CRC Handbook of Microbiology

2nd Edition

Volume VI
Growth and Metabolism

Editors

Allen I. Laskin

Hubert A. Lechevalier

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CRC Press, Inc.
Boca Raton, Florida

Library of Congress Cataloging in Publication Data
(Revised for vol. 6)
Main entry under title:

CRC handbook of microbiology.

Includes bibliographical references and indexes.
CONTENTS: v. 1. Bacteria.--v. 2. Fungi, algae, protozoa, and viruses.--[etc.]--v. 5. Microbial products.
1. Microbiology--Collected works. I. Laskin, Allen I., 1928- . II. Lechevalier, Hubert A. III. Chemical Rubber Company, Cleveland. IV. Title: Handbook of microbiology. [DNLM: 1. Microbiology. QW 4 H234 1977]
QR6.C2 1977 576 77-12460
ISBN 0-8493-7200-3 (set)
ISBN 0-8493-7206-2 (vol. VI)

Direct all inquiries to CRC Press, Inc., 2000 Corporate Blvd., N.W., Boca Raton, Florida, 33431.

International Standard Book Number 0-8493-7206-2

Library of Congress Card Number 77-12460
Printed in the United States

CRC HANDBOOK OF MICROBIOLOGY

EDITORS:
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Outline for the Second Edition

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BACTERIA

Volume II
FUNGI, ALGAE, PROTOZOA, AND VIRUSES

Volume III
MICROBIAL COMPOSITION:
Amino Acids, Proteins, and Nucleic Acids

Volume IV
MICROBIAL COMPOSITION:
Carbohydrates, Lipids, and Minerals

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GROWTH AND METABOLISM

Volume VII
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Volume VIII
GENETICS AND IMMUNOLOGY

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TOXINS, ENZYMES, AND ANTIBIOTICS

PREFACE

The 1st Edition of the *CRC HANDBOOK OF MICROBIOLOGY* consisted of four volumes. Updating and additions have increased the length of the text to the point that the 2nd Edition of this series will probably consist of nine volumes. Some chapters have become extremely long, necessitating the splitting of some volumes into parts.

The present book contains data on growth and metabolism of microorganisms. New topics have been added in this edition, more than doubling the number of subjects covered. We draw attention to the monumental review on the effect of nutrition on microbial cellular differentiation written by L. Kalakoutskii and S. Dobritsa. We hope that those who will consult this book will find useful the subjects covered though, no doubt, they will regret many omissions.

We join the staff of CRC Press in thanking all the authors who so generously contributed to this volume and the members of our advisory board who helped in its planning.

THE EDITORS

Allen I. Laskin, Head of Biosciences Research at Exxon Research and Engineering Company, Annandale, N.J., received his B.S. degree in Biology from the City College of New York in 1950. His M.A. and Ph.D. degrees in Microbiology were obtained from the University of Texas in 1952 and 1955, respectively.

From 1955 to 1969 Dr. Laskin was at the Squibb Institute for Medical Research, first as Senior Research Microbiologist, then as Head of Microbial Biochemistry, and subsequently as Assistant Director of Microbiology. His research on microbial transformations of steroids led to several publications and more than 20 U.S. patents. Dr. Laskin then switched to molecular biology and studies on cell-free protein and cell-wall synthesis, which led to work on the mode of action of tetracycline and several other antibiotics.

In 1969 Dr. Laskin joined Exxon Research and Engineering Company to head the laboratory program concerned with single-cell protein. In 1971 he moved to his present position, heading the research on petroleum microbiology and enzymology.

Dr. Laskin is past president of the Society of Industrial Microbiology and the Theobald Smith Society (New Jersey Branch, American Society for Microbiology) and was National Councilor for many years. He was Vice-Chairman of the local committee for the 1965 ASM National Meeting in Atlantic City and served as Chairman for the 1976 meeting. He was Chairman of the Environmental and General Applied Microbiology Division of ASM, Chairman of the Fermentation Division, and is presently a Divisinal Group Councilor, coordinating the activities of four divisions of the Society. He was also on the Membership Committee of ASM and served as Chairman of its Sustaining Membership Sub-Committee. In addition, Dr. Laskin was Chairman of the Microbiology Section of the New York Academy of Sciences. He is a member of the Panel on Microbial Degradation of Oil of the American Petroleum Institute and was Chairman of a subgroup for a National Academy of Sciences/National Research Council Panel on Underutilized Microbial Processes of Potential Value.

In 1974 Dr. Laskin was awarded the Selman A. Waksman Honorary Lectureship Award. He is a fellow of the American Academy of Microbiology and a Fellow of the New York Academy of Sciences. In 1971 to 1972 he was a Foundation for Microbiology Lecturer, and in 1977 he was the I. M. Lewis (Texas Branch, ASM) Lecturer.

Dr. Laskin is not only Co-Editor of the *CRC Handbook of Microbiology* and of *CRC Critical Reviews in Microbiology*, but also of a series entitled *Methods in Molecular Biology* as well as of the books *Extracellular Microbial Polysaccharides, The Problems of Drug-Resistant Bacteria,* and *The Genetics of Industrial Microorganisms*. In addition, he serves as Editor for a series of books on microbiology. Dr. Laskin has also authored and co-authored reviews on the mode of action of tetracycline and on single cell protein, and has organized and chaired numerous symposia, seminars, and conferences.

THE EDITORS

Hubert A. Lechevalier, Professor of Microbiology and Associate Director at the Waksman Institute of Microbiology of Rutgers University, New Brunswick, N.J., received a Licence ès Sciences Naturelles (*summa cum laude*) in 1947 and his M.S. degree (*cum laude*) in 1948 from Laval University, Quebec City, Canada. He obtained his Ph.D. from Rutgers University in 1951.

Dr. Lechevalier remained at Rutgers University as Assistant Professor of Microbiology from 1951 to 1956, and subsequently as Associate Professor, before advancing to Professor in 1966. Within this period he also was an exchange scientist at the Academy of Sciences of the U.S.S.R. in Moscow, Visiting Investigator at the Czechoslowak Academy of Sciences in Prague, and Visiting Investigator at the Pasteur Institute, Section of Mycology, in Paris. His research, dealing with actinomycetes and their products, has led to U.S. patents for neomycin and candicidin as well as to 16 foreign patents.

A recipient of Fellowships from the National Research Council of Canada, from Rutgers University, and from the U.S. Public Health Service, Dr. Lechevalier was also awarded membership in Sigma Xi and is an Associate Member of the Société Francaise de Microbiologie. In 1976 he received the Lindbach Award for Distinguished Research and in 1982, jointly with his wife Mary, the Charles Thom Award of the Society for Industrial Microbiology for outstanding contributions in the field of industrial microbiology.

In addition to his membership in the American Society for Microbiology (ASM), in the Canadian Society for Microbiologists, the Society for Industrial Microbiology, and in the Mycological Society of America, Dr. Lechevalier has served as a participant on the Editorial Boards of *Applied Microbiology* and of *Annales de Microbiologie,* on the subcommittee on the Taxonomy of the Actinomycetes of the International Committee on Bacteriological Nomenclature, on the Subcommittee on Tastes and Odors of the American Water Works Association, and on the ASM Archives Committee. He also served as Chairman of the ASM Subcommittee on Actinomycetes, as a Trustee of the American Type Culture Collection, and as consultant to various industrial and legal firms.

Dr. Lechevalier is not only Co-Editor of the *CRC Handbook of Microbiology* and a former Co-Editor of *CRC Critical Reviews in Microbiology*, but has also collaborated on a number of books: *A Guide to the Actinomycetes and Their Antibiotics; Neomycin — Nature, Formation, Isolation, and Practical Application; Neomycin — Its Nature and Practical Application; Antibiotics of Actinomycetes; Three Centuries of Microbiology; The Microbes.* He has also authored or co-authored numerous papers.

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CARDINAL TEMPERATURES OF YEASTS

N. van Uden

GENERAL

While the temperature range of microbial growth in general extends from several degrees below the freezing point of water to a few degrees below its boiling point at normal pressure, the temperature ranges of individual strains do not normally comprise more than 40 to 50°C and are often much narrower. This is also the case with the yeasts.[1]

Depending on whether the maximum temperature for growth (T_{max}) is well above 50°C, between about 25 and 50°C or below 25°C, microorganisms are conventionally and roughly subdivided into three temperature groups: thermophilic, mesophilic, and psychrophilic microorganisms. Nearly all known yeasts are mesophilic, a few are psychrophilic, while thermophilic yeasts as defined above have so far not been encountered. Yeasts such as *Cyniclomyces guttulatus, Saccharomyces telluster (Candida bovina), Candida slooffii*, and *Torulopsis pintolopesii* (which are able to grow only within a narrow range of temperatures with 20 to 30°C as the lower limit and 42 to 45°C as the upper limit[1]) are sometimes referred to as "thermophilic" yeasts[2] but are more appropriately called "psychrophobic" yeasts.[3]

Widely scattered references indicate that many yeasts are able to grow at 37°C and some at 45°C.[4-8] The highest T_{max} so far reported is 49 to 50°C for a strain of *Hansenula polymorpha*.[9] Interest in the biology of the Antarctic and other cold habitats, which reached a peak in the 1960s, led to the description of a number of psychrophilic yeasts with T_{max} values around 20°C.[10-12]

Stokes[13] compiled cardinal temperatures of 40 yeast strains belonging to 31 species (Table 1). Vidal-Leiria et al.[14] determined the T_{max} values of 594 yeast strains belonging to 112 species of the genera *Candida, Torulopsis, Hansenula, Pichia, Metschnikowia,* and *Leucosporidium* (Table 1). Less than 2% of these strains were psychrophilic having T_{max} values below 24°C. More than 98% consisted of mesophilic strains with T_{max} values ranging from 26 to 48°C, with the highest frequency in the 34 to 38°C range. No thermophilic strains were encountered. Davenport[15] compiled cardinal temperatures of 82 yeasts and yeast-like organisms reported to have been isolated from cold environments (Table 1).

CARDINAL TEMPERATURES AND YEAST TAXONOMY

Wickerham[4] in his monograph on the genus *Hansenula* introduced the ability to grow at 37°C as a test in yeast identification. Later it was found[16,17] that T_{max} was fixed within narrow limits on the species level in a number of species. T_{max} was used as a character in yeast species description in the taxonomic treatments of the following genera: *Lipomyces*,[18] *Metschnikowia*,[19] *Nematospora*,[20] *Schizosaccharomyces*,[21] *Candida*,[22] *Oosporidium*,[23] *Torulopsis*,[24] *Trichosporon*[25] and *Trigonopsis*[26] (Table 1).

The T_{max} variation in 41 yeast species of which more than five strains each were studied did not exceed 5°C in 75% of the species, the highest frequency pertaining to the variation range of 3°C.[14] Indeed, when the T_{max} values of a collection of yeast strains supposedly belonging to the same species cover a wide range of temperatures with subgroups of strains clustering around distinct T_{max} values, these subgroups may represent distinct species.[27,28]

TEMPERATURE PROFILES

When an Arrhenius plot is prepared of the specific growth rates of a yeast for temperatures

Table 1
CARDINAL TEMPERATURES OF YEASTS (°C)

Species (no. of strains)	T_{min}	T_{op}	T_{max}	Ref.
Aessosporon salmonicolor			30	15
Aureobasidium pullulans			37	15
Bullera alba			30	15
B. gradispora			30	15
B. tsugae			30	15
Candida aaseri (1)			37—38	14, 22
C. albicans (22)			42—46	14, 22
C. albicans		33	38($T_{max f}$) 42($T_{max i}$)	31
C. aquatica (1)			26—27	14, 22
C. beechii (1)			31—32	14, 22
C. berthetii (1)			40—41	14, 22
C. blankii (1)			46—47	14, 22
C. bogoriensis (2)			26—27	14, 22
C. boidinii (3)			34—36	14, 22
C. brumptii (1)			32—33	14, 22
C. buffonii (1)			26—28	14, 22
C. cacaoi (1)			45—46	14, 22
C. catenulata (1)			36—37	14, 22
C. ciferrii (4)			37—43	14, 22
C. claussenii (2)			26—27	14, 22
C. conglobata (2)			35—37	14, 22
C. curiosa (3)			22—23	14, 22
C. curiosa		16	17	34
C. curvata (10)			35—38	14, 22
C. diddensii (11)			32—40	14, 22
C. diffluens (1)			30—31	14, 22
C. diversa (1)			37—38	14, 22
C. foliarum (1)			38—39	14, 22
C. freyschussii (2)			46—47	14, 22
C. friedrichii (2)			30—31	14, 22
C. frigida	−5—−7	15	20	13
C. gelida	−5—−7	15	20	13
C. glaebosa (1)			29—30	14, 22
C. guilliermondii (12)			38—43	14, 22
C. guilliermondii var. *carpophila* (3)			37—38	14, 22
C. guilliermondii var. *membranaefaciens* (*Pichia ohmeri*) (11)			39—43	14, 22
C. humicola (12)			28—39	14, 22
C. ingens (6)			36—38	14, 22
C. intermedia (7)			34—37	14, 22
C. javanica (1)			29—30	14, 22
C. kefyr (4)			37—42	14, 22
C. krusei (18)			42—45	14, 22
C. lambica (7)			35—39	14, 22
C. langeroni (1)			44—45	14, 22
C. lipolytica (9)			33—37	14, 22
C. lipolytica var. *deformans* (3)			29—32	14, 22
C. lusitaniae (11)			41—45	14, 22
C. macedoniensis (4)			47—48	14, 22
C. macedoniensis	5		45	13
C. marina (1)			30—31	14, 22
C. maritima (3)			31—32	14, 22

Table 1 (continued)
CARDINAL TEMPERATURES OF YEASTS (°C)

Species (no. of strains)	T_{min}	T_{op}	T_{max}	Ref.
C. melibiosica (1)			40—41	14, 22
C. melinii (1)			40—41	14, 22
C. membranaefaciens (8)			33—38	14, 22
C. mesenterica (6)			25—27	14, 22
C. mogii (3)			39—40	14, 22
C. muscorum (1)			35—36	14, 22
C. nivalis	−5—−7	15	20	13
C. norvegensis (10)			41—44	14, 22
C. obtusa (2)			42—43	14, 22
C. oregonensis (1)			30—31	14, 22
C. parapsilosis (21)			35—42	14, 22
C. parapsilosis	0	20—25	30	13
C. pelliculosa (Hansenula anomala) (2)			35—37	14, 22
C. pelliculosa var. *cylindrica (H. anomala) var. schneggii)* (1)			37—38	14, 22
C. pseudotropicalis (7)			44—47	14, 22
C. pulcherrima (Metschnikowia pulcherrima) (16)			31—39	14, 22
C. ravautii (7)			36—40	14, 22
C. reukauffii (M. reukauffii) (7)			30—36	14, 22
C. rhagii (4)			33—37	14, 22
C. rugosa (11)			37—43	14, 22
C. sake (26)			28—42	14, 22
C. salmanticensis (1)			35—37	14, 22
C. salmonicola (1)			30—32	14, 22
C. santamraiae (1)			31—32	14, 22
C. scottii (Leucosporidium scottii) (7)			22—24	14, 22
C. scottii	0	4—15	15—20	13
C. shehatae (6)			32—37	14, 22
C. silvae (7)			35—38	14, 22
C. silvicola (H. holstii)			37—43	14, 22
C. slooffii (7)			45—46	14, 22
C. slooffii	27		45	13
C. solani (2)			32—34	14, 22
C. sorbosa (2)			37—40	14, 22
C. stellatoidea (5)			41—43	14, 22
C. tenuis (11)			31—42	14, 22
C. tropicalis (14)			41—44	14, 22
C. tropicalis	5		44	15
C. utilis (13)			39—44	14, 22
C. utilis	5—10			13
C. utilis	−2		43	15
C. valida (15)			32—37	14, 22
C. vartiovaarai (3)			30—31	14, 22
C. veronae (1)			42—43	14, 22
C. vini (9)			27—31	14, 22
C. viswanathii (3)			40—43	14, 22
C. zeylanoides (13)			32—34	14, 22
Cryptococcus albidus	−12		35	15
Cr. gastricus			26	15
Cr. hungaricus			24	15
Cr. laurentii			37	15
Cr. luteolus			34	15
Cr. macerans			<30	15
Cr. neoformans		34	40	36

Table 1 (continued)
CARDINAL TEMPERATURES OF YEASTS (°C)

Species (no. of strains)	T_{min}	T_{op}	T_{max}	Ref.
Cr. skinneri			30	15
Cr. terreus	÷10		35	15
Debaryomyces hansenii	0		35	13
Deb. hansenii	−12.5		37	15
Hansenula anomala	2		37	15
H. suaveolens	3	30	30—35	13
H. polymorpha			49—50	9
H. subpelliculosa	5		37	15
H. valbyensis	5		32—33	13
Kloeckera apiculata	3	30	35	13
K. apiculata	8		35	15
Kluyveromyces fragilis	8		47	15
K. lactis	5		40	15
Leucosporidium antarcticum			19	15
Leu. frigidum	<−1		19	15
Leu. nivalis	<−1		19	15
Leu. scottii	−1		35	15
Leu. stokesii			19	15
Lipomyces anomalus	5		35	15
L. kononenkoae (2)			37—40	18
L. kononenkoae		32—33	35	35
L. lipofer (4)			<35	18
L. lipofer	5		35	15
L. starkeyi (11)			37—40	18
L. starkeyi	5		37	15
Metschnikowia bicuspidata (10)			27—34	19
M. krissii (4)			34—35	19
M. pulcherrima (see *Candida pulcherrima*)				
M. reukauffii (see *Candida reukauffii*)				
M. zobellii (8)			34—35	19
Nadsonia commutata			<30	15
N. elongata	0		25	13
N. fulvescens			<30	
Nematospora coryli (9)			39—42	19
Oosporidium margaritiferum			32—34	23
Pichia membranaefaciens	3		30	13
Rhodosporidium bisporidii			30	15
Rhodosp. capitatum			24	15
Rhodosp. dacryoidum			30	15
Rhodosp. diobovatum			35	15
Rhodosp. infirmo-miniatum			30	15
Rhodosp. malvinellum			30	15
Rhodosp. sphaerocarpum			30	15
Rhodosp. toruloides			40	15
Rhodotorula aurantiaca			38	15
Rh. glutinis	—2		39	15
Rh. glutinis	0	23	<30	13
Rh. gracilis	5	27	37—42	13
Rh. gramminis			33	15
Rh. lactosa			30	15
Rh. marina			<30	15
Rh. minuta	—2		38	15
Rh. pallida			34	15

Table 1 (continued)
CARDINAL TEMPERATURES OF YEASTS (°C)

Species (no. of strains)	T_{min}	T_{op}	T_{max}	Ref.
Rh. rubra			38	15
Saccharomyces carlsbergensis	0	25	33.5	13
S. cerevisiae	0—5	28—36	40—42	13
S. cerevisiae		37.6	40.1(T_{max1}); 43.8 (T_{max1})	30
S. fragilis (*Kluyveromyces fragilis*)	5		45	13
S. intermedius	0.5		40	13
S. ludwigii	1—3		37—38	13
S. marxianus (*Kluyveromyces marxianus*)	0.5		46—47	13
S. mellis	23		35	13
S. octosporus	17		33	13
S. pastorianus	0.5		24	13
S. turbidans	0.5		40	13
S. validus	0.5		39—40	13
Saccharomycopsis guttulata (*Cyniclomyces guttulatus*)	35		40	13
Schizosaccharomyces japonicus (8)			±42	21
Schiz. malidevorans (1)			±42	21
Schiz. octosporus (7)			±40	21
Schiz. pombe (25)			40—42	21
Schwanniomyces alluvius			37	15
Schw. castellii			37	15
Schw. occidentalis			30	15
Schw. persoonii			30	15
Sporidiobolus johnsonii			37	15
Sporid. ruinenii			30	15
Sporobolomyces alborubescens			30	15
Sp. antarcticus			30	15
Sp. gracilis			<30	15
Sp. hispanicus			30	15
Sp. holsaticus			30	15
Sp. odorus			30	15
Sp. pararoseus			30	15
Sp. runicea			<30	15
Sp. roseus			<30	15
Sp. singularis			<30	15
Sterigmatomyces elviae			37	15
St. halophilus			30	15
St. indicus			30	15
Torulopsis anatomiae (1)			35—36	14, 24
T. apicola (4)			32—37	14, 24
T. apis (1)			35—36	14, 24
T. bovina (5)			44—45	14, 24
T. candida (15)			32—37	14, 24
T. candida	5	22	32	13
T. cantarellii (4)			37—38	14, 24
T. colliculosa (1)			37—38	14, 24
T. dattila (2)			37—38	14, 24
T. domercquii (3)			33—38	14, 24
T. ernobii (3)			31—32	14, 24
T. etchellsii (5)			33—35	14, 24
T. fujisanensis (1)			27—28	14, 24