance (plasmid)	U	uracil
r	rho factor	U_L,U_S	unique long, unique short
RBC	red blood cell	UDP	uridine diphosphate
redox	reduction-oxidation	UDPG	uridine disphosphate glucose
RER	rough endoplasmic reticulum	UV	ultraviolet light

PREFACE

The second edition of *Instant Notes in Microbiology* has been updated throughout the sections, including suggestions from readers of the first edition, new developments in the taxonomy of microbes, and new insights in molecular biology.

The section on Biochemistry has been completely rewritten (Section B) reflecting a change in authorship. Recent changes in the taxonomy of the Prokarya have necessitated the inclusion of a new topic of the Archea (D5) and the bacteriology and molecular biology sections have been updated to reflect the latest understanding of these rapidly evolving subjects.

The first edition sections on Algae and Protozoa have been combined into a new section, the Protista, reflecting the newest evidence and ideas on the evolution of this group of micro-organisms. Current taxonomic terms have been adopted throughout the sections on the fungi and protista.

The virology text remains a basic introduction to the topic. However, our knowledge of viruses, their replication mechanisms and interactions with their hosts is forever increasing as molecular and immunological techniques become more rapid and sophisticated. The second edition makes such revisions in our knowledge base. Virus classification has been updated and account has been made of trends in emerging viruses e.g. hepatitis C. A chapter on prions (whilst not viruses) and transmissible spongiform encephalopathies, has been introduced in the virology section.

We would like to thank the readers for their feedback, they are much appreciated as reviewers and we hope that this new edition has included as many of their suggestions as possible.

CONTENTS

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A1 THE MICROBIAL WORLD

Key Notes

What is a microbe?

The word microbe (microorganism) is used to describe an organism that is so small that, normally, it cannot be seen without the aid of a microscope. Viruses, Bacteria, Archaea, fungi, and protista are all included in this category.

Prokaryotes and eukaryotes

Microbes are found in all three major kingdoms of life: the Bacteria, the Archaea and the Eukarya. The Bacteria and Archaea are prokaryotes, while all other microbes are **eukaryotes.** There are many differences between prokaryote and eukaryote cells, the major distinction being the presence of a nucleus and other membrane-bound organelles in eukaryotes.

The importance of microbiology

Microbes are essential to life. Among their many roles, they are necessary for geochemical cycling and soil fertility. They are used to produce food as well as pharmaceutical and industrial compounds. On the negative side, they are the cause of many diseases of plants and animals and are responsible for the spoilage of food. Finally, microbes are used extensively in research laboratories to investigate cellular processes.

What is a microbe?

A **microbe** or **microorganism** is a member of a large, extremely diverse, group of organisms that are lumped together on the basis of one property – the fact that, normally, they are so small that they cannot be seen without the use of a microscope. The word microbe is therefore used to describe **viruses, Bacteria, Archaea, fungi** and **protista**: the relative sizes and nature of these are shown in *Table 1*. However, there are a few macroscopic microbes that can be seen by the naked eye including the fruiting bodies of many fungi; and a recently isolated bacterium, *Thiomargarita namibiensis*, whose cells grow up to 0.75 mm in width.

Microbes generally do not have complex multicellular structures. Most of the Bacteria, Archaea, protista and fungi are single-celled microorganisms. Microbes that are multicellular tend to have a limited range of cell types. Viruses are not cells, just genetic material surrounded by a protein coat, and are incapable of independent existence.

Table 1. Types of microbes, their sizes and cell type

Microbe	Approximate range of sizes	Nature of cell	Section of book
Viruses	0.01–0.25 μm	Acellular	J
Bacteria	0.1–750 μm	Prokaryote	D,E,F
Fungi	2 μm–>1 m	Eukaryote	G,H
Protista	2–1000 μm	Eukaryote	I

The science of microbiology did not start until the invention of the microscope in the mid 16th century and it was not until the late 17th century that Robert Hooke and Antoine van Leeuwenhoek made their first records of fungi, bacteria and protists. The late 19th century was the time when the first real breakthroughs on the role of microbes in the environment and medicine were made. Louis Pasteur disproved the theory of **spontaneous generation** (that living organisms spontaneously arose from inorganic material) and Robert Koch's development of **pure culture** techniques (see Topic D8) allowed him to show unequivocally that a bacterium was responsible for a particular disease. Since then the science has grown dramatically as microbiology impinges on all aspects of life and the environment.

Prokaryotes and eukaryotes

Within the microbial world can be found examples of the three distinct cell lineages that have evolved from the first original cell (*Fig.* 1). These lineages (called **kingdoms** or **domains**) have been established using DNA sequencing technology which has shown that these groups called the **Bacteria** (previously known as the Eubacteria), the **Archaea** and the **Eukarya** diverged very early in history. All the Bacteria and the Archaea are microbes but the Eukarya contain higher plants and animals as well as those fungi and protista considered to be microbes. Bacteria and Archaea have a **prokaryotic** cell structure. Their cells lack a distinct nuclear membrane, and they do not have complex internal organelles, such as mitochondria or chloroplasts which are associated with energy generation in eukaryotes. Prokaryotes have neither endoplasmic reticulum nor Golgi apparatus membranes. The Eukarya are **eukaryote** meaning they have a nucleus but there are many other differences between the two cell types. A comparison of the main features of these two categories of cell is shown in *Table* 2, but other differences do occur which will be examined in the individual sections. It is also now recognized that the organelles found in eukaryotes arose as a result of endosymbiotic events early in their evolution, as mitochondria and chloroplasts show considerable similarities to some prokaryotic cells.

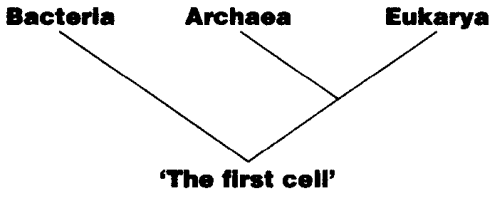


Fig. 1. The three cell lineages evolved from a common ancestor.

The importance of microbiology

Microbes impinge on all aspects of life; just a few of these are listed below.

- **The environment.** Microbes are responsible for the cycling of carbon, nitrogen and phosphorus (geochemical cycles), all essential components of living organisms (Topic F1). They are found in association with plants in symbiotic relationships, maintain soil fertility and may also be used to clean up the environment of toxic compounds (bio-remediation; Topic H4). Some microbes are devastating plant pathogens (Topic H5), which destroy important food crops, but others may act as biological control agents against these diseases.

Table 2. The major differences between prokaryote and eukaryote genetic and cellular organization

Prokaryotes	Eukaryotes
Organization of the genetic material and replication	
DNA free in the cytoplasm	DNA is contained within a membrane bound nucleus. A nucleolus is also present
Generally only one chromosome present but there are exceptions	>1 chromosome. Two copies of each chromosome may be present (diploid)
DNA associated with histone-like proteins	DNA complexed with histone proteins
May contain extrachromosomal elements called plasmids	Plasmids rarely found
Introns very rarely found in mRNA (except Archaea)	Introns found in all genes
Cell division by binary fission – asexual replication only	Cells divide by mitosis
Transfer of genetic information occurs by conjugation, transduction and transformation	Exchange of genetic information occurs during sexual reproduction. Meiosis leads to the production of haploid cells (gametes) which can fuse
Cellular organization	
Cytoplasmic membrane contains hopanoids (except Archaea). Lipopolysaccharides and teichoic acids found	Cytoplasmic membrane contains sterols
Energy metabolism associated with the cytoplasmic membrane	Mitochondria present in most cases (not present in some anaerobic microbes)
Photosynthesis associated with membrane systems and vesicles in cytoplasm	Chloroplasts present in algal and plant cells
	Internal membranes, endoplasmic reticulum and Golgi apparatus present associated with protein synthesis and targetting
	Membrane vesicles such as lysosomes and peroxisomes present
	Cytoskeleton of microtubules present
Flagella consist of one protein, flagellin	Flagella have a complex structure with 9+2 microtubular arrangement
Ribosomes – 70S	Ribosomes – 80S (mitochondrial and chloroplast ribosomes are 70S)
Peptidoglycan cell walls (Bacteria only: different polymers in archaebacteria)	Polysaccharide cell walls, where present, are generally either cellulose or chitin

- **Medicine.** The disease causing ability of some microbes is well known. Human pathogens include viruses (e.g. Variola virus causes smallpox, Topic J8), protista (e.g. *Plasmodium* causes malaria Topic I5) and bacteria (e.g. *Vibrio cholera* causes cholera, Topic F3). To date there are no known instances of the Archaea acting as human pathogens. Microorganisms have also provided us with the means to control some non-viral infections in the form of antibiotics (Topic F7). They also provide us with many other medicinally important drugs.
- **Food.** Microbes have been used for thousands of years, in many different processes, to produce foods such as cheese and bread, alcoholic drinks including beer and wine, and condiments like soy sauce (Topic F2). At the other end of the scale, microbes are responsible for food spoilage, and disease-causing microbes are frequently carried on food (Topic F5).

- **Biotechnology.** Traditionally, microbes have been used to synthesize many important chemicals including acetone, butanol and acetic acid (Topic F2). More recently, the advent of genetic engineering techniques has led to the cloning of pharmaceutically important polypeptides (for example, insulin) into microbes, which may then be produced on a large scale.
- **Research.** Microbes have been used extensively as model organisms for the investigation of biochemical and genetical processes as they are much easier to work with than more complex animals and plants. Millions of copies of the same single cell can be produced in large numbers very quickly and at low cost to give plenty of homogeneous experimental material. An additional advantage is that most people have no ethical objections to experiments with these microorganisms.

B1 Heterotrophic Pathways

Key Notes

High-energy compounds

Heterotrophy refers to the breaking down of organic molecules to obtain energy. This energy is generally stored in the form of high-energy compounds, such as ATP and NAD^+. The formation of such compounds relies on balanced redox reactions that generate organic molecules containing oxygen and phosphate groups.

Glycolysis

Glycolysis is a cytoplasmic pathway that is used by most microorganisms to break down sugars (such as glucose and fructose) to pyruvate, yielding two molecules of ATP. Pyruvate then enters the citric acid cycle, and its utilization through this pathway yields energy-rich compounds including ATP and NADH.

Alternatives to glycolysis

There are a number of hexose monophosphate pathways (including the Entner-Douderoff pathway, the phosphoketolase pathway and the pentose phosphate pathway) that can be used as alternatives to glycolysis for the oxidation of glucose. These pathways yield less ATP per molecule of glucose than glycolysis, but they generate important metabolic intermediates including NADPH and pentose sugars for nucleic acid synthesis.

Citric acid cycle and respiration

The citric acid cycle occurs in the cytoplasm of aerobic bacteria and in the mitochondria of aerobic eukaryotes. Respiration is the complete oxidation of an organic substrate to carbon dioxide and water. It requires an external electron acceptor, usually oxygen, and results in the formation of large amounts of ATP. For each glucose molecule oxidized by the citric acid cycle, 12 molecules of ATP are generated. Important intermediates for fatty acid synthesis, nucleotide synthesis and amino acid synthesis are also generated by the citric acid cycle.

Fermentation

Fermentation is the incomplete oxidation of an organic substrate and it occurs under anaerobic conditions. Energy yields from fermentation are lower than comparative yields from respiration. The products of incomplete oxidation can include pyruvate, lactate, formate and ethanol.

High-energy compounds

The ability to produce high-energy compounds for metabolism and storage is a prerequisite for cell survival. Energy is acquired by cells through a series of balanced **oxidation-reduction (redox)** reactions from organic or inorganic substrates. The simplest redox reaction can be seen in the reaction below

$$H_2 + \tfrac{1}{2} O_2 \rightarrow H_2O$$

H_2 = reductant (electron donor) that becomes oxidized
O_2 = oxidant (electron acceptor) that becomes reduced

The energy that is released in redox reactions is stored in a variety of organic molecules that contain oxygen atoms and phosphate groups. **ATP**, adenosine triphosphate, is a **high-energy compound** found in almost all living organisms. It is synthesized in catabolic reactions, where substrates are oxidized, and utilized in anabolic, biosynthetic reactions. Intermediates called **carriers** participate in the flow of energy from the electron donor to the terminal electron acceptor. The co-enzyme **nicotinamide adenine nucleotide** (NAD^+) is a freely diffusable carrier that transfers two electrons and a proton, and a second proton from water, to the next carrier in the chain.

$$NAD^+ + 2H^+ + 2e^- \rightleftarrows NADH + H^+$$

The reactions for the phosphorylated derivative ($NADP^+$) are similar. NAD^+ is usually used in energy-generating reactions and $NADP^+$ in biosynthetic reactions.

All protozoa, all fungi and most bacteria synthesize ATP by oxidizing organic molecules. This can be either via **respiration** or by **fermentation**. Respiration requires a terminal electron acceptor. This is usually oxygen, but nitrate or sulfate are among the compounds used in anoxic conditions. Fermentation requires an organic terminal oxygen acceptor.

Microorganisms can be grouped according to the source of energy they use, and by the source of carbon which may either be an organic molecule or from CO_2 (carbon dioxide fixation) (*Table 1*).

Table 1. Classification of microorganisms by energy and carbon source utilized

	Type	Electron donor	Energy source	Carbon source	Examples
Organotrophs	Chemo-organotroph	Organic compounds	Redox reactions of organic compounds	Organic compounds	All fungi, all protists, most terrestrial bacteria
	Photo-organotroph	Organic compounds	Light	Carbon dioxide and organic compounds	Nonsulphur bacteria
Lithotrophs	Chemo-lithotrophs	Inorganic compounds	Redox reactions of inorganic compounds	CO_2	*Thiobacillus, Nitrosomonas, Nitrobacter, Hydrogenomonas, Beggiotia*
	Photolithotrophs	Inorganic compounds	Light	CO_2	Photosynthetic green and purple bacteria, photosynthetic protista

Glycolysis (Embden-Meyerhof-Parnas)

The reactions termed **glycolysis** take place in the cytoplasm of all prokaryotes and eukaryotes. The pathway generates two ATP molecules per molecule of glucose degraded, and feeds substrates into subsequent metabolic pathways.

The steps in glycolysis are shown in *Fig. 1* but the overall net reaction can be summarized as follows:

$$Glucose + 2ADP + 2P_i + 2NAD^+ \rightarrow 2\ pyruvate + 2ATP + 2NADH + 2H^+$$

The reactions at the beginning of the pathway require two ATP molecules, but the gross yield of ATP per glucose molecule is four, giving a net gain of two ATP per glucose.

The initial reactions at the beginning of the pathway transform the 6 carbon sugar glucose into glucose 1,6-bisphosphate, via two phosphorylation reactions.

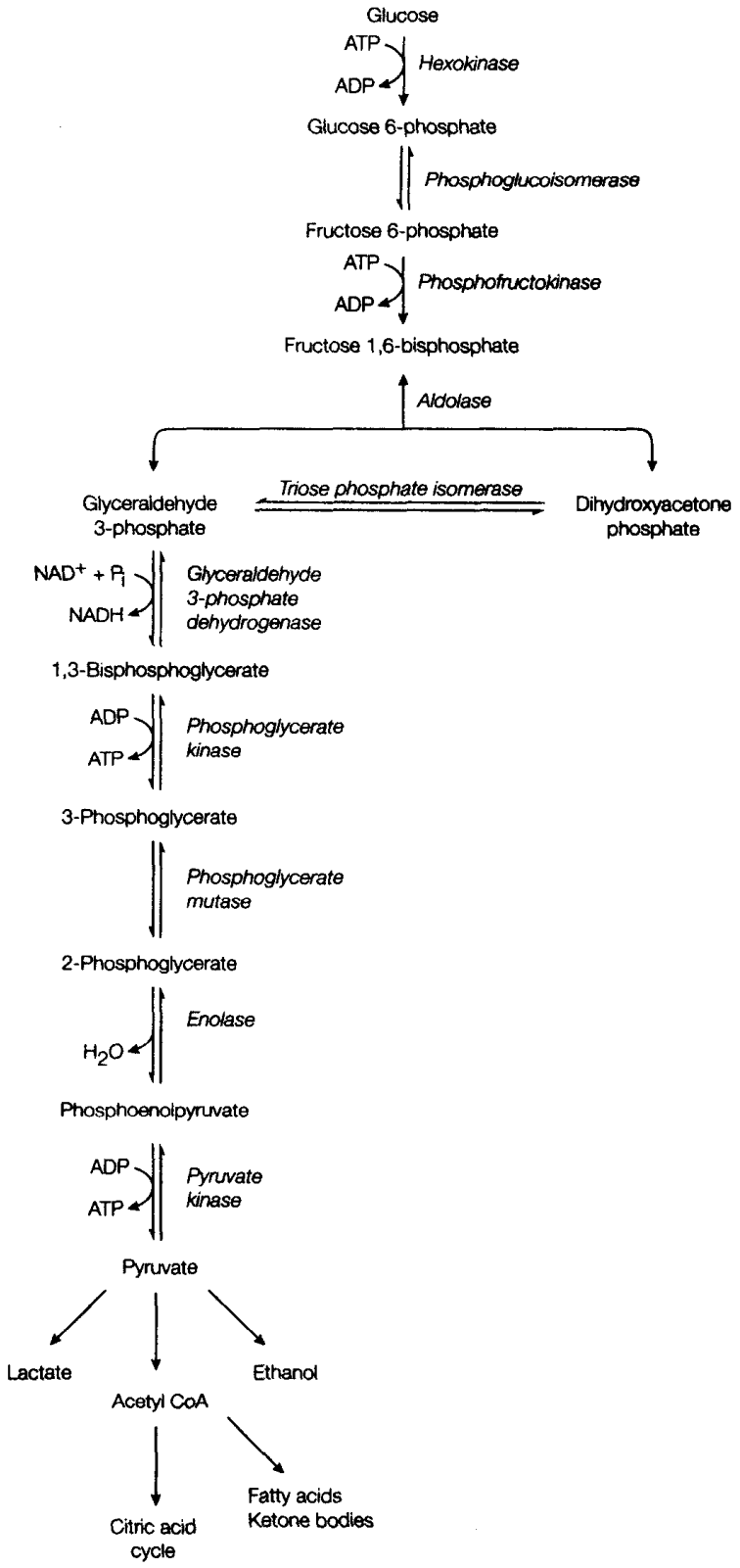


Fig. 1. Glycolysis.

There follows a near symmetrical split into two 3C phosphorylated compounds (glyceraldehyde-3-phosphate and dihydroxyacetone phosphate (DHA)). These compounds will interconvert as an equilibrium reaction via the enzyme triose phosphate isomerase. Glyceraldehyde-3-phosphate is the substrate for subsequent reactions of glycolysis.

Further energy is added to the glyceraldehyde-3-phosphate by the addition of a second high-energy phosphate group, from NADPH to the aldehyde group. There then follow two reactions where the high-energy phosphate groups of 1,3-bisphosphoglycerate are used to form ATP from ADP, mediated by two kinase enzymes, phosphoglycerate kinase and pyruvate kinase. These reactions are termed **substrate level phosphorylations**.

The final product of glycolysis is pyruvate, which feeds into respiration in aerobic conditions.

Alternatives to glycolysis

Some important groups of bacteria, for example some Gram-negative rods, do not use glycolysis to oxidize glucose. They use a different mechanism, the **Entner-Douderoff** (*Fig. 2*), which yields one mole of ATP, NADPH and NADH from every mole of glucose. This is a **hexose monophosphate pathway** (HMP), and in this pathway only one molecule of ATP is produced per molecule of glucose metabolized.

Another HMP is the **phosphoketolase** pathway, which is another method for glucose breakdown found in *Lactobacillus* and *Leuconostoc* spp. when grown on 5-carbon sugars (pentoses). The pathway produces lactic acid, CO_2 and either ethanol or acetate (*Fig. 3*).

An important HMP is the **pentose phosphate pathway** (PPP), which often operates in conjunction with glycolysis or other HMP pathways. The PPP is an important provider of intermediates that serve as substrates for other biosynthetic

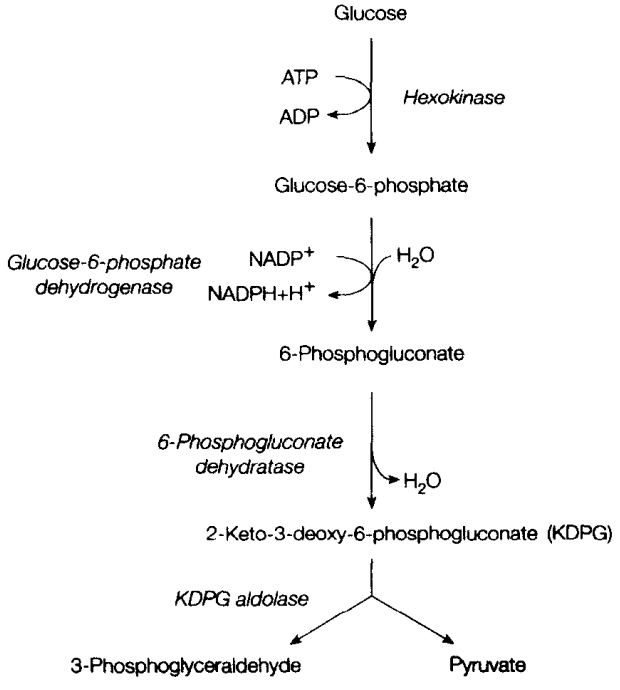


Fig. 2. Entner-Douderoff pathway.

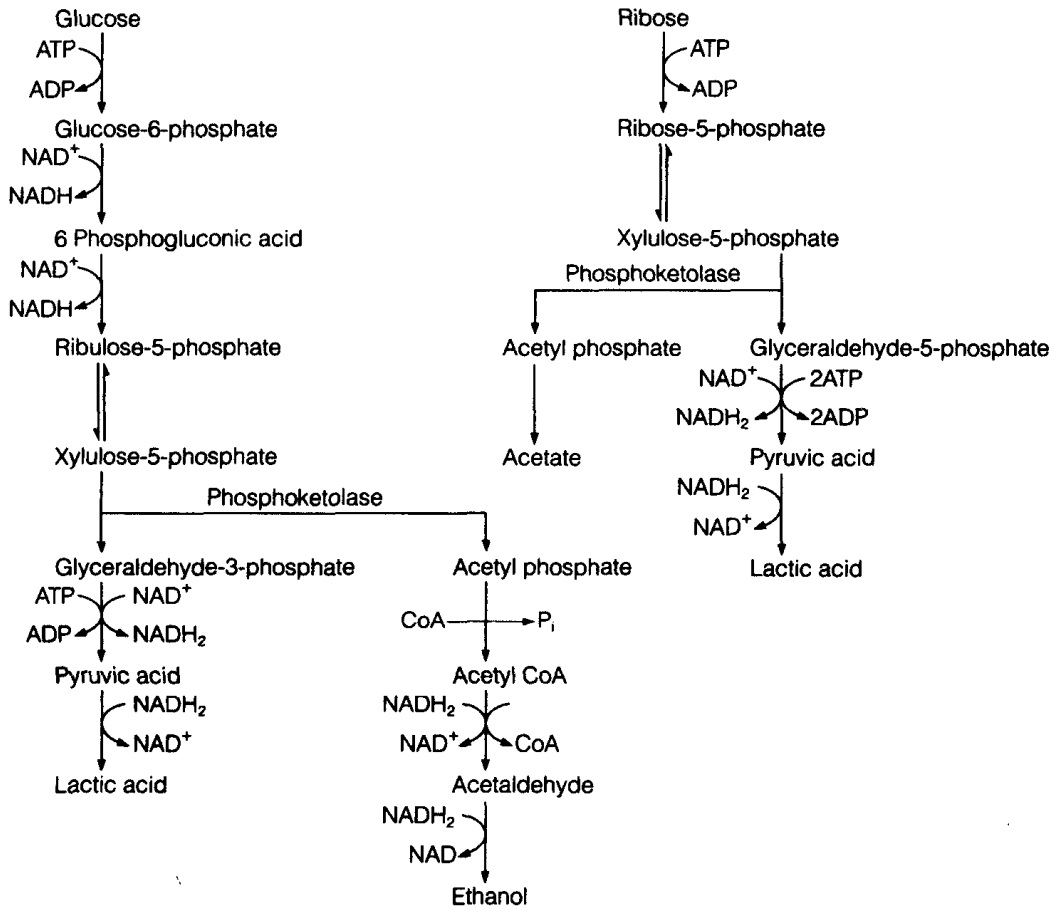


Fig. 3. The phosphoketolase pathway.

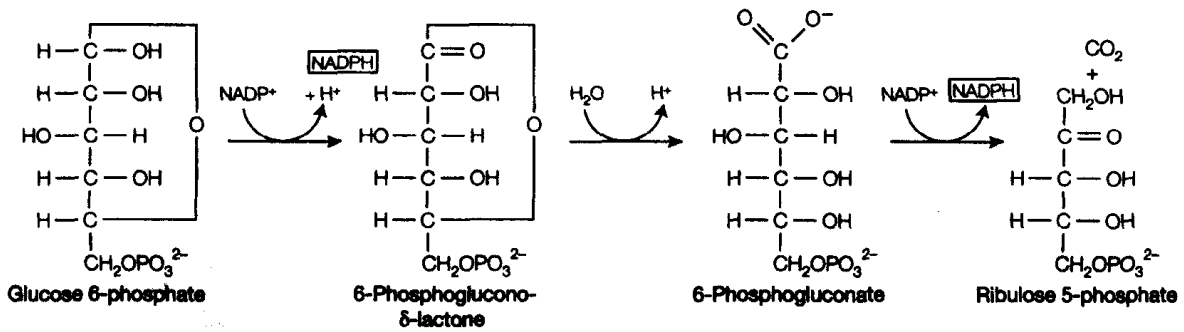
pathways. This pathway yields NADPH/+H⁺ and pentoses which are used in the synthesis of nucleotides including, FAD, ATP and coenzyme A (CoA).

The reactions can be summarized as

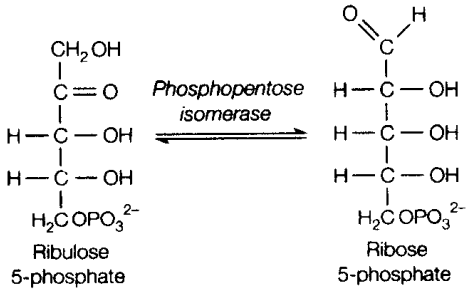
$$\text{Glucose-6-phosphate} + 2\,NADP^+ + \text{water} \rightarrow \text{Ribose-5-phosphate} + 2\,NADPH + 2H^+ + CO_2$$

There are three important stages to this pathway:

1. Glucose-6-phosphate is converted to ribulose-5-phosphate, generating two NADPH + 2H⁺



2. Ribulose-5-phosphate isomerises to ribose-5-phosphate



3. Excess ribose-5-phosphate is converted to fructose-6-phosphate and glyceraldehyde, via a series of reactions, to enter glycolysis.

The citric acid cycle and respiration

The **citric acid cycle** is found in the cytosol of aerobic Prokaryotes, and the mitochondria of eukaryotes. Anaerobic organisms have incomplete cycles whilst facultative aerobic organisms only have a functional citric acid cycle in the presence of O_2.

Complete oxidation of organic substrates to CO_2 and water via the citric acid cycle requires an external electron acceptor; the best studied are oxygen, nitrate or sulfate. This process yields large amounts of energy stored as ATP. The product of glycolysis, pyruvate, can be completely oxidized using enzymes of the citric acid cycle.

In summary, during the operation of the citric acid cycle three carbon atoms of pyruvate are completely oxidized to CO_2, and four hydrogen atoms reduce NAD^+ and FAD (*Fig. 4*, reactions 1–10).

The cycle begins with an oxidative decarboxylation (reaction 1), where CO_2 is released and NADH is formed. The resulting 2C (acetyl) unit is linked to CoA (reaction 2), and this high energy compound couples with oxaloacetate (4C) to form a 6C unit, citric acid. The acetyl group of the citric acid is then further metabolized, with 2 decarboxylation reactions releasing CO_2 (reactions 15 and 16) and 4 more coenzyme molecules are reduced. At the end of the cycle oxaloacetate is regenerated as the acceptor of further acetyl units (reaction 10).

The reduced co-enzymes are then oxidized by a respiratory electron transport chain which may use oxygen, nitrate or sulfate as terminal electron acceptors. This allows for NAD^+ regeneration and the synthesis of ATP, a process known as oxidative phosphorylation. NAD^+ regeneration is essential as levels are limited in cells.

Each turn of the citric acid cycle yields three NADH molecules and one $FADH_2$ molecule which via oxidative phosphorylation generates ATP molecules. Including the single ATP molecule that is formed in the conversion of succinyl CoA to succinate, each molecule of glucose oxidized by the citric acid cycle produces 12 ATP molecules.

The cycle produces intermediates for many other biosynthetic pathways, including fatty acid biosynthesis (citrate), amino acid synthesis (α-ketoglutarate), and nucleotide synthesis (α-ketoglutarate and oxaloacetate).

Fermentation

Fermentation is an **incomplete oxidation** of an organic substrate. During fermentations an electron donor becomes reduced, and energy is trapped by **substrate level phosphorylation**. Fermentation products include pyruvate if the