7
Production of Pentoses by Micro-organisms

KEN-ICHI SASAJIMA* AND MASAHIKO YONEDA†

**Institute for Fermentation, Osaka and †Applied Microbiology Laboratories, Central Research Division, Takeda Chemical Industries, Ltd., Yodogawa, Osaka, Japan*

Introduction

Pentoses are widely distributed in nature: they have important biological roles as components of biopolymers such as DNA, RNA, xylan and arabinan, as components of coenzymes (NAD, NADP, FAD, ADP, UDP, CDP, GDP), or as metabolic intermediates in, for instance, the pentose phosphate pathway, the uronic acid cycle, and in the assimilation of aldopentoses and pentitols in micro-organisms. Pentoses also exist as components of nucleoside antibiotics.

D-Ribose is used industrially for the chemical synthesis of riboflavin (Kuhn *et al.*, 1935) and has long been prepared from D-glucose by a chemical process involving several stages (Gehrke and Aichner, 1927). Recently developed methods of D-ribose production employ micro-organisms or microbial enzymes. Hydrolysis of RNA by microbial enzymes was first used. D-Ribose 5-phosphate is one of the major intermediates of the pentose phosphate pathway: thus micro-organisms were sought which would be able to produce and excrete D-ribose directly into the culture medium. Among those micro-organisms with this capability, transketolase (EC 2.2.1.1) mutants of *Bacillus* spp. have been used in particular for economic production of large amounts of D-ribose in the culture medium (Sasajima and Yoneda, 1971). The transketolase-deficient (*tkt*) mutant was improved by further mutation. The improved strains have been used widely during the past 10 years for the industrial production of D-ribose, replacing the chemical method used hitherto, and thereby avoiding the use of mercury which is essential for the electrolytic reduction required in the chemical process.

†Present address: Personnel Training Center, Takeda Chemical Industries, Ltd., 50–2, Yamada Minami, Suita-City, Japan.

Abbreviations: ADP, adenosine 5′-diphosphate; CDP, cytidine 5′-diphosphate; CMP, 5′-cytidylic acid; FAD, flavin adenine dinucleotide; GDP, guanosine 5′-diphosphate; GMP, 5′-guanylic acid; HFCS, high-fructose corn syrup; IMP, 5′-inosinic acid; NAD, nicotinamide adenine dinucleotide; NADP, nicotinamide adenine dinucleotide phosphate; PRPP, 5-phosphoribosyl 1-pyrophosphate; TPP, thiamine pyrophosphate; UDP, uridine 5′-diphophate; UMP, 5′-uridylic acid.

Biotechnology and Genetic Engineering Reviews – Vol. 2, October 1984
0264–8725/84/02/175–39$10.00 + $0.00

Xylitol, which previously was derived from D-xylose by chemical reduction, is used as an energy source for diabetic patients (Mellinghoff, 1961). Recently, a process for the efficient production of xylitol from D-xylose was developed, using a mutant strain of *Candida tropicalis* (Gong, Chen and Tsao, 1981).

D-Xylose and D-xylulose available from vegetable matter have been investigated as potential feedstocks for ethanol production by yeasts (Gong *et al.*, 1981a; Jeffries, 1983; McCracken and Gong, 1983). The conversion of D-xylose to D-xylulose is also being studied because D-xylulose is a better carbon source than D-xylose for yeasts (Wang, Shopsis and Schneider, 1980; Gong *et al.*, 1981b).

This review describes investigations into the microbial production of aldopentoses, ketopentoses, pentitols, aldopentonic acids and some rare derivatives, with particular emphasis on the production of D-ribose, which is the most industrially important pentose.

Naturally occurring pentoses

Pentoses and their derivatives occur widely in various organisms (*Table 1*). The major pentoses, D-ribose, D-xylose and L-arabinose, are most abundant as components of biopolymers. There is a remarkable difference between D-ribose and the other two aldopentoses, in the forms in which they are found: D-ribose and its 2-deoxy derivative, 2-deoxy-D-ribose, are mainly components of the nucleic acids, DNA and RNA, which are concerned with heredity, genetic function and protein synthesis, whereas D-xylose and L-arabinose exist mainly in plant-cell walls as components of the hemicelluloses xylan and arabinan, respectively.

Aldopentoses also exist in compounds other than those described above. D-Ribose occurs in organisms as a component of nucleotide coenzymes such as NAD, NADP, FAD, ADP, UDP, CDP and GDP, as well as in various nucleoside antibiotics. D-Ribose is also present in the cell walls of some bacteria as a component of lipopolysaccharide or of polysaccharide (*Table 1*). 3-Deoxy-D-ribose is a component of the antibiotic cordycepin produced by *Cordyceps militaris* (*Table 1*). 3-Amino-3-deoxy-D-ribose is a component of the antibiotics 3′-amino-3′-deoxyadenosine and puromycin produced by *Streptomyces alboniger* (*Table 1*). With regard to the phosphate derivatives, D-ribose 5-phosphate is an intermediate in the pentose phosphate pathway, and D-ribose 1-phosphate and 5-phosphoribosyl 1-pyrophosphate take part in purine and pyrimidine nucleotide biosynthesis (*see Figures 1* and *3*). Ribitol (adonitol), the reduction product, was first isolated from *Adonis vernalis* (Ranunculaceae) and subsequently was found in the roots of *Bupleurum falcatum*, in pneumococci as a capsular polysaccharide, and in the cell walls of various bacteria as a component of ribitol teichoic acid and of lipopolysaccharide (*Table 1*); it is also a component of riboflavin. The oxidation product, D-riburonic acid, is found in the cell-wall polysaccharides of *Rhizobium meliloti*. 5-Methylthioribose is a component of 5′-methylthioadenosine which has an important role in the metabolism of adenosylmethionine (*Table 1*). Recently, the conversion of 5-methylthioribose to methionine by yeast cells (Shapiro and Schlenk, 1980), by cell-free extracts of *Enterobacter aerogenes* (Shapiro and Barrett, 1981), by

cell-free homogenates of rat liver (Backlund and Smith, 1981) and by apple tissues (Yung, Yang and Schlenk, 1982) has been described.

L-Arabinose is a component of cherry gum and of gum arabic; 4-amino-4-deoxy-L-arabinose has been found in the cell walls of various bacteria as a component of lipopolysaccharide; 2,4-diamino-2,4-dideoxy-L-arabinose is also a component of the antibiotic, prumycin, produced by *Streptomyces* sp. No. 1028; D-xylose is found in cherry gum and in the antibiotic butirosin A produced by *Bacillus circulans (Table 1)*.

Apart from these ubiquitous aldopentoses there are others which occur more rarely: D-arabinose is found in bacterial-cell walls as a component of lipid A, lipopolysaccharide or polysaccharide and is also found in the antibiotic, primycin produced by *Streptomyces primycini*; a derivative of L-xylose, 3-*O*-methyl-L-xylose, is found in the cell wall of *Pseudomonas maltophilia* and *Rhodopseudomonas viridis*, while 3-*O*-methyl-D-xylose is found in the cell wall of *Myxococcus fulvus*, as a component of lipopolysaccharide; L-lyxose is a component of the antibiotic, curamycin produced by *Streptomyces cura-coi* (*Table 1*).

All the four ketopentoses and their phosphates are metabolic intermediates in the assimilation of aldopentoses and their reduced derivatives (pentitols) in micro-organisms (*Figure 1*). In particular, D-ribulose 5-phosphate and D-xylulose 5-phosphate, together with D-ribose 5-phosphate, are major intermediates of the pentose phosphate pathway (*Figures 1* and *3*). D-Ribulose and D-xylulose are also components of ribulose-peptide in egg yolk, human follicular fluid and human seminal fluid, and of lipopolysaccharide of *Pseudomonas diminuta*, respectively. D-Xylulose and L-xylulose are themselves also intermediates of the uronic acid cycle (Touster and Shaw, 1962), and L-xylulose is found in pentosuric urine (*Table 1*). L-Ribulose 5-phosphate and L-xylulose 5-phosphate are intermediates in the metabolism of L-arabinose, L-xylose, L-lyxose, ribitol and L-arabinitol (*Figure 1*). A rare derivative of D-xylulose, 1-deoxy-D-*threo*-pentulose (1-deoxy-D-xylulose) has been described as an antibiotic produced by *Streptomyces hygroscopicus* (*Table 1*). This compound has also been postulated as a precursor of the thiazole moiety of thiamine biosynthesis in *Escherichia coli* (Thérisod, Fischer and Estramareix, 1981).

Pentitols (reduction products of aldopentoses) are also naturally occurring: ribitol, as described above, is a derivative of D-ribose; D-arabinitol has been found in *Fistulina hepatica* and subsequently in various lichens (*Table 1*).

The metabolism of pentoses and their derivatives in micro-organisms is shown in *Figure 1*. Many enzymes involved in pentose metabolism are used for the production of various pentoses and their derivatives, as described in the following sections.

Production of aldopentoses

D-RIBOSE

Hydrolysis of nucleosides

It should be possible to produce D-ribose and its derivatives from compounds related to the nucleic acids, by using the hydrolytic enzymes found in

Table 1. Natural occurrence of pentoses and their derivatives

Pentose or derivative	Source	Reference
D-Ribose	RNA	
	Nucleotide coenzymes	
	Nucleoside antibiotics	
	Lipopolysaccharide of *Salmonella typhimurium*	Kauffman *et al.*, 1962
	Polysaccharide of *Eubacterium saburreum*	Hofstad and Lygre, 1977; Hoffman *et al.*, 1977
2-Deoxy-D-ribose	DNA	
3-Deoxy-D-ribose	Cordycepin (from *Cordyceps militaris*)	Bentley, Cunningham and Spring, 1951
3-Amino-3-deoxy-D-ribose	Puromycin (from *Streptomyces alboniger*)	Waller *et al.*, 1953
	3′-Amino-3′-deoxyadenosine	Gerber and Lechevalier, 1962; Guarino and Kredich, 1963
Ribitol	*Adonis vernalis*	
	Bupleurum falcatum	Wessely and Wang, 1938
	Ribitol teichoic acid of Gram-positive bacteria	Ward, 1981
	Polysaccharide of *Pneumococcus* sp.	Rebers and Heidelberger, 1959, 1961; Roberts, Buchanan and Baddiley, 1963
	Lipopolysaccharide of *Proteus mirabilis*	Gmeiner *et al.*, 1977; Gmeiner, 1977
	Lipopolysaccharide of *Vibrio parahaemolyticus*	Miyano *et al.*, 1983
	Riboflavin	
D-Riburonic acid	Polysaccharide of *Rhizobium meliloti*	Amemura *et al.*, 1981
5-Methylthioribose	5′-Methylthioadenosine	Schlenk and Smith, 1953
D-Xylose	Xylan	
	Cherry gum	Jones, 1939, 1947
	Butirosin A (from *Bacillus circulans*)	Dion *et al.*, 1972
3-*O*-Methyl-L-xylose	Lipopolysaccharide of cell wall of *Myxococcus fulvus*	Weckesser *et al.*, 1971

3-*O*-Methyl-L-xylose	Lipopolysaccharide of *Pseudomonas maltophilia* Lipopolysaccharide of *Rhodopseudomonas viridis*	Brown, Neal and Wilkinson, 1977 Weckesser *et al.*, 1971, 1974
L-Arabinose	Arabinan Cherry gum Gum arabic	 Jones, 1939, 1947 Smith, 1939
4-Amino-4-deoxy-L-arabinose	Lipopolysaccharide of *Salmonella* spp. Lipid A of *Chromobacterium violaceum* Lipid A of *Rhodospirillum tenue* Lipid A of *Salmonella* spp. Lipid A of *Salmonella minnesota* Lipid A of *Proteus mirabilis*	Volk, Galanos and Luderitz, 1970 Hase and Rietschel, 1977 Tharanathan, Weckesser and Mayer, 1977, 1978 Mühlradt, Wray and Lehmann, 1977 Batley, Packer and Redmond, 1982 Sidorczyk, Zähringer and Rietschel, 1983
2,4-Diamino-2, 4-dideoxy-L-arabinose	Prumycin (from *Streptomyces* sp.)	Ōmura *et al.*, 1974
D-Arabinose	Lipid A of *Rhodospirillum tenue* Lipopolysaccharide of *Pseudomonas maltophilia* Polysaccharide of *Mycobacterium tuberculosis* Polysaccharide of *Corynebacterium diphtheriae* Primycin (from *Streptomyces primycini*)	Tharanathan, Weckesser and Mayer 1977, 1978; Weckesser *et al.*, 1977 Wilkinson, Galbraith and Anderson, 1983 Chargaff and Anderson, 1930; Maxim, 1930; Haworth, Kent and Stacey, 1948a, b Holdsworth, 1952; Cummins, 1956 Aberhart *et al.*, 1970
D-Arabinitol	*Fistulina hepatica* Lichens	Frèrejacque, 1939 Lindberg, Misiorny and Wachtmeister, 1953; Briner, Gream and Riggs, 1960; Aghoramurthy, Sarma and Seshadri, 1961
L-Lyxose	Curamycin (from *Streptomyces cura-coi*)	Galmarini and Deulofeu, 1961
D-Ribulose	Ribulose-peptide of chick yolk Ribulose-peptide of human follicular fluid Ribulose-peptide of human seminal fluid	Amano, 1970 Hayashi, 1971 Nagaoka, 1973
D-Xylulose	Lipopolysaccharide of *Pseudomonas diminuta*	Wilkinson, 1981
L-Xylulose	Urine of patients with pentosuria	
1-Deoxy-D-*threo*-pentulose (1-deoxy-D-xylulose)	Antibiotic produced by *Streptomyces hygroscopicus*	Slechta and Johnson, 1976; Hocksema and Baczynskyj, 1976

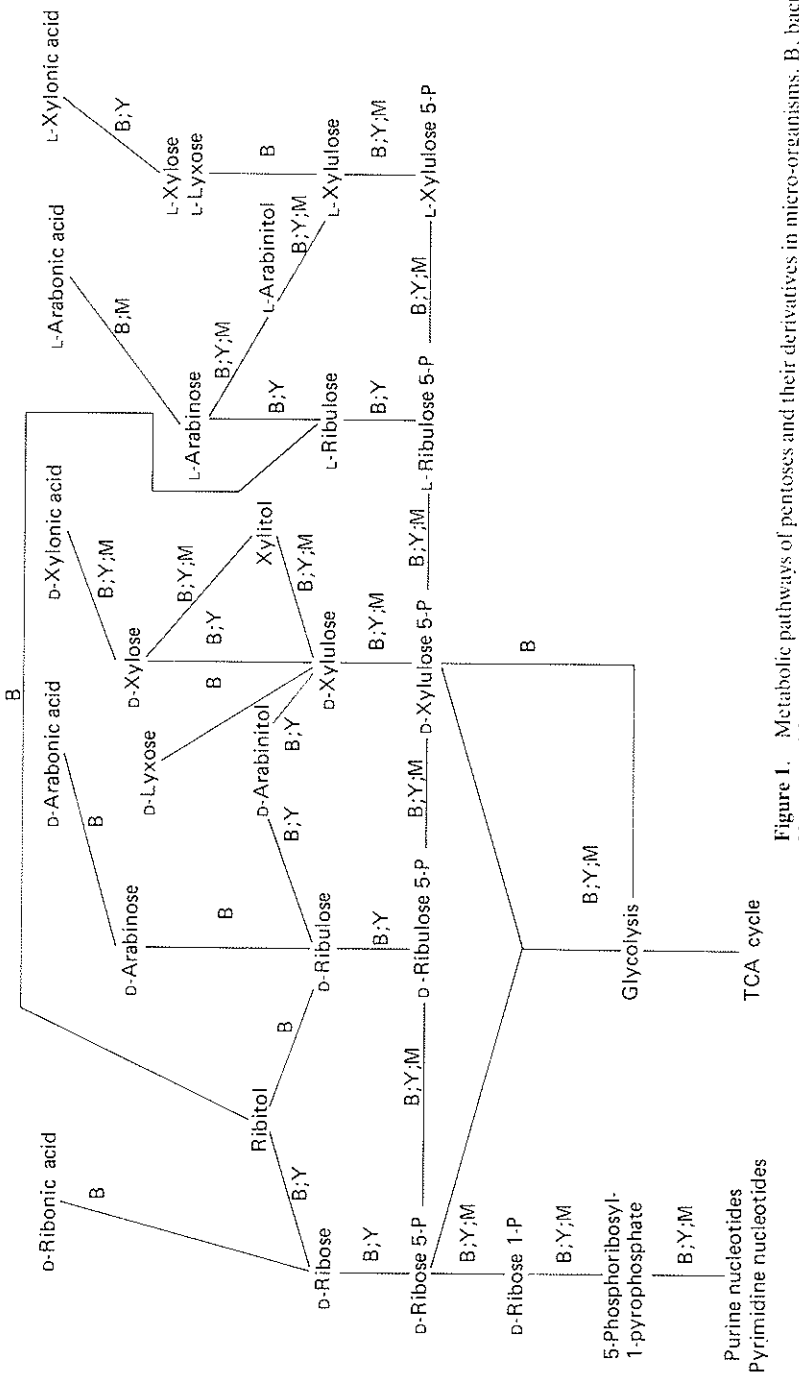

Figure 1. Metabolic pathways of pentoses and their derivatives in micro-organisms. B, bacteria; Y, yeasts; M, moulds.

micro-organisms. The discovery that DNA is the entity that bears genes (Avery, MacLeod and McCarty, 1944; Hershey and Chase, 1952; Watson and Crick, 1953) stimulated many investigations into the mechanism of genetic expression, during which, many enzymes involved in the metabolism of nucleic acids were found, including nucleoside hydrolases (e.g. purine nucleosidase, EC 3.2.2.1; uridine nucleosidase, EC 3.2.2.3, *N*-ribosylpyrimidine ribohydrolase, EC 3.2.2.8), nucleotide *N*-glycoside hydrolases (e.g. AMP nucleosidase, EC 3.2.2.4; pyrimidine-5′-nucleotide nucleosidase, EC 3.2.2.10), nucleoside phosphorylases and nucleotide pyrophosphorylases. In addition, investigations into the production of the flavour enhancers, inosine monophosphate (IMP) and guanosine monophosphate (GMP), by enzymatic degradation of yeast RNA, started in Japan in the late 1950s (Ogata, 1976): during the course of these investigations, nucleoside hydrolases, nucleotide *N*-glycoside hydrolases and nucleoside phosphorylases were also found in various bacteria, actinomycetes and moulds.

The successful production of IMP and GMP from yeast RNA on an industrial scale gives rise to large amounts of the by-products uridine monophosphate (UMP) and cytidine monophosphate (CMP). D-Ribose, D-ribose 5-phosphate, D-ribose 1-phosphate and 5-phosphoribosyl 1-pyrophosphate (PRPP) can be produced from ribonucleosides and ribonucleotides by hydrolysis with nucleoside hydrolases and nucleotide *N*-glycoside hydrolases, by phosphorolysis with nucleoside phosphorylases and by pyrophosphorolysis with nucleotide pyrophosphorylases, as shown in equations 1–4:

$$\text{nucleoside} + H_2O \xleftrightarrow{\text{nucleoside hydrolase}} \text{base} + \text{D-ribose} \quad \text{Eq. (1)}$$

$$\text{nucleotide} + H_2O \xleftrightarrow{\text{nucleotide } N\text{-glycoside hydrolase}} \text{base} + \text{D-ribose 5-phosphate} \quad \text{Eq. (2)}$$

$$\text{nucleoside} + H_3PO_4 \xleftrightarrow{\text{nucleoside phosphorylase}} \text{base} + \text{D-ribose 1-phosphate} \quad \text{Eq. (3)}$$

$$\text{nucleotide} + H_2PO_3OPO_3H_2 \xleftrightarrow{\text{nucleotide pyrophosphorylase}} \text{base} + \text{PRPP} \quad \text{Eq. (4)}$$

The formulae of D-ribose and its derivatives are shown in *Figure 2*.

The nucleoside hydrolases and nucleotide *N*-glycoside hydrolases found in bacteria, actinomycetes and moulds are listed in *Table 2*. The nucleoside phosphorylases have been reviewed by Imada (1970) and the reverse reaction of equation 4, in which nucleotides are formed from PRPP and bases, has been described by Flaks (1963). D-Ribose production from 5-amino-4-imidazolecarboxamide-riboside by hydrolysis with a nucleoside hydrolase from *Bacillus thiaminolyticus* has been reported (Sano, Yokozeki and Mitsugi, 1977a). The utilization of UMP as the basis of D-ribose 5-phosphate production has also been described (Sakai, Watanabe and Chibata, 1971); UMP was hydrolysed by the nucleotide phosphoribohydrolase of *Pseudomonas oleovolans*.

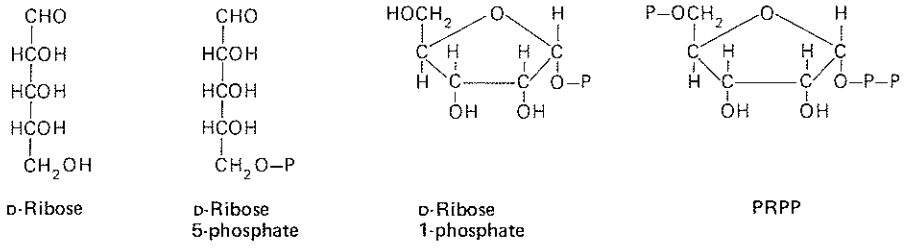

Figure 2. Formulae of D-ribose, D-ribose 5-phosphate, D-ribose 1-phosphate and PRPP.

Table 2. Nucleoside hydrolases and nucleotide *N*-glycoside hydrolases in various micro-organisms

Enzyme	Micro-organism	Reference
Nucleoside hydrolases (e.g. purine nucleosidase, EC 3.2.2.1; uridine nucleosidase, EC 3.2.2.3; *N*-ribosyl-pyrimidine ribohydrolase, EC 3.2.2.8)	(Bacterium)	
	Bacillus cereus spores	Lawrence, 1955; Powell and Hunter, 1956
	Bacillus thiaminolyticus	Sano, Yokozeki and Mitsugi, 1977a, b
	Lactobacillus delbrueckii	Takagi and Horecker, 1957
	Lactobacillus pentosus	Lampen and Wang, 1952
	Pseudomonas fluorescens	Terada, Tatibana and Hayaishi, 1967
	Xanthomonas phaseoli	Hochster and Nozzolillo, 1961
	(Yeast)	
	Baker's yeast	Heppel and Hilmoe, 1952
	Fleishman's yeast	Carter, 1951
Nucleotide *N*-glycoside hydrolases (e.g. AMP nucleosidase, EC 3.2.2.4; pyrimidine-5′-nucleotide nucleosidase, EC 3.2.2.10)	(Bacterium)	
	Azotobacter vinelandii	Hurwitz, Heppel and Horecker, 1957
	Pseudomonas graveolens	Imada *et al.*, 1963
	Pseudomonas oleovorans	Sakai, Watanabe and Chibata, 1968, 1971
	(Actinomycetes)	
	Streptomyces virginiae	Imada, Kuno and Igarashi, 1967
	(Mould)	
	Aspergillus oryzae	Kuninaka, 1956, 1957, 1959

Production and accumulation in the culture medium by wild-type micro-organisms

The accumulation of small amounts of D-ribose was first observed in culture media of *Penicillium brevi-compactum* (Simonart and Godin, 1951) during studies on the biosynthesis of components of benzene derivatives in *P. brevi-compactum* (Godin, 1953a,b). An unidentified bacterium was later found to excrete both D-ribose and D-ribose 5-phosphate into the culture medium (Suzuki *et al.*, 1963). When the culture medium contained Mn^{2+}, Fe^{2+} or Zn^{2+} ions, D-ribose (5 mg/ml) accumulated: however, if these ions were not

present, D-ribose 5-phosphate accumulated instead, in concentrations of up to 7 mg/ml. A smaller degree of D-ribose accumulation was also described by Saito and Sugiyama (1966), working with *Pseudomonas reptilivora*.

D-Ribose production by transketolase-deficient Bacillus *spp. mutants*

Mutant strains of bacteria, which have various blocks in their metabolic pathways, have been used for the production of many metabolic intermediates that are useful chemicals, such as amino acids and substances related to nucleic acids. A microbial method for the industrial production of D-ribose was first brought about by the isolation and development of transketolase-deficient mutants of *Bacillus* spp. (Sasajima and Yoneda, 1971).

During research into the production of inosine (one of the precursor substances for IMP synthesis) (Nogami *et al.*, 1968) attempts were made to isolate *Bacillus* spp. mutants that were defective in the pentose phosphate pathway, in order to improve inosine productivity (Sasajima, Nogami and Yoneda, 1970), as D-ribose 5-phosphate is a precursor of purine nucleotide biosynthesis. However, inosine productivity of certain of these mutants unexpectedly decreased, whereas it was found that large amounts of pentoses were excreted into the culture medium. These mutants were found to be deficient in transketolase or in D-ribulose 5-phosphate 3-epimerase (ribulosephosphate 3-epimerase; EC 5.1.3.1) (Sasajima and Yoneda, 1974). The transketolase-deficient (*tkt*) mutants produced only D-ribose, whereas the epimerase-deficient mutant produced both D-ribose and D-ribulose simultaneously in the ratio of about 2:1. D-Ribose was purified, isolated by crystallization and identified by its chemical and physicochemical properties. The *tkt* mutants were found among those which were isolated as strains requiring shikimic acid, because transketolase also catalyses the first step of the aromatic biosynthetic pathway; thus, the *tkt* mutant is defective both in the pentose phosphate pathway and in the aromatic biosynthetic pathway (*Figure 3*). The mutant strain therefore cannot assimilate carbohydrates such as D-gluconate, D-xylose and L-arabinose and, moreover, requires aromatic compounds such as L-tryptophan, L-phenylalanine, L-tyrosine, coenzyme Q, vitamin K and folic acid (Sasajima and Yoneda, 1974). Revertants could not produce D-ribose, indicating that the production of a large amount of D-ribose is directly related to the transketolase deficiency.

D-Glucose, sorbitol, D-mannitol and maltose are good carbon sources for D-ribose production, and yeast extract is an excellent nitrogen source.

The *tkt* mutant was modified by further mutation to obtain improved strains, the best of which produced about 70 mg of D-ribose per ml of culture medium (Sasajima, 1976). *Figure 4* shows a typical time course for D-ribose production by fermentation. Derepressed synthesis of a spore-specific enzyme, D-glucose dehydrogenase (EC 1.1.1.119) was shown by the vegetative cells of this improved mutant strain (Yokota, Sasajima and Yoneda, 1979; Yokota and Sasajima, 1981). Synthesis of D-glucose dehydrogenase usually starts at stage III of sporulation, in parallel with the morphological changes attendant on spore formation (Warren, 1968). The initiation of sporulation

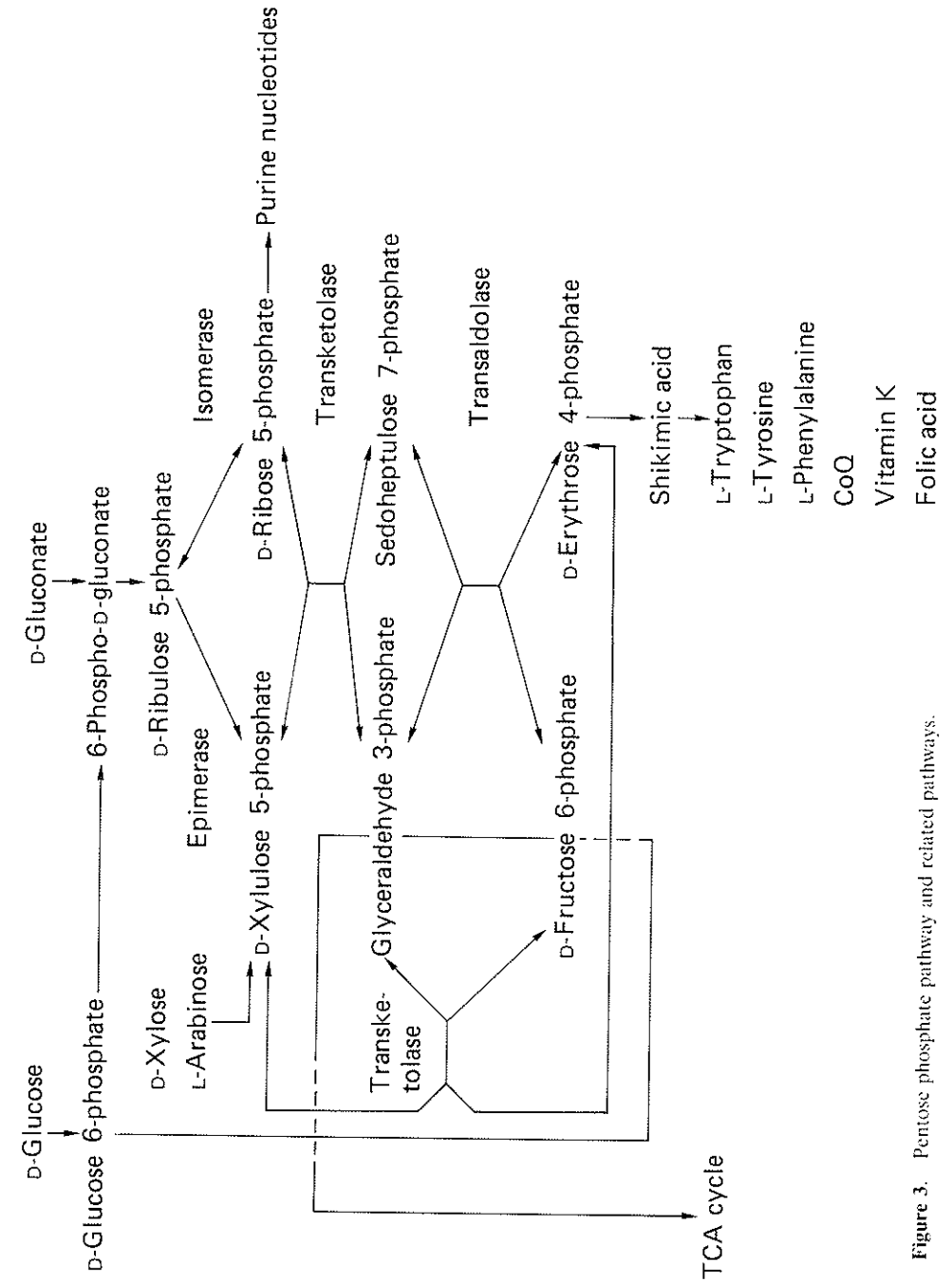

Figure 3. Pentose phosphate pathway and related pathways.

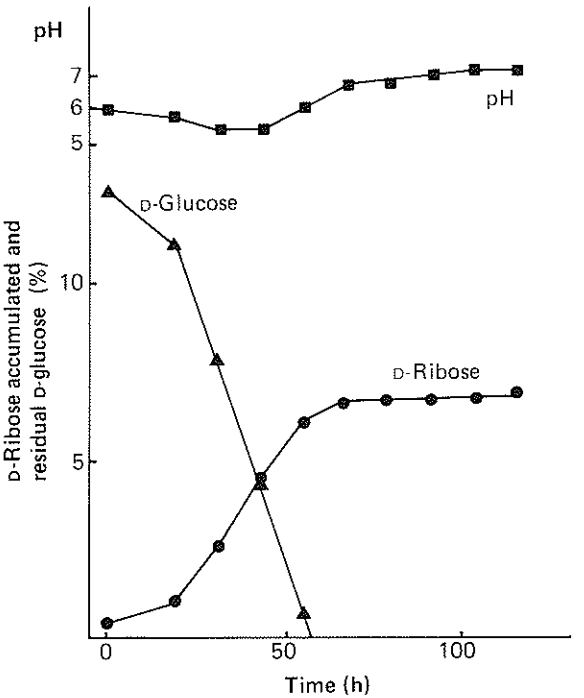

Figure 4. Time course of D-ribose production.

normally occurs only after depletion of the carbon source or of another essential nutrient. However, in the improved *tkt* mutant strain, synthesis of D-glucose dehydrogenase occurs even in the presence of D-glucose and is not associated with the morphological changes of sporulation (Yokota, Sasajima and Yoneda, 1979; Yokota and Sasajima, 1981). In the mutant strain, both the non-phosphorylated pathway (from D-glucose to the pentose phosphates via D-gluconate) and the phosphorylated pathway are active (*Figure 5*). The gluconate pathway may contribute greatly to the high productivity of the improved strain. The ratio of D-ribose and D-gluconate production depends on the oxygen partial pressure during fermentation (K. Sasajima and co-workers, unpublished work); oxygen deficiency leads to D-gluconate rather than D-ribose accumulation. Further improvement of D-ribose production was achieved by another mutation which rendered the improved mutant strain asporogenous (Sasajima, 1976) but the mechanism of this effect has not been elucidated.

The kinetics of D-ribose production by the high-yielding mutant strain was studied by Asai *et al.* (1978) who showed that the ratio of D-ribose to D-gluconate production was influenced by temperature, the maximum yield of D-ribose being noted at 36·6°C when using exponential growth cells as the inoculum.

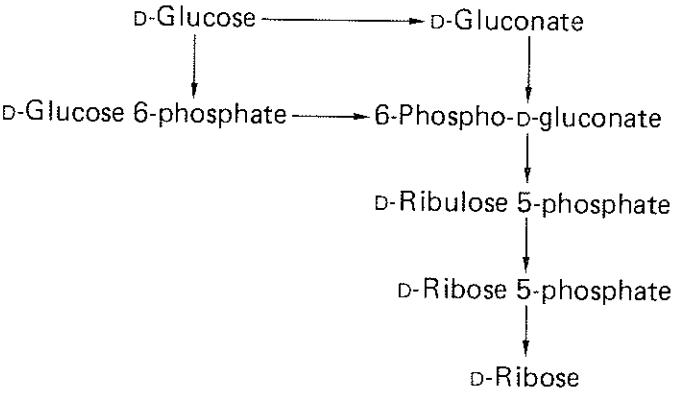

Figure 5. Pathways of D-ribose formation.

A mutant strain of this type has been used over the past decade for production of D-ribose (for riboflavin synthesis) on an industrial scale. Almost all of the world's D-ribose production is now thought to be by the microbial process.

Transketolase and D-ribulose 5-phosphate 3-epimerase mutants of the IFO 3026 strain of *Bacillus subtilis* were subsequently isolated and found also to produce pentoses (Sasajima, 1976). These mutants produced both D-ribose and D-ribulose. The transketolase mutant of another strain of *B. subtilis*, IFO 12114, also formed a pentose, in this case D-ribose only (A. Yokota and K. Sasajima, unpublished work). Because transketolase is one of the enzymes requiring thiamine pyrophosphate (TPP) as a cofactor, thiamine-requiring mutants of *B. subtilis* IFO 12114 were then isolated. These could produce D-ribose when grown in a thiamine-depleted medium but, even so, yields were less than with the *tkt* mutant, probably because the thiamine levels could not be decreased sufficiently to eliminate transketolase activity without adversely affecting the activity of certain enzymes (such as the pyruvate dehydrogenase complex (EC 1.2.4.1) and α-ketoglutarate dehydrogenase (oxoglutarate dehydrogenase; EC 1.2.4.2)) for which TPP is required.

A pleiotropic effect was noted in the transketolase mutant in that it could not utilize D-glucose, which normally is the best carbon source for D-ribose production (Sasajima and Yoneda, 1974; Sasajima, Kumada and Yokota, 1977). The mutant strain preferentially used other substances in the medium as a carbon and energy source and for growth, and only later was able to use D-glucose for D-ribose production. Investigation showed that the transport function of the $EnzII^{glc}$ (phosphohistidinoprotein – hexose phosphotransferase; EC 2.7.1.69) of the PEP-dependent D-glucose phosphotransferase system (Postma and Roseman, 1976; Saier, 1977) was defective in the *tkt* mutant (Sasajima and Kumada, 1979). Utilization of D-mannitol, D-fructose and glycerol, but not of sorbitol, was inhibited by D-glucose. The *tkt* mutant was found to be hypersensitive to D-glucose repression of synthesis of the enzymes

of D-mannitol catabolism (such as D-mannitol 1-phosphate dehydrogenase, EC 1.1.1.17 and the D-mannitol transport system). On the other hand, the *tkt* mutant was resistant to D-glucose repression of synthesis of enzymes of sorbitol catabolism, (such as the sorbitol transport system and sorbitol dehydrogenase (Sasajima and Kumada, 1981a). D-Gluconate, D-xylose and L-arabinose were also found to repress the synthesis of enzymes of D-mannitol catabolism in the *tkt* mutant, although not in the parental strain. These changes in the regulation of enzyme synthesis may be caused by a defect in the cell membrane of the *tkt* mutant. Subsequently, various functions relating to the cell surface were found to differ from those of the parental strain: (1) during the exponential growth phase the *tkt* mutant formed chains which were thicker in cell width than those of the parental strain; (2) sensitivity to bacteriophages SP10 and SP01 was altered; (3) the cell walls of the mutant strain autolysed more slowly than did those of the parental strain; (4) the sporulation frequency of the mutant strain decreased markedly (Sasajima and Kumada, 1981b, 1983a). The flagellae are also defective in the mutant strain, which is therefore non-motile (Sasajima and Kumada, 1983b). Isolation and characterization of a true revertant confirmed that these pleiotropic properties were generated by a single mutation (Sasajima and Kumada, 1979, 1981a, 1983a,b). Chemical changes in the membrane components are being investigated.

Tkt mutants of *Escherichia coli* and *Salmonella typhimurium* have also been isolated (Josephson and Fraenkel, 1969; Eidels and Osborn, 1971). The *tkt* mutants of *E. coli* did not accumulate any pentose, either intracellularly or extracellularly (Josephson and Fraenkel, 1974); accumulation of pentoses was not studied in the *S. typhimurium tkt* mutants. The *tkt* mutants of these Gram-negative bacteria also showed defective synthesis of heptose which is important in the biosynthesis of the outer-membrane lipopolysaccharides, resulting in the formation of a defective cell surface (Eidels and Osborn, 1971; Ames, Spudich and Nikaido, 1974; Koplow and Goldfine, 1974; Bayer, Koplow and Goldfine, 1975; Irvin *et al.*, 1975; Smit, Kamio and Nikaido, 1975; van Alphen, Lugtenberg and Berendsen, 1976). The difference in D-ribose productivity between the *tkt* mutants of *E. coli* and those of *Bacillus* spp. may result from their different genetic backgrounds.

D-XYLOSE AND L-ARABINOSE

These two aldopentoses occur in plant-cell walls as the hemicelluloses xylan and arabinan, and can comprise a large proportion of plant biomass. As a consequence there is interest in the conversion of xylan and arabinan to D-xylose and L-arabinose respectively (*Figure 6*), and subsequent conversion of these pentoses to valuable products such as ethanol and single-cell protein; the utilization of D-xylose has recently been reviewed (Gong *et al.*, 1981a; Jeffries, 1983; McCracken and Gong, 1983).

Hemicelluloses can be hydrolysed either by a chemical process using dilute sulphuric acid, or by an enzymatic method using hemicellulases; chemical hydrolysis is now the more usual technique (Jeffries, 1983). In the enzymatic

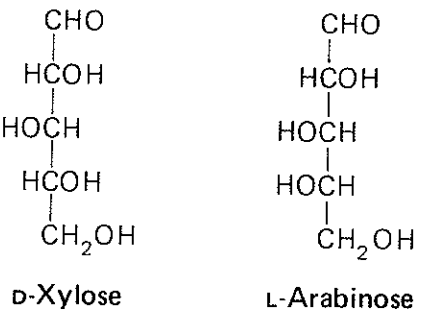

Figure 6. Formulae of D-xylose and L-arabinose.

process a complex enzyme mixture must be used because hemicelluloses comprise various sugar components with different types of chemical bonds. Investigations from 1950 to 1973 on the occurrence, purification, properties and mode of action of the hemicellulases, including the xylan- and arabinan-degrading enzymes, have been reviewed (Dekker and Richards, 1976). *Table 3* summarizes studies since 1974 on enzymes from micro-organisms, including xylanases (EC 3.2.1.8), β-xylosidases (exo-1,4-β-D-xylosidase, EC 3.2.1.37), endo-1,5-α-L-arabinases (EC 3.2.1.99), exo-type arabinases and α-L-arabinofuranosidases (EC 3.2.1.55).

Acid hydrolysates of the hemicelluloses are much more difficult for micro-organisms to utilize, probably because of the formation of furfural and other inhibitory by-products. Hemicellulases therefore could become of value for the large-scale production of D-xylose and L-arabinose from biomass if their production and use could be made more economic. Studies on cloning genes encoding these enzymes (*see* page 198) may offer promise, together with isolation of constitutive mutants for production of these enzymes, because xylan and arabinan are required to induce xylanases and arabinases, respectively (Takenishi and Tsujisaka, 1975; Johnson *et al.*, 1979; Esteban, Villanueva and Villa, 1982; Kaji, Sato and Tsutsui, 1981).

Production of ketopentoses

OXIDATION OF PENTITOLS

The oxidation of polyols to ketoses by polyol dehydrogenases of acetic acid bacteria is a well-known reaction; the oxidation of sorbitol to sorbose by acetic-acid bacteria has been used by the pharmaceutical industry in the production of vitamin C. Pentitols are also oxidized by acetic-acid bacteria to ketopentoses. Ribitol and D-arabinitol were first found to be oxidized to L-ribulose and D-xylulose (*Figure 7*), respectively, by polyol dehydrogenases of

Table 3. Xylanases, β-xylosidases, arabinases and α-L-arabinofuranosidases in various micro-organisms

Enzyme	Micro-organism	Reference
Xylanase (EC 3.2.1.8)	(Bacterium)	
	Bacillus circulans	Johnson *et al.*, 1979; Esteban, Villanueva and Villa, 1982
	Bacillus subtilis	Bernier *et al.*, 1983
	Bacillus sp.	Uchino and Nakane, 1981; Williams and Withers, 1983
	(Actinomycetes)	
	Streptomyces sp.	Nakanishi, Yasui and Kobayashi, 1976
	(Yeast)	
	Schizophyllum commune	Paice *et al.*, 1978
	(Mould)	
	Aspergillus niger	Takenishi and Tsujisaka, 1975
	Gliocladium virens	Takahashi and Kutsumi, 1979
	Malbranchea pulchella var. *sulfurea*	Matsuo, Yasui and Kobayashi, 1975
	Basidiomycetes	Kubačková, Karácsonyi and Váradi, 1975
β-Xylosidase (EC 3.2.1.37)	(Bacterium)	
	Bacillus pumilus	Claeyssens *et al.*, 1975
	Bacillus spp.	Williams and Withers, 1983
	(Mould)	
	Basidiomycetes	Kubačková, Karácsonyi and Váradi, 1975
	Malbranchea pulchella var. *sulfurea*	Matsuo, Yasui and Kobayashi, 1977a, b
Endo-1, 5-α-L-arabinase (EC 3.2.1.99)	(Bacterium)	
	Bacillus subtilis	Kaji and Saheki, 1975
	Bacillus spp.	Williams and Withers, 1983
Exo-type arabinase	(Bacterium)	
	Erwinia carotovora	Kaji and Shimokawa, 1984
α-L-Arabinofuranosidase (EC 3.2.1.55)	(Bacterium)	
	Bacillus subtilis	Yoshihara and Kaji, 1983
	Bacillus spp.	Williams and Withers, 1983
	(Actinomycetes)	
	Streptomyces diastatochromogenes	Higashi *et al.*, 1983
	Streptomyces purpurascens	Komae, Kaji and Sato, 1982
	Streptomyces sp.	Kaji, Sato and Tsutsui, 1981; Kusakabe, Yasui and Kobayashi, 1975
	(Yeast)	
	Rhodotorula flava	Kusakabe, Yasui and Kobayashi, 1975
	(Mould)	
	Aspergillus niger	Kusakabe, Yasui and Kobayashi, 1975

Acetobacter suboxidans (Reichstein, 1934; Prince and Reichstein, 1937). *Table 4* lists the pentitol dehydrogenases found in various micro-organisms.

Moses and Ferrier (1962) described the use of cell suspensions of *Acetobacter suboxidans* in the preparation of D-xylulose and L-ribulose from D-arabinitol and ribitol, respectively. Subsequently, ribitol dehydrogenase (EC 1.1.1.56) and D-arabinitol dehydrogenase (EC 1.1.1.11) of *Aerobacter aerogenes* were

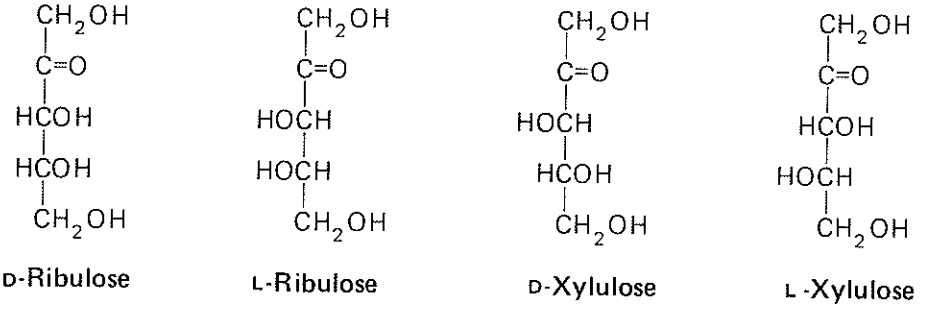

Figure 7. Formulae of ketopentoses.

Table 4. Pentitol dehydrogenases in various micro-organisms

Enzyme	Micro-organism	Reference
Pentitol dehydrogenases (and non-specific polyol dehydrogenases)	(Bacterium)	
	Acetobacter suboxidans	Reichstein, 1934; Prince and Reichstein, 1937; Hann, Tilden and Hudson, 1938; Arcus and Edson, 1956; Moses and Ferrier, 1962
	Azotobacter agilis	Marcus and Marr, 1961
	Pseudomonas spp.	Stanier, Palleroni and Doudoroff, 1966
	(Yeast)	
	Candida utilis	Arcus and Edson, 1956
	Pichia miso	Ōnishi and Saito, 1962
	Various yeasts	Barnett, 1968
Xylitol dehydrogenase (D-xylulose reductase, EC 1.1.1.9)	(Bacterium)	
	Rhizobium trifolii	Primrose and Ronson, 1980
	(Yeast)	
	Candida utilis	Chakravorty *et al.*, 1962; Horitsu and Tomoeda, 1966
	(Mould)	
	Penicillium chrysogenum	Chiang and Knight, 1960b
	Various moulds and yeasts	Chiang and Knight, 1960a
Ribitol dehydrogenase (EC 1.1.1.56)	(Bacterium)	
	Aerobacter aerogenes	Wood, McDonough and Jacobs, 1961; Mortlock and Wood, 1964; Mortlock, Fossitt and Wood, 1965; Mortlock *et al.*, 1965
	Escherichia coli	Scangos and Reiner, 1978
	Rhizobium trifolii	Primrose and Ronson, 1980
D-Arabinitol dehydrogenase (EC 1.1.1.11)	(Bacterium)	
	Aerobacter aerogenes	Wood, McDonough and Jacobs, 1961; Lin, 1961; Mortlock and Wood, 1964; Mortlock, Fossitt and Wood, 1965; Mortlock *et al.*, 1965
	Escherichia coli	Scangos and Reiner, 1978
	Rhizobium trifolii	Primrose and Ronson, 1980

utilized to prepare D-ribulose from ribitol and L-xylulose from L-arabinitol, and D-xylulose from D-arabinitol, respectively (Mortlock and Wood, 1966). The particular pentulose produced from ribitol was found to vary according to the origin of the pentitol dehydrogenases employed.

A cell suspension of an *Aerobacter aerogenes* mutant that was ribitol dehydrogenase-constitutive and D-ribulokinase (EC 2.7.1.47)-deficient was most effective in the formation of D-ribulose (Oliver *et al.*, 1969). In the parental strain, the D-ribulose that was formed was further metabolized and assimilated.

ISOMERIZATION OF ALDOPENTOSES

During investigations into the pentose phosphate pathway in the early 1950s, pentose isomerases were found in various bacteria. Cohen (1953) noted the conversion of D-ribulose to D-arabinose by the D-arabinose isomerase (EC 5.3.1.3) of *Escherichia coli* and then the formation of D-xylulose from D-xylose by D-xylose isomerase (EC 5.3.1.5) of *Lactobacillus pentosus, Pseudomonas hydrophila* and *Pasteurella pestis* was described. Studies on other isomerases (D- and L-arabinose, D-xylose and D-lyxose isomerases) in other bacteria have been reported (*Table 5*). Subsequent investigations revealed that D-arabinose isomerase might be identical to L-fucose isomerase (Green and Cohen, 1956; Camyre and Mortlock, 1965; Oliver and Mortlock, 1971; Izumori and Yamanaka, 1974), because D-arabinose is a rare pentose (*Table 1*). L-Arabinose isomerases (EC 5.3.1.4), which catalyse the initial reaction of L-arabinose assimilation, have also been found in various bacteria (*Table 5*).

The D-xylose isomerase of *Pseudomonas hydrophila* was found to catalyse interconversion between D-glucose and D-fructose (Marshall and Kooi, 1957) and therefore has been intensively studied for practical use in the production of D-fructose from D-glucose (Chen, 1980a,b). Glucose isomerases (essentially D-xylose isomerases) were found in various micro-organisms and some are now used for the industrial production of high-fructose corn syrup (HFCS) (Chen, 1980a, b; *see also* Harada (1984) and Poulsen (1984) in volume 1 of this Series).

D-Lyxose ketol-isomerase (EC 5.3.1.15) has been found in *Aerobacter aerogenes* (*Table 5*). Both L-xylose and L-lyxose can be isomerized into L-xylulose by L-fucose isomerase (Anderson and Wood, 1962; Mortlock, Fossitt and Wood, 1965).

D-Ribose is unusual in its catabolism as well as in its mode of occurrence. Other aldopentoses may be reduced to pentitols by reductases or isomerized to ketopentoses by isomerases (*Figure 1*): D-ribose, however, is first phosphorylated by ribokinase (EC 2.7.1.15) before transformation. Thus a strictly defined D-ribose isomerase has not yet been identified, but an isomerase (L-rhamnose isomerase, EC 5.3.1.14), which acts not only on L-rhamnose but also on D-ribose and L-lyxose and is induced by any one of these sugars, was found in *Mycobacterium smegmatis* (Izumori, Rees and Elbein, 1975; Izumori, Yamanaka and Elbein, 1976; Izumori, Mitchell and Elbein, 1976) and will convert D-ribose into D-ribulose.

D-Xylose isomerase and L-arabinose isomerase have been found in *Candida*

Table 5. Pentose isomerases in various micro-organisms

Enzyme	Micro-organism	Reference
D-Arabinose isomerase (EC 5.3.1.3)	(Bacterium)	
	Aerobacter aerogenes	Mortlock and Wood, 1964; Camyre and Mortlock, 1965; Oliver and Mortlock, 1971; Izumori and Yamanaka, 1974
	Escherichia coli	Cohen, 1953; Green and Cohen, 1956
	Mycobacterium smegmatis	Izumori, Yamanaka and Elbein, 1976
L-Arabinose isomerase (EC 5.3.1.4)	(Bacterium)	
	Aerobacter aerogenes	Simpson, Wolin and Wood, 1958
	Escherichia coli	Lee and Englesberg, 1962
	Lactobacillus gayonii	Yamanaka, 1962
	Lactobacillus plantarum	Heath *et al.*, 1958
	Lactobacillus spp.	Yamanaka, 1958
	Mycobacterium smegmatis	Izumori, Yamanaka and Elbein, 1976; Izumori, Ueda and Yamanaka, 1978
	(Yeast)	
	Candida utilis	Horitsu, Sasaki and Tomoyeda, 1970
D-Xylose isomerase (EC 5.3.1.5)	(Bacterium)	
	Aerobacter aerogenes	Natake and Yoshimura, 1963
	Aerobacter cloacae	Tsumura and Sato, 1960, 1961a,b, 1965a
	Bacillus coagulans	Yoshimura, Danno and Natake, 1966; Danno, 1970, 1971
	Bacillus megaterium	Takasaki and Tanabe, 1962a,b
	Brevibacterium pentosoaminoacidicum	Ichimura *et al.*, 1965
	Escherichia coli	David and Wiesmeyer, 1970
	Escherichia intermedia	Natake and Yoshimura, 1964a,b
	Flavobacterium arborescens	Boguslawski, 1983
	Lactobacillus brevis	Yamanaka, 1963a,b
	Lactobacillus gayonii	Yamanaka, 1962
	Lactobacillus pentosus	Mitsuhashi and Lampen, 1953
	Lactobacillus xylosus	Yamanaka and Takahara, 1977
	Lactobacillus spp.	Yamanaka, 1958
	Pasteurella pestis	Slein, 1955
	Pseudomonas hydrophila	Hochster and Watson, 1953, 1954
	Salmonella typhimurium	Mortlock and Old, 1979; Shamanna and Sanderson, 1979a
	(Actinomycetes)	
	Actinoplanes missouriensis	Scallet *et al.*, 1974
	Streptomyces albus	Sanchez and Smiley, 1975
	Streptomyces flavogriseus	Chen, Anderson and Han, 1979
	Streptomyces griseus	Giovenco, Morisi and Pansolli, 1973
	Streptomyces phaeochromogenes	Tsumura and Sato, 1965b; Strandberg and Smiley, 1971
	Streptomyces sp.	Takasaki, 1966; Takasaki, Kosugi and Kanbayashi, 1969; Chou, Ladisch and Tsao, 1976
	(Yeast)	
	Candida utilis	Tomoyeda and Horitsu, 1964
	Rhodotorula gracilis	Höfer, Betz and Kotyk, 1971
D-Lyxose ketol-isomerase (EC 5.3.1.15)	(Bacterium)	
	Aerobacter aerogenes	Anderson and Allison, 1965

utilis and *Rhodotorula gracilis*, and in *Candida utilis*, respectively (*Table 5*) although pentose isomerases are not commonly found in fungi because, in these species, aldopentoses are normally metabolized by reduction to pentitols which are then oxidized to ketopentoses (Chiang and Knight, 1960b).

Because D-xylulose was found to be more efficiently converted to ethanol by yeasts than was D-xylose (Wang, Shopsis and Schneider, 1980; Gong *et al.*, 1981b), the conversion of D-xylose to D-xylulose has been studied by, for instance, the use of immobilized whole cells of *Bacillus* spp. (Chiang *et al.*, 1981). *Fusarium oxysporum* f.sp. *lini* and *Aspergillus niger* have been used to consume D-xylose in the preisomerized mixture of D-xylose and D-xylulose to provide a purified D-xylulose solution. In another instance, borate was added to the reaction mixture to push the isomerization equilibrium point towards D-xylulose (Hsiao *et al.*, 1982). Wang, Johnson and Schneider (1980) and Gong *et al.* (1981b) added D-xylose isomerase directly to the fermentation medium to produce ethanol via D-xylulose from D-xylose.

ACCUMULATION IN THE CULTURE MEDIUM

Saito and Sugiyama (1964) first reported the accumulation (up to 1·3 mg/ml) of a ketopentose in the culture medium of *Brevibacterium fuscum*. Subsequently, non-tumorigenic strains of *Agrobacterium tumefaciens* were found to accumulate D-ribulose in the culture medium, whereas the tumorigenic strains produced relatively little D-ribulose (Suzuki and Hochster, 1965). Both D-ribulose and D-xylulose were found (7–8 mg/ml) in the culture medium of several *Brevibacterium* and *Corynebacterium* spp. (Misawa, Nara and Kinoshita, 1967). Shimamura, Yoshitake and Imai (1971) noted the formation of up to 9·5 mg of D-ribulose per ml, by a thiamine-requiring *Corynebacterium* sp. in a thiamine-deficient medium containing 6% D-gluconate as the carbon source. Investigation showed that the D-ribulose accumulation resulted from the decreased transketolase activity in media containing low levels of thiamine (Shimamura, Yoshitake and Imai, 1973). The derived D-ribulose 5-phosphate 3-epimerase mutant of *Bacillus* spp. accumulated both D-ribose and D-ribulose in the culture medium, in an approximate ratio of 2:1 (Sasajima and Yoneda, 1971). The total pentose yield was 40 mg per ml of the culture medium.

Production of pentitols

Production of D-arabinitol (*Figure 8*) by yeasts was first suggested by Binkley and Wolfrom (1950). Subsequently, during the course of studies on glycerol production, it was found that D-arabinitol was produced from D-glucose together with glycerol by osmophilic yeasts (*Table 6*). D-Arabinitol was the main product under conditions of nitrogen restriction (Spencer and Sallans, 1956; Ōnishi, Saito and Koshiyama, 1961; Hajny, 1964), high sugar concentration (Ōnishi, 1960a; Moran and Witter, 1979) or low inorganic phosphate concentration (Peterson, Hendershot and Hajny, 1958). Low pH also stimulated D-arabinitol production by *Moniliella tomentosa* (Hanssen, van Regenmortel and Verachtert, 1972), *Candida lipolytica* (Tabuchi and Hara, 1973) and *Candida tropicalis* (Hattori and Suzuki, 1974a).

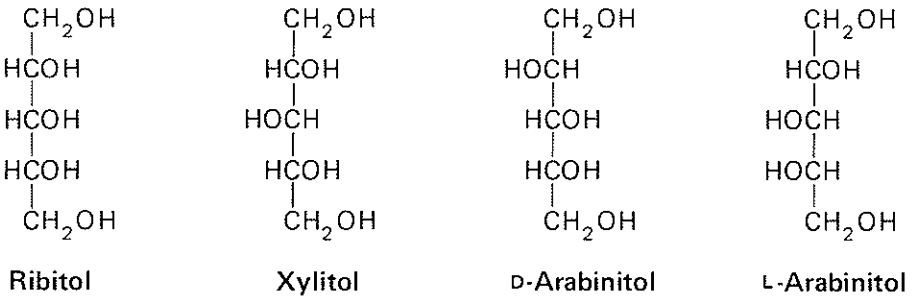

Figure 8. Formulae of pentitols.

Table 6. Yeasts producing D-arabinitol from D-glucose and *n*-alkane

Yeast	Reference
(From D-glucose)	
Fermentation residue	Binkley and Wolfrom, 1950
Candida lipolytica	Tabuchi and Hara, 1973
Candida tropicalis	Hattori and Suzuki, 1974a
Debaryomyces subglobosus	Anderson and Harris, 1963
Endomycopsis chodati	Hajny, 1964
Hansenula arabitolgenes	Chang, Wang and Yang, 1963; Chang, Yang and Wang, 1963
Moniliella tomentosa	Hanssen, van Regenmortel and Verachtert, 1972
Pichia miso	Ōnishi, Saito and Koshiyama, 1961
Saccharomyces rouxii	Spencer, Roxburgh and Sallans, 1957; Ōnishi, 1960a; Moran and Witter, 1979
Zygosaccharomyces chevalieri	Chang, Wang and Yang, 1963
Zygosaccharomyces spp.	Peterson, Hendershot and Hajny, 1958
Zygosaccharomyces spp. and other osmophilic yeasts	Spencer and Sallans, 1956
Various yeasts	Ōnishi, 1960b
(From *n*-alkane)	
Candida tropicalis	Hattori and Suzuki, 1974a
Candida zeylanoides	Hattori and Suzuki, 1974b

Investigation into the useful conversion of petroleum products revealed that *Candida tropicalis* and *Candida zeylanoides* produced D-arabinitol from *n*-alkanes at low pH (*Table 6*).

The production of pentitols from aldopentoses by bacteria and yeasts has also been investigated (*Table 7*). Ōnishi and Perry (1965) first found that *Pichia miso* produced xylitol (*Figure 8*) and heptitols from D-xylose, while Ōnishi and Suzuki (1966) reported that *Candida polymorpha* produced xylitol from D-xylose, L-arabinitol (*Figure 8*) from L-arabinose and ribitol (*Figure 8*) from D-ribose in a yield of 30–40% of sugars consumed. *Pichia quercuum* was reported simultaneously to produce both xylitol (the reduced product) and D-xylonic acid (the oxidized product) from D-xylose (Suzuki and Ōnishi, 1967,

Table 7. Micro-organisms reducing aldopentoses to pentitols

Micro-organism	Reference
(Bacterium)	
Corynebacterium sp.	Yoshitake *et al.*, 1971; Yoshitake, Shimamura and Imai, 1973, 1976
Enterobacter liquifaciens	Yoshitake *et al.*, 1973, 1976
(Yeast)	
Candida polymorpha	Ōnishi and Suzuki, 1966
Candida tropicalis mutant	Gong, Chen and Tsao, 1981
Pichia quercuum	Suzuki and Ōnishi, 1967, 1973

1973). Some bacterial strains also produced pentitols from aldopentoses (*Table 7*). A *Corynebacterium* sp. produced xylitol from D-xylose, L-arabinitol from L-arabinose and ribitol from D-ribose using D-gluconate as the energy and carbon source (Yoshitake *et al.*, 1971; Yoshitake, Shimamura and Imai, 1973, 1976). *Enterobacter liquifaciens* was shown to produce xylitol in culture media containing only D-xylose as the sole carbon source (Yoshitake *et al.*, 1973, 1976). A mutant strain of *Candida tropicalis* has been reported to produce xylitol from D-xylose in a very high yield (Gong, Chen and Tsao, 1981).

Xylitol has been prepared from D-glucose in a three-stage process: (1) D-arabinitol was produced from D-glucose by *Debaryomyces hansenii*; (2) D-arabinitol was then converted to D-xylulose by *Acetobacter suboxidans*; (3) finally, D-xylulose was reduced to xylitol by *Candida guilliermondii* (Ōnishi and Suzuki, 1969).

Production of aldopentonic acids

Various micro-organisms have been reported to oxidize aldopentoses to the corresponding aldopentonic acids, the formulae of which are shown in *Figure 9*. Bertrand (1898a,b) first demonstrated the formation of xylonic acid from xylose and of arabonic acid from arabinose by *Acetobacter xylinum:* subsequently the production of aldopentonic acids from aldopentoses by numerous

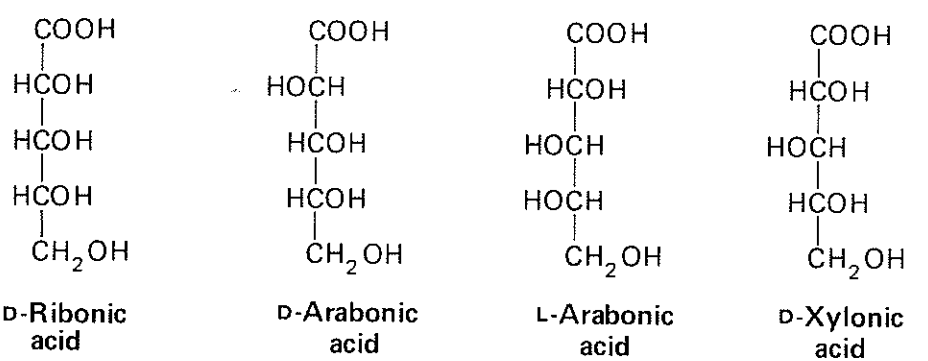

Figure 9. Formulae of aldopentonic acids.

Table 8. Micro-organisms oxidizing aldopentoses to aldopentonic acids

Pentose oxidized*	Micro-organism	Reference
D-Xylose→D-xylonic acid	(Bacterium)	
	Acetobacter melanogenum	Bernhauer and Riedl-Tâmová, 1950
	Acetobacter suboxidans	Bernhauer and Riedl-Tâmová, 1950
	Acetobacter xylinum	Bertrand, 1898a
	Aerobacter aerogenes	Masuo and Nozaki, 1956
	Erwinia milletiae	Uchida and Suzuki, 1975
	Micrococcus sp.	Ohsugi, Tochikura and Ogata, 1970
	Pseudomonas fragi	Weimberg, 1961
	Pseudomonas spp.	Lockwood and Nelson, 1946
	(Yeast)	
	Pichia quercuum	Suzuki and Ônishi, 1967, 1973
	Pullularia pullulans	Kiessling, Lindberg and McKay, 1962
	(Mould)	
	Fusarium lini	Hayashida, 1938
	Penicillium corylophilum	Ikeda and Yamada, 1963a,b
L-Arabinose→L-arabonic acid	(Bacterium)	
	Acetobacter melanogenum	Bernhauer and Riedl-Tâmová, 1950
	Acetobacter suboxidans	Bernhauer and Riedl-Tâmová, 1950
	Acetobacter xylinum	Bertrand, 1898b
	Aerobacter aerogenes	Masuo and Nozaki, 1956
	Erwinia milletiae	Uchida and Suzuki, 1975
	Pseudomonas fragi	Weimberg, 1961
	Pseudomonas saccharophila	Weimberg and Doudoroff, 1955
	Pseudomonas spp.	Lockwood and Nelson, 1946
	(Mould)	
	Fusarium lini	Hayashida, 1938
D-Arabinose→D-arabonic acid	(Bacterium)	
	Pseudomonas fragi	Weimberg, 1961
	Pseudomonas riboflavina	Foster, 1944
	Pseudomonas saccharophila	Palleroni and Doudoroff, 1957
	Pseudomonas spp.	Lockwood and Nelson, 1946
D-Ribose→D-ribonic acid	(Bacterium)	
	Pseudomonas fragi	Weimberg, 1961
	Pseudomonas riboflavina	Foster, 1944
	Pseudomonas spp.	Lockwood and Nelson, 1946

* Detailed enzyme studies were not reported in the literature cited. For details of aldopentose dehydrogenases *see Table 9*.

micro-organisms was described, as listed in *Table 8*. The enzymes (aldopentose dehydrogenases and oxidases) which catalyse these reactions, have also been characterized and are listed in *Table 9*.

Production of rare derivative sugars of pentoses

The accumulation of 1-deoxy-D-*threo*-pentulose (*Figure 10*) by *Streptomyces hygroscopicus* has been described (Slechta and Johnson, 1976; Hoeksema and Baczynskyj, 1976). During the course of studies on D-ribose production by the *tkt* mutants of *Bacillus* spp., it was found that the *tkt* mutant of *Bacillus pumilus* formed a new monosaccharide, 1-deoxy-D-*altro*-heptulose (Yokota, Sasajima

Table 9. Aldopentose dehydrogenases in various micro-organisms

Enzyme	Micro-organism	Reference
D-Xylose oxidase (unpurified)	(Yeast)	
	Phellinus igniarius	Lyr, 1962
	Trametes versicolor	Lyr, 1962
D-Xylose dehydrogenase (EC 1.1.1.175)	(Bacterium)	
	Arthrobacter sp.	Yamanaka, Kaneda and Sakai, 1977; Yamanaka, Gino and Kaneda, 1977
L-Xylose dehydrogenase (EC 1.1.1.113)	(Yeast)	
	Baker's yeast	Uehara and Takeda, 1962
L-Arabinose dehydrogenase (EC 1.1.1.46)	(Bacterium)	
	Rhizobium japonicum	Pedrosa and Zancan, 1974
	Rhizobium spp.	Duncan, 1979
D-Arabinose dehydrogenase (EC 1.1.1.117)	(Bacterium)	
	Pseudomonas sp.	Hu and Cline, 1964; Cline and Hu, 1965; Dahms and Anderson, 1969
D-*threo*-Aldose dehydrogenase	(Bacterium)	
	Pseudomonas caryophylli	Sasajima and Sinskey, 1979

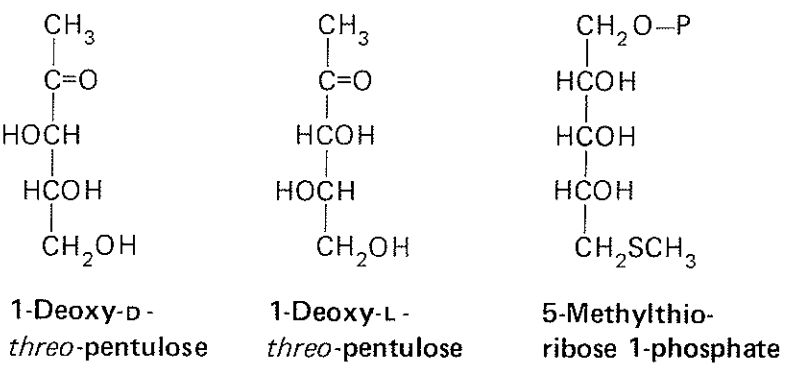

Figure 10. Formulae of 1-deoxy-D-*threo*-pentulose, 1-deoxy-L-*threo*-pentulose and 5-methylthioribose 1-phosphate.

and Horii, 1978). Further studies on the mechanism of the heptulose formation (Yokota and Sasajima, 1983) revealed that 1-deoxy-D-*threo*-pentulose and 1-deoxy-L-*threo*-pentulose (*Figure 10*) were also formed from acetoin, methylacetoin or pyruvate plus D- or L-glyceraldehyde, respectively, by the cell-free extracts of the mutant strain (Yokota and Sasajima, 1984). 1-Deoxy-D-*threo*-pentulose has been reported to be a precursor of the thiazole moiety of thiamine biosynthesis in *Escherichia coli* (Thérisod, Fischer and Estramareix, 1981). Investigation of the origin of 1-deoxy-D-*threo*-pentulose and 1-deoxy-L-*threo*-pentulose in various micro-organisms demonstrated the presence in them of enzymes synthesizing the deoxy-pentuloses (Yokota and Sasajima, 1984).

Another unusual pentose derivative, 5-methylthioribose 1-phosphate (*Figure 10*) was produced from 5'-methylthioadenosine by a phosphorylase (Ferro, Wrobel and Nicolette, 1979).

Gene manipulation in pentose production

The isolation and utilization of mutants with blocked carbohydrate-metabolism pathways has been found to be of great value for the production of D-ribose, D-ribulose and xylitol. Gene manipulations such as DNA recombination and cell fusion now promise new methods to improve pentose-production processes. These techniques will improve yields and formation of microbial enzymes essential for the economic production of pentoses and their derivatives. Although industrial applications have not yet been achieved, the following notes indicate some of the topics which are now being intensively investigated.

Cloning of DNA fragments encoding D-xylose isomerase has been achieved in *Escherichia coli* (Maleszka, Wang and Schneider, 1982; Polaina *et al.*, 1982; Wovcha, Steuerwald and Brooks, 1983; Ohira, Takahashi and Saito, 1983) and in *Salmonella typhimurium* (Ghangas and Wilson, 1984). The activity of D-xylose isomerase of *E. coli* was amplified fivefold by employing the recombinant plasmid pUC1002 (Wovcha, Steuerwald and Brooks, 1983). D-Xylose isomerase activity of *S. typhimurium* carrying the plasmid pGG22 was one and a half times that of the wild-type strain (Ghangas and Wilson, 1984). The D-xylose operon is situated at the 78–79 min site of chromosomes of both *E. coli* (Maleszka, Wang and Schneider, 1982; Bachmann, 1983) and *S. typhimurium* (Shamanna and Sanderson, 1979b; Sanderson and Roth, 1983). Attempts are being made to construct a plasmid carrying the D-xylose isomerase gene and permitting expression in yeast (Ohira, Takahashi and Saito, 1983). If successful, this work could contribute to the economic production of ethanol from D-xylose.

Cloning of xylanase and β-xylosidase genes could contribute to the hydrolysis of xylan to D-xylose by xylan-degrading enzymes and could assist the utilization of plant biomass. In fact, genes encoding the xylanase and β-xylosidase of *Bacillus pumilus* have already been cloned and expressed in *Escherichia coli* (Panbangred *et al.*, 1983; Shinmyo *et al.*, 1983). One of the isolated plasmids, pOXN29R, expressed in *E. coli* β-xylosidase activity seven to eight times that shown in *B. pumilus*. Construction of a hybrid plasmid which carries the xylanase gene and expresses its activity in *B. subtilis* has also been reported, although the full paper has not yet appeared in the literature (Panbangred, Shinmyo and Okada, 1983; Shinmyo *et al.*, 1983): *B. subtilis* with the hybrid plasmid had xylanase activity which was two- to threefold that of *B. pumilus*. In this instance, xylanase was excreted into the culture medium, whereas expression of the gene in *E. coli* was limited to the cytoplasm. The xylanase gene of *Bacillus subtilis* was also cloned and expressed in *E. coli* (Bernier, Driguez and Desrochers, 1983). The intracellular xylanase produced by the transformed *E. coli* strain was purified and found to have an activity equivalent to one-quarter of the extracellular production by *B. subtilis*.

A hybrid plasmid, carrying genes for xylanase, β-xylosidase and D-xylose isomerase, and capable of expression in *Saccharomyces cerevisiae*, is envisaged because of its potential value in the production of ethanol from xylan.

Conclusions

The production of D-ribose, D-xylose, D-xylulose and xylitol are all of practical importance: D-ribose provides material for riboflavin synthesis; D-xylose and D-xylulose are intermediates in the utilization of xylan from biomass; xylitol is used in the treatment of diabetic patients.

Interest in pentose production on an industrial scale is now centred on D-ribose production for the synthesis of riboflavin for use in pharmaceuticals and as an animal-feed additive. The isolation and utilization of mutant strains, notably the transketolase-deficient mutant of *Bacillus* spp., which has been improved by further mutation, is being used in microbial processes of D-ribose production which are now replacing chemical methods. Mutants blocked in certain metabolic pathways have also been obtained for efficient production of D-ribulose and xylitol.

Future work involving genetic engineering techniques such as DNA recombination and cell fusion will help to develop and to improve processes for the production of pentoses as well as other useful compounds.

References

ABERHART, J., FEHR, T., JAIN, R.C., DE MAYO, P., MOTL, O., BACZYNSKYJ, L., GRACEY, D.E.F., MACLEAN, D.B. AND SZILÁGYI, I. (1970). Primycin. *Journal of the American Chemical Society* **92**, 5816–5817.

AGHORAMURTHY, K., SARMA, K.G. AND SESHADRI, T.R. (1961). Chemical investigation of indian lichens-XXIV. The chemical components of *Alectoria virens* Tayl. Constitution of a new depsidone, virensic acid. *Tetrahedron* **12**, 173–177.

AMANO, H. (1970). Separation of a substance containing ribulose in chick yolk at the early stage of chick embryo development. *Seikagaku* **42**, 68–73.

AMEMURA, A., HISAMATSU, M., GHAI, S.K. AND HARADA, T. (1981). Structural studies on a new polysaccharide, containing D-riburonic acid, from *Rhizobium meliloti* IFO 13336. *Carbohydrate Research* **91**, 59–65.

AMES, G.F.-L., SPUDICH, E.N. AND NIKAIDO, H. (1974). Protein composition of the outer membrane of *Salmonella typhimurium:* effect of lipopolysaccharide mutations. *Journal of Bacteriology* **117**, 406–416.

ANDERSON, R.L. AND ALLISON, D.P. (1965). Purification and characterization of D-lyxose isomerase. *Journal of Biological Chemistry* **240**, 2367–2372.

ANDERSON, F.B. AND HARRIS, G. (1963). The production of riboflavin and D-arabitol by *Debaryomyces subglobosus*. *Journal of General Microbiology* **33**, 137–146.

ANDERSON, R.L. AND WOOD, W.A. (1962). Pathway of L-xylose and L-lyxose degradation in *Aerobacter aerogenes*. *Journal of Biological Chemistry* **237**, 296–303.

ARCUS, A.C. AND EDSON, N.L. (1956). Polyol dehydrogenases. 2. The polyol dehydrogenases of *Acetobacter suboxydans* and *Candida utilis*. *Biochemical Journal* **64**, 385–394.

ASAI, T., DOI, M., KONO, T. AND FUKUDA, H. (1978). Kinetic study on the production of D-ribose by *Bacillus* sp. *Journal of Fermentation Technology* **56**, 91–95.

AVERY, O.T., MACLEOD, C.M. AND MCCARTY, M. (1944). Studies on the chemical nature of the substance inducing transformation of pneumococcal types. *Journal of Experimental Medicine* **79**, 137–158.

BACHMANN, B.J. (1983). Linkage map of *Escherichia coli* K-12, Edition 7. *Microbiological Reviews* **47**, 180–230.

BACKLUND, P.S., JR AND SMITH, R.A. (1981). Methionine synthesis from 5'-methylthioadenosine in rat liver. *Journal of Biological Chemistry* **256**, 1533–1535.

BARNETT, J.A. (1968). The catabolism of acyclic polyols by yeasts. *Journal of General Microbiology* **52**, 131–159.

BATLEY, M., PACKER, N.H. AND REDMOND, J.W. (1982). Configurations of glycosidic phosphates of lipopolysaccharide from *Salmonella minnesota* R595. *Biochemistry* **21**, 6580–6586.

BAYER, M.E., KOPLOW, J. AND GOLDFINE, H. (1975). Alterations in envelope structure of heptose-deficient mutants of *Escherichia coli* as revealed by freeze-etching. *Proceedings of the National Academy of Sciences of the United States of America* **72**, 5145–5149.

BENTLEY, H.R., CUNNINGHAM, K.G. AND SPRING, F.S. (1951). Cordycepin, a metabolic product from cultures of *Cordyceps militaris* (Linn.) Link. Part II. The structure of cordycepin. *Journal of the Chemical Society* **1951**, 2301–2305.

BERNHAUER, K. AND RIEDL-TŮMOVÁ, E. (1950). Oxidationen mittels Essigbakterien. 10. Mitteilung. Notiz über die Oxidation der enantiomorphen Formen der Xylose und Arabinose. *Biochemische Zeitschrift* **321**, 26–30.

BERNIER, R., JR, DRIGUEZ, H. AND DESROCHERS, M. (1983). Molecular cloning of a *Bacillus subtilis* xylanase gene in *Escherichia coli*. *Gene* **26**, 59–65.

BERNIER, R., JR, DESROCHERS, M., JURASEK, L. AND PAICE, M.G. (1983). Isolation and characterization of a xylanase from *Bacillus subtilis*. *Applied and Environmental Microbiology* **46**, 511–514.

BERTRAND, G. (1898a). Action de la bactérie du sorbose sur le sucre de bois. *Comptes rendus des séances de l'Académie des sciences* **127**, 124–127.

BERTRAND, G. (1898b). Action de la bactérie du sorbose sur les sucres aldèhydiques. *Comptes rendus des séances de l'Académie des sciences* **127**, 728–731.

BINKLEY, W.W. AND WOLFROM, M.L. (1950). Chromatographic fractionation of cane blackstrap molasses and of its fermentation residue. *Journal of the American Chemical Society* **72**, 4778–4782.

BOGUSLAWSKI, G. (1983). Purification and characterization of glucose isomerase from *Flavobacterium arborescens*. *Journal of Applied Biochemistry* **5**, 186–196.

BRINER, G.P., GREAM, G.E. AND RIGGS, N.V. (1960). Chemistry of australian lichens. I. Some constituents of *Parmelia conspersa* (Ehrh.) Arc., *Ramalina fraxinea* (L.) Ach., *Usnea barbata* (L.) Wigg., and *U. ceratina* Ach., from the New England region. *Australian Journal of Chemistry* **13**, 277–284.

BROWN, F., NEAL, D.J. AND WILKINSON, S.G. (1977). Presence of 3-*O*-methyl-L-xylose in the lipopolysaccharide of *Pseudomonas maltophilia* N.C.T.C. 10257. *Biochemical Journal* **163**, 173–175.

CAMYRE, K.P. AND MORTLOCK, R.P. (1965). Growth of *Aerobacter aerogenes* on D-arabinose and L-xylose. *Journal of Bacteriology* **90**, 1157–1158.

CARTER, C.E. (1951). Partial purification of a non-phosphorylytic uridine nucleosidase from yeast. *Journal of the American Chemical Society* **73**, 1508–1510.

CHAKRAVORTY, M., VEIGA, L.A., BACILA, M. AND HORECKER, B.L. (1962). Pentose metabolism in *Candida*. II. The diphosphopyridine nucleotide-specific polyol dehydrogenase of *Candida utilis*. *Journal of Biological Chemistry* **237**, 1014–1020.

CHANG, S.-C., WANG, H.-L. AND YANG, L.-W. (1963). The production of glycerol and arabitol by osmophilic yeasts. *Wei Sheng Wu Hsueh Pao* **9**, 334–343. (*Chemical Abstracts* **60**, 12407).

CHANG, S.-C., YANG, L.-W. AND WANG, H.-L. (1963). Studies on the production of glycerol and arabitol by osmophilic yeasts. II. Arabitol production by *Hansenula arabitolgenes* Fang. *Acta Microbiologica Sinica* **9**, 134–139 (*Biological Abstracts* **45**, 105778).

CHARGAFF, E. AND ANDERSON, R.J. (1930). Ein Polysaccharid aus den Lipoiden der Tuberkelbakterien. *Hoppe-Seyler's Zeitschrift für Physiologische Chemie* **191**, 172–178.

CHEN, W.-P. (1980a). Glucose isomerase. *Process Biochemistry* **15**, 30–35.

CHEN, W.-P. (1980b). Glucose isomerase. *Process Biochemistry* **15**, 36–41.

CHEN, W.P., ANDERSON, A.W. AND HAN, Y.W. (1979). Production of glucose isomerase by *Streptomyces flavogriseus*. *Applied and Environmental Microbiology* **37**, 324–331.

CHIANG, C. AND KNIGHT, S.G. (1960a). Metabolism of D-xylose by molds. *Nature* **188**, 79–81.

CHIANG, C. AND KNIGHT, S.G.(1960b). A new pathway of pentose metabolism. *Biochemical and Biophysical Research Communications* **3**, 554–559.

CHIANG, L.-C., HSIAO, H.-Y., UENG, P.P. AND TSAO, G.T. (1981). Enzymatic and microbial preparation of D-xylulose from D-xylose. *Applied and Environmental Microbiology* **42**, 66–69.

CHOU, C.C., LADISCH, M.R. AND TSAO, G.T. (1976). Studies on glucose isomerase from a *Streptomyces* species. *Applied and Environmental Microbiology* **32**, 489–493.

CLAEYSSENS, M., SAMAN, E., KERSTERS-HILDERSON, H. AND DE BRUYNE, C.K. (1975). β-Xylosidase from *Bacillus pumilus*. *Biochimica et biophysica acta* **405**, 475–481.

CLINE, A.L. AND HU, A.S.L. (1965). The isolation of three sugar dehydrogenases from a pseudomonad. *Journal of Biological Chemistry* **240**, 4488–4492.

COHEN, S.S. (1953). Studies on D-ribulose and its enzymatic conversion to D-arabinose. *Journal of Biological Chemistry* **201**, 71–84.

CUMMINS, C.S. (1956). Some observations on the nature of the antigens in the cell wall of *Corynebacterium diphtheriae*. *British Journal of Experimental Pathology* **35**, 166–180.

DAHMS, A.S. AND ANDERSON, R.L. (1969). 2-Keto-3-deoxy-L-arabonate aldolase and its role in a new pathway of L-arabinose degradation. *Biochemical and Biophysical Research Communications* **36**, 809–814.

DANNO, G. (1970). Studies on D-glucose-isomerizing enzyme from *Bacillus coagulans*, strain HN-68. Part V. Comparative study on the three activities of D-glucose, D-xylose and D-ribose isomerization of the crystalline enzymes. *Agricultural and Biological Chemistry* **34**, 1805–1814.

DANNO, G. (1971). Studies on D-glucose-isomerizing enzyme from *Bacillus coagulans*, strain HN-68. Part VI. The role of metal ions on the isomerization of D-glucose and D-xylose by the enzyme. *Agricultural and Biological Chemistry* **35**, 997–1006.

DAVID, J.D. AND WIESMEYER, H. (1970). Control of xylose metabolism in *Escherichia coli*. *Biochimica et biophysica acta* **201**, 497–499.

DEKKER, R.F.H. AND RICHARDS, G.N. (1976). Hemicellulases: their occurrence, purification, properties, and mode of action. *Advances in Carbohydrate Chemistry and Biochemistry* **32**, 277–352.

DION, H.W., WOO, P.W.K., WILLMER, N.E., KERN, D.L., ONAGA, J. AND FUSARI, S.A. (1972). Butirosin, a new aminoglycosidic antibiotic complex: isolation and characterization. *Antimicrobial Agents and Chemotherapy* **2**, 84–88.

DUNCAN, M.J. (1979). L-Arabinose metabolism in Rhizobia. *Journal of General Microbiology* **113**, 177–179.

EIDELS, L. AND OSBORN, M.J. (1971). Lipopolysaccharide and aldoheptose biosynthesis in transketolase mutants of *Salmonella typhimurium*. *Proceedings of the National Academy of Sciences of the United States of America* **68**, 1673–1677.

ESTEBAN, R., VILLANUEVA, J.R. AND VILLA, T.G. (1982). β-D-Xylanases of *Bacillus circulans* WL-12. *Canadian Journal of Microbiology* **28**, 733–739.

FERRO, A.J., WROBEL, N.C. AND NICOLETTE, J.A. (1979). 5-Methylthioribose 1-phosphate: a product of partially purified, rat liver 5′-methylthioadenosine phosphorylase activity. *Biochimica et biophysica acta* **570**, 65–73.

FLAKS, J.G. (1963). Nucleotide synthesis from 5-phosphoribosylpyrophosphate. In *Methods in Enzymology* (S.P. Colowick and N.O. Kaplan, Eds), volume 6, pp. 136–158. Academic Press, New York and London.

FOSTER, J.W. (1944). Microbiological aspects of riboflavin. III. Oxidation studies with *Pseudomonas riboflavina*. *Journal of Bacteriology* **48**, 97–111.

FRÈREJACQUE, M.M. (1939). Présence du d-arabitol dans *Fistulina hepatica*. *Comptes*

rendus des séances de l'Académie des sciences **208**, 1123–1124.

GALMARINI, O.L. AND DEULOFEU, V. (1961). Curamycin I. (1963) Isolation and characterization of some hydrolysis products. *Tetrahedron* **15**, 76–86.

GEHRKE, M. AND AICHNER, F.X. (1927). Über das Arabinal. *Chemische Berichte* **60**, 918–922.

GERBER, N.N. AND LECHEVALIER, H.A. (1962). 3'-Amino-3'-deoxyadenosine, an antitumor agent from *Helminthosporium* sp. *Journal of Organic Chemistry* **27**, 1731–1732.

GHANGAS, G.S. AND WILSON, D.B. (1984). Isolation and characterization of the *Salmonella typhimurium* LT2 xylose regulon. *Journal of Bacteriology* **157**, 158–164.

GIOVENCO, S., MORISI, F. AND PANSOLLI, P. (1973). Properties of free and immobilized glucose isomerase. *FEBS Letters* **36**, 57–60.

GMEINER, J. (1977). The ribitol-phosphate-containing lipopolysaccharide from *Proteus mirabilis*, strain D52. Investigations on the structure of *O*-specific chains. *European Journal of Biochemistry* **74**, 171–180.

GMEINER, J., MAYER, H., FROMME, I., KOTELKO, K. AND ZYCH, K. (1977). Ribitol-containing lipopolysaccharides from *Proteus mirabilis* and their serological relationship. *European Journal of Biochemistry* **72**, 35–40.

GODIN, P. (1953a). Étude du métabolisme terminaire de *Penicillium brevi-compactum* I. Analyse chromatographique du milieu de culture. *Biochimica et biophysica acta* **11**, 114–118.

GODIN, P. (1953b). Étude du métabolisme terminaire de *Penicillium brevi-compactum*. II. Analyse chromatographique de la solution glucosée substituée au milieu de culture initial. *Biochimica et biophysica acta* **11**, 119–121.

GONG, C.-S., CHEN, L.-F. AND TSAO, G.T. (1981). Quantitative production of xylitol from D-xylose by a high-xylitol producing yeast mutant *Candida tropicalis* HXP2. *Biotechnology Letters* **3**, 125–130.

GONG, C.-S., CHEN, L.F., FLICKINGER, M.C. AND TSAO, G.T. (1981a). Conversion of hemicellulose carbohydrates. *Advances in Biochemical Engineering/Biotechnology* **20**, 93–118.

GONG, C.-S., CHEN, L.-F., FLICKINGER, M.C., CHIANG, L.-C. AND TSAO, G.T. (1981b). Production of ethanol from D-xylose by using D-xylose isomerase and yeasts. *Applied and Environmental Microbiology* **41**, 430–436.

GREEN, M. AND COHEN, S.S. (1956). Enzymatic conversion of L-fucose to L-fuculose. *Journal of Biological Chemistry* **219**, 557–568.

GUARINO, A.J. AND KREDICH, N.M. (1963). Isolation and identification of 3'-amino-3'-deoxyadenosine from *Cordyceps militaris*. *Biochimica et biophysica acta* **68**, 317–319.

HAJNY, G.J. (1964). D-Arabitol production by *Endomycopsis chodati*. *Applied and Environmental Microbiology* **12**, 87–92.

HANN, R.M., TILDEN, E.B. AND HUDSON, C.S. (1938). The oxidation of sugar alcohols by *Acetobacter suboxydans*. *Journal of the American Chemical Society* **60**, 1201–1203.

HANSSEN, L., VAN REGENMORTEL, A. AND VERACHTERT, H. (1972). pH-Dependent polyol production in *Moniliella tomentosa*. *Applied and Environmental Microbiology* **24**, 831–833.

HARADA, T. (1984). Isoamylase and its industrial significance in the production of sugars from starch. In *Biotechnology and Genetic Engineering Reviews* (G.E. Russell, Ed.), volume 1, pp. 39–63. Intercept, Newcastle upon Tyne.

HASE, S. AND RIETSCHEL, E.T. (1977). The chemical structure of the lipid A component of lipopolysaccharides from *Chromobacterium violaceum* NCTC 9694. *European Journal of Biochemistry* **75**, 23–34.

HATTORI, K. AND SUZUKI, T. (1974a). Microbial production of D-arabitol by n-alkane-grown *Candida tropicalis*. *Agricultural and Biological Chemistry* **38**, 1875–1881.

HATTORI, K. AND SUZUKI, T. (1974b). Enzymatic studies on the conversion of citric acid

fermentation to polyol fermentation in hydrocarbon-assimilating yeast *Candida zeylanoides*. *Agricultural and Biological Chemistry* **38**, 2419–2424.

HAYASHI, H. (1971). Separation of a substance containing D-ribulose in human follicular fluid. *Japanese Journal of Fertility and Sterility* **16**, 161–165.

HAYASHIDA, A. (1938). Nachweis der Aero-Pentosedehydrase (Pentoseoxidase) und Katalase bei Fusarien. *Biochemische Zeitschrift* **298**, 169–178.

HAWORTH, N., KENT, P.W. AND STACEY, M. (1948a). The constitution of a specific somatic polysaccharide from *M. tuberculosis* (Human strain). *Journal of the Chemical Society* **1948**, 1211–1220.

HAWORTH, N., KENT, P.W. AND STACEY, M. (1948b). The constitution of a lipid-bound polysaccharide from *M. tuberculosis* (Human strain). *Journal of the Chemical Society* **1948**, 1220–1224.

HEATH, E.C., HORECKER, B.L., SMYRNIOTIS, P.Z. AND TAKAGI, Y. (1958). Pentose fermentation by *Lactobacillus plantarum*. *Journal of Biological Chemistry* **231**, 1031–1037.

HEPPEL, L.A. AND HILMOE, R.J. (1952). Phosphorolysis and hydrolysis of purine ribosides by enzymes from yeast. *Journal of Biological Chemistry* **198**, 683–694.

HERSHEY, A.D. AND CHASE, M. (1952). Independent functions of viral protein and nucleic acid in growth of bacteriophage. *Journal of General Physiology* **36**, 39–56.

HIGASHI, K., KUSAKABE, I., YASUI, T., ISHIYAMA, T. AND OKIMOTO, Y. (1983). Arabinan-degrading enzymes from *Streptomyces diastatochromogenes* 065. *Agricultural and Biological Chemistry* **47**, 2903–2905.

HOCHSTER, R.M. AND NOZZOLILLO, C.G. (1961). The breakdown of ribonucleosides in extracts of the phytopathogenic organism *Xanthomonas phaseoli*. *Canadian Journal of Microbiology* **7**, 389–397.

HOCHSTER, R.M. AND WATSON, R.W. (1953). Xylose isomerase. *Journal of the American Chemical Society* **75**, 3284–3285.

HOCHSTER, R.M. AND WATSON, R.W. (1954). Enzymatic isomerization of D-xylose to D-xylulose *Archives of Biochemistry and Biophysics* **48**, 120–129.

HOEKSEMA, H. AND BACZYNSKYJ, L. (1976). A new metabolite from *Streptomyces hygroscopicus*. II. Identification as l-deoxy-D-*threo*-pentulose. *Journal of Antibiotics* **XXIX**, 688–691.

HÖFER, M., BETZ, A. AND KOTYK, A. (1971). Metabolism of the obligatory aerobic yeast *Rhodotorula gracilis* IV. Induction of an enzyme necessary for D-xylose catabolism. *Biochemica et biophysica acta* **252**, 1–12.

HOFFMAN, J., LINDBERG, B., HOFSTAD, T. AND LYGRE, H. (1977). Structural studies of the polysaccharide antigen of *Eubacterium saburreum*, strain L.452. *Carbohydrate Research* **58**, 439–442.

HOFSTAD, T. AND LYGRE, H. (1977). Composition and antigenic properties of a surface polysaccharide isolated from *Eubacterium saburreum*, strain L 452. *Acta pathologica, microbiologica et immunologica scandinavica* Section B, **85**, 14–17.

HOLDSWORTH, E.S. (1952). The nature of the cell wall of *Corynebacterium diphtheriae*. Isolation of an oligosaccharide. *Biochimica et biophysica acta* **9**, 19–28.

HORITSU, H. AND TOMOYEDA, M. (1966). Pentose metabolism by *Candida utilis*. Part III. Polyol: NAD oxidoreductase. *Agricultural and Biological Chemistry* **30**, 962–966.

HORITSU, H., SASAKI, I. AND TOMOYEDA, M. (1970). Pentose metabolism in *Candida utilis*. Part V. L-Arabinose ketol isomerase. *Agricultural and Biological Chemistry* **34**, 676–683.

HSIAO, H.-Y., CHIANG, L.-C., CHEN, L.-F. AND TSAO, G.T. (1982). Effects of borate on isomerization and yeast fermentation of high xylulose solution and acid hydrolysate of hemicellulose. *Enzyme and Microbiological Technology* **4**, 25–31.

HU, A.S.L. AND CLINE, A.L. (1964). The regulation of some sugar dehydrogenases in a pseudomonad. *Biochimica et biophysica acta* **93**, 237–245.

HURWITZ, J., HEPPEL, L.A. AND HORECKER, B.L. (1957). The enzymatic cleavage of adenylic acid to adenine and ribose 5-phosphate. *Journal of Biological Chemistry* **226**, 525–540.

ICHIMURA, M., HIROSE, Y., KATSUYA, N. AND YAMADA, K. (1965). Production and properties of D-glucose isomerase from *Brevibacterium pentoso-aminoacidicum*. *Journal of the Agricultural and Chemical Society of Japan* **139**, 291–298.

IKEDA, S. AND YAMADA, K. (1963a). Studies on xylonic acid fermentation. Part I. Isolation of the acid-producing mold strain and identification of D-xylonic acid in fermentation broth. *Journal of the Agricultural and Chemical Society of Japan* **37**, 514–517.

IKEDA, S. AND YAMADA, K. (1963b). Studies on xylonic acid fermentation. Part II. On taxonomical characteristics of the strain and some cultural conditions. *Journal of the Agricultural and Chemical Society of Japan* **37**, 518–523.

IMADA, A. (1970). Metabolism of pyrimidine nucleosides and nucleotides by microorganisms. *Journal of the Takeda Research Laboratories* **29**, 722–775.

IMADA, A., KUNO, M. AND IGARASHI, S. (1967). Degradation of pyrimidine nucleotides by pyrimidine 5′-nucleotide phosphoribo (deoxyribo) hydrolase of *Streptomyces*. *Amino Acid and Nucleic Acid* **15**, 49–58.

IMADA, A., NAKAO, Y., NOGAMI, I., IGARASHI, S. AND OGATA, K. (1963). Excretion of 5′-nucleotides by bacteria. Part IV. Excretion of 5′-nucleotides by *Pseudomonas graveolens*. *Amino Acid and Nucleic Acid* **8**, 118–126.

IRVIN, R.T., CHATTERJEE, A.K., SANDERSON, K.E. AND COSTERTON, J.W. (1975). Comparison of the cell envelope structure of a lipopolysaccharide-defective (heptose-deficient) strain and a smooth strain of *Salmonella typhimurium*. *Journal of Bacteriology* **124**, 930–941.

IZUMORI, K. AND YAMANAKA, K. (1974). Purification and crystallization of D-arabinose (L-fucose) isomerase from *Aerobacter aerogenes* by polyethylene glycol. *Agricultural and Biological Chemistry* **38**, 267–273.

IZUMORI, K., MITCHELL, M. AND ELBEIN, A.D. (1976). Evidence that the isomerization of D-ribose and L-rhamnose is catalyzed by the same enzyme in *Mycobacterium smegmatis*. *Journal of Bacteriology* **126**, 553–555.

IZUMORI, K., REES, A.W. AND ELBEIN, A.D. (1975). Purification, crystallization, and properties of D-ribose isomerase from *Mycobacterium smegmatis*. *Journal of Biological Chemistry* **250**, 8085–8087.

IZUMORI, K., UEDA, Y. AND YAMANAKA, K. (1978). Pentose metabolism in *Mycobacterium smegmatis*: comparison of L-arabinose isomerases induced by L-arabinose and D-galactose. *Journal of Bacteriology* **133**, 413–414.

IZUMORI, K., YAMANAKA, K. AND ELBEIN, A.D. (1976). Pentose metabolism in *Mycobacterium smegmatis*: specificity of induction of pentose isomerases. *Journal of Bacteriology* **128**, 587–591.

JEFFRIES, T.W. (1983). Utilization of xylose by bacteria, yeasts, and fungi. *Advances in Biochemical Engineering/Biotechnology* **27**, 1–32.

JOHNSON, E.A., VILLA, T.G., LEWIS, M.J. AND PHAFF, H.J. (1979). Lysis of the cell wall of the yeast *Phaffia rhodozyma* by a lytic enzyme complex from *Bacillus circulans* WL-12. *Journal of Applied Biochemistry* **1**, 273–282.

JONES, J.K.N. (1939). The constitution of cherry gum. Part I. Composition. *Journal of the Chemical Society* **1939**, 558–563.

JONES, J.K.N. (1947). The constitution of cherry gum. Part II. The products of hydrolysis of methylated cherry gum. *Journal of the Chemical Society* **1947**, 1055–1059.

JOSEPHSON, B.L. AND FRAENKEL, D.G. (1969). Transketolase mutants of *Escherichia coli*. *Journal of Bacteriology* **100**, 1289–1295.

JOSEPHSON, B.L. AND FRAENKEL, D.G. (1974). Sugar metabolism in transketolase mutants of *Escherichia coli*. *Journal of Bacteriology* **118**, 1082–1089.

KAJI, A. AND SAHEKI, T. (1975). Endo-arabinanase from *Bacillus subtilis* F-11. *Biochimica et biophysica acta* **410**, 354–360.

KAJI, A. AND SHIMOKAWA, K. (1984). New exo-type arabinase from *Erwinia carotovora* IAM 1024. *Agricultural and Biological Chemistry* **48**, 67–72.

KAJI, A., SATO, M. AND TSUTSUI, Y. (1981). An α-L-arabinofuranosidase produced by

wild-type *Streptomyces* sp. No. 17–1. *Agricultural and Biological Chemistry* **45**, 925–931.

KAUFFMANN, F., JANN, B., KRÜGER, L., LÜDERITZ, O. AND WESTPHAL, O. (1962). Zur Immunchemie der O-Antigene von Enterobacteriaceae. *Zentralblatt für Bakteriologie und Parasitenkunde* Abteilung 1, **186**, 509–516.

KIESSLING, H., LINDBERG, B. AND MCKAY, J. (1962). Some products of the metabolism of D-xylose by *Pullularia pullulans*. *Acta chemica scandinavica* **16**, 1858–1862.

KOMAE, K., KAJI, A. AND SATO, M. (1982). An α-L-arabinofuranosidase from *Streptomyces purpurascens* IFO 3389. *Agricultural and Biological Chemistry* **46**, 1899–1905.

KOPLOW, J. AND GOLDFINE, H. (1974). Alterations in the outer membrane of the cell envelope of heptose-deficient mutants of *Escherichia coli*. *Journal of Bacteriology* **117**, 527–543.

KUBAČKOVÁ, M., KARÁCSONYI, Š. AND VÁRADI, J. (1975). Studies on xylanase from *Basidiomycetes*. *Folia Microbiologica* **20**, 29–37.

KUHN, R., REINEMUND, K., WEYGAND, F. AND STRÖBELE, R. (1935). Über die Synthese des Lactoflavins (Vitamin B_2). *Chemische Berichte* **68**, 1765–1774.

KUNINAKA, A. (1956). Studies on the decomposition of nucleic acid by microorganisms. Part V. On the enzymatic degradation of inosinic acid by *Aspergillus oryzae*. *Journal of the Agricultural and Chemical Society of Japan* **30**, 583–588.

KUNINAKA, A. (1957). Enzymic degradation of yeast ribonucleic acid and its related compounds by *Aspergillus oryzae*. *Journal of General and Applied Microbiology* **3**, 55–92.

KUNINAKA, A. (1959). Studies on the decomposition of nucleic acid by microorganisms. Part VI. On the ribosidase of *Aspergillus oryzae* acting on 6-hydroxypurine ribonucleosides and their 5'-monophosphates. *Agricultural and Biological Chemistry* **23**, 281–288.

KUSAKABE, I., YASUI, T. AND KOBAYASHI, T. (1975). Some properties of araban degrading enzymes produced by microorganisms and enzymatic preparation of arabinose from sugar beet pulp. *Journal of the Agricultural and Chemical Society of Japan* **49**, 295–305.

LAMPEN, J.O. AND WANG, T.P. (1952). The mechanism of action of *Lactobacillus pentosus* nucleosidase. *Journal of Biological Chemistry* **198**, 385–395.

LAWRENCE, N.L. (1955). The cleavage of adenosine by spores of *Bacillus cereus*. *Journal of Bacteriology* **70**, 577–582.

LEE, N. AND ENGLESBERG, E. (1962). Dual effects of structural genes in *Escherichia coli*. *Proceedings of the National Academy of Sciences of the United States of America* **48**, 335–348.

LIN, E.C.C. (1961). An inducible D-arabitol dehydrogenase from *Aerobacter aerogenes*. *Journal of Biological Chemistry* **236**, 31–36.

LINDBERG, B., MISIORNY, A. AND WACHTMEISTER, C.A. (1953). Studies on the chemistry of lichens IV. Investigation of the low-molecular carbohydrate constituents of different lichens. *Acta chemica scandinavica* **7**, 591–595.

LOCKWOOD, L.B. AND NELSON, G.E.N. (1946). The oxidation of pentoses by *Pseudomonas*. *Journal of Bacteriology* **52**, 581–586.

LYR, H. (1962). Nachweis einer Xylose-Oxidase (Xylose-O_2-Transhydrogenase) bei höheren Pilzen. *Enzimologia* **24**, 69–80.

MCCRACKEN, L.D. AND GONG, C.-S. (1983). D-Xylose metabolism by mutant strains of *Candida* sp. *Advances in Biochemical Engineering/Biotechnology* **27**, 33–55

MALESZKA, R., WANG, P.Y. AND SCHNEIDER, H. (1982). A ColE1 hybrid plasmid containing *Escherichia coli* genes complementing D-xylose negative mutants of *Escherichia coli* and *Salmonella typhimurium*. *Canadian Journal of Biochemistry* **60**, 144–151.

MARCUS, L. AND MARR, A.G. (1961). Polyol dehydrogenases of *Azotobacter agilis*. *Journal of Bacteriology* **82**, 224–232.

MARSHALL, R.O. AND KOOI, E.R. (1957). Enzymatic conversion of D-glucose to

D-fructose. *Science* **125**, 648–649.

MASUO, E. AND NOZAKI, Y. (1956). On the oxidation of some hexoses and pentoses by *Aerobacter aerogenes*. Studies on oxidation of carbohydrates by bacteria (VII). *Annual Report of Shionogi Research Laboratories* **6**, 110–114.

MATSUO, M., YASUI, T. AND KOBAYASHI, T. (1975). Production and saccharifying action for xylan of xylanase from *Malbranchea pulchella* var *sulfurea*. No. 48. *Journal of the Agricultural and Chemical Society of Japan* **49**, 263–270.

MATSUO, M., YASUI, T. AND KOBAYASHI, T. (1977a). Purification and some properties of β-xylosidase from *Malbranchea pulchella* var. *sulfurea* No. 48. *Agricultural and Biological Chemistry* **41**, 1593–1599.

MATSUO, M., YASUI, T. AND KOBAYASHI, T. (1977b). Enzymatic properties of β-xylosidase from *Malbranchea pulchella* var *sulfurea* No. 48. *Agricultural and Biological Chemistry* **41**, 1601–1606.

MAXIM, M. (1930). Die Kohlenhydratfracktion der Tuberkelbazillen und des Tuberkulin. d-Mannose und d-Arabinose. *Biochemische Zeitschrift* **223**, 404–407.

MELLINGHOFF, C.H. (1961). Über die Verwendbarkeit des Xylit als Ersatzzucker bei Diabetikern. *Klinische Wochenschrift* **39**, 447.

MISAWA, M., NARA, T. AND KINOSHITA, S. (1967). Bacterial accumulation of ribulose and xylulose. *Agricultural and Biological Chemistry* **31**, 611–615.

MITSUHASHI, S. AND LAMPEN, J.O. (1953). Conversion of D-xylose to D-xylulose in extracts of *Lactobacillus pentosus*. *Journal of Biological Chemistry* **204**, 1011–1018.

MIYANO, K., ISHIBASHI, M., KUNITA, N., TAKEDA, Y. AND MIWATANI, T. (1983). Demonstration of the presence of alditols and galacturonic acid in *Vibrio parahaemolyticus* O10 lipopolysaccharide. *FEMS Microbiology Letters* **20**, 225–228.

MORAN, J.W. AND WITTER, L.D. (1979). Effect of sugars on D-arabitol production and glucose metabolism in *Saccharomyces rouxii*. *Journal of Bacteriology* **138**, 823–831.

MORTLOCK, R.P. AND OLD, D.C. (1979). Utilization of D-xylose by wild-type strains of *Salmonella typhimurium*. *Journal of Bacteriology* **137**, 173–178.

MORTLOCK, R.P. AND WOOD, W.A. (1964). Metabolism of pentoses and pentitols by *Aerobacter aerogenes*. I. Demonstration of pentose isomerase, pentulokinase, and pentitol dehydrogenase enzyme families. *Journal of Bacteriology* **88**, 838–844.

MORTLOCK, R.P. AND WOOD, W.A. (1966). 2-Ketopentoses. In *Methods in Enzymology* (S.P. Colowick and N.O. Kaplan, Eds), volume 9, pp. 39–41. Academic Press, New York and London.

MORTLOCK, R.P., FOSSITT, D.D. AND WOOD, W.A. (1965). A basis for utilization of unnatural pentoses and pentitols by *Aerobacter aerogenes*. *Proceedings of the National Academy of Sciences of the United States of America* **54**, 572–579.

MORTLOCK, R.P., FOSSITT, D.D., PETERING, D.H. AND WOOD, W.A. (1965). Metabolism of pentoses and pentitols by *Aerobacter aerogenes*. III. Physical and immunological properties of pentitol dehydrogenases and pentulokinases. *Journal of Bacteriology* **89**, 129–135.

MOSES, V. AND FERRIER, R.J. (1962). The biochemical preparation of D-xylulose and L-ribulose. Details of the action of *Acetobacter suboxidans* on D-arabitol, ribitol and other polyhydroxy compounds. *Biochemical Journal* **83**, 8–14.

MÜHLRADT, F., WRAY, V. AND LEHMANN, V. (1977). A ^{31}P-nuclear-magnetic-resonance study of the phosphate groups in lipopolysaccharide and lipid A from *Salmonella*. *European Journal of Biochemistry* **81**, 193–203.

NAGAOKA, S. (1973). Separation of a substance containing D-ribulose in human seminal fluid. *Japanese Journal of Fertility and Sterility* **18**, 67–74.

NAKANISHI, K., YASUI, T. AND KOBAYASHI, T. (1976). A preliminary experiment on the xylanase production by *Streptomyces* sp. *Journal of Fermentation Technology* **54**, 813–817.

NATAKE, M. AND YOSHIMURA, S. (1963). Studies on glucose isomerase of bacteria. Part I. Formation of glucose isomerase by *Aerobacter aerogenes*, strain HN-56, and its relationship to xylose isomerase. *Agricultural and Biological Chemistry* **27**, 342–348.

NATAKE, M. AND YOSHIMURA, S. (1964a). Studies on glucose isomerase of bacteria. Part II. The glucose isomerizing activity of *Escherichia intermedia*, strain HN-500. *Agricultural and Biological Chemistry* **28**, 505–509.

NATAKE, M. AND YOSHIMURA, S. (1964b). Studies on glucose isomerase of bacteria. Part III. The mode of action of glucose isomerase from *Escherichia intermedia*, strain HN-500. *Agricultural and Biological Chemistry* **28**, 510–516.

NOGAMI, I., KIDA, M., IIJIMA, T. AND YONEDA, M. (1968). Studies on the fermentative production of purine derivatives. Part I. Derivation of guanosine and inosine-producing mutants from a *Bacillus* strain. *Agricultural and Biological Chemistry* **32**, 144–152.

OGATA, K. (1976). History and prospects. In *Microbial Production of Nucleic Acid-Related Substances* (K. Ogata, S. Kinoshita, T. Tsunoda and K. Aida, Eds), pp. xiii–xviii. Kodansha Ltd., Tokyo and John Wiley & Sons, New York, London, Sydney, Toronto.

OHIRA, K., TAKAHASHI, H. AND SAITO, H. (1983). Physical map of xylose operon and its use. In *Abstracts of the Annual Meeting of the Society of Fermentation Technology, Osaka, Japan, 7–9 November 1983* (H. Taguchi *et al.*, Eds), p. 47. Society of Fermentation Technology, Japan.

OHSUGI, M., TOCHIKURA, T. AND OGATA, K. (1970). The production of D-xylonic acid by *Micrococcus* sp. *Agricultural and Biological Chemistry* **34**, 357–363.

OLIVER, E.J. AND MORTLOCK, R.P. (1971). Metabolism of D-arabinose by *Aerobacter aerogenes:* purification of the isomerase. *Journal of Bacteriology* **108**, 293–299.

OLIVER, E.J., BISSON, T.M., LEBLANC, D.J. AND MORTLOCK, R.P. (1969). D-Ribulose production by a mutant of *Aerobacter aerogenes*. *Analytical Biochemistry* **27**, 300–305.

ŌMURA, S., KATAGIRI, M., ATSUMI, K., HATA, T., JAKUBOWSKI, A.A., SPRINGS, E.B. AND TISHLER, M. (1974). Structure of prumycin. *Journal of the Chemical Society Perkin Transactions I* **1974**, 1627–1631.

ŌNISHI, H. (1960a). Studies on osmophilic yeasts. Part VII. Production of polyalcohols by *Saccharomyces rouxii* in the concentrated media of sodium chloride and sugars, and identification of polyalcohols produced. *Agricultural and Biological Chemistry* **24**, 126–130.

ŌNISHI, H. (1960b). Studies on osmophilic yeasts. Part VIII. Polyalcohol production by various genera and species of yeasts. *Agricultural and Biological Chemistry* **24**, 131–140.

ŌNISHI, H. AND PERRY, M.B. (1965). The production of *meso-glycero-ido*-heptitol and D-*glycero*-D-*ido*-heptitol by *Pichia miso*. *Canadian Journal of Microbiology* **11**, 929–934.

ŌNISHI, H. AND SAITO, N. (1962). Studies on osmophilic yeasts. Part XIV. Partial purification of polyol dehydrogenase from *Pichia miso* and the properties of this enzyme. *Agricultural and Biological Chemistry* **26**, 245–251.

ŌNISHI, H. AND SUZUKI, T. (1966). The production of xylitol, L-arabitol, and ribitol by yeasts. *Agricultural and Biological Chemistry* **30**, 1139–1144.

ŌNISHI, H. AND SUZUKI, T. (1969). Microbial production of xylitol from glucose. *Applied and Environmental Microbiology* **18**, 1031–1035.

ONISHI, H., SAITO, N. AND KOSHIYAMA, I. (1961). Studies on osomphilic yeasts. Part XI. Various factors affecting polyalcohol production by *Pichia miso*. *Agricultural and Biological Chemistry* **25**, 124–130.

PAICE, M.G., JURASEK, L., CARPENTER, M.R. AND SMILLIE, L.B. (1978). Production, characterization, and partial amino acid sequence of xylanase A from *Schizophyllum commune*. *Applied and Environmental Microbiology* **36**, 802–808.

PALLERONI, N.J. AND DOUDOROFF, M. (1957). Metabolism of carbohydrates by *Pseudomonas saccharophila* III. Oxidation of D-arabinose. *Journal of Bacteriology* **74**, 180–185.

PANBANGRED, W., SHINMYO, A. AND OKADA, H. (1983). Expression of xylanase gene of *Bacillus pumilus* in *Bacillus subtilis*. In *Abstracts of the Annual Meeting of the*

Society of Fermentation Technology, Osaka, Japan, 7–9 November 1983 (H. Taguchi *et al.*, Eds), p. 55. Society of Fermentation Technology, Japan.

PANBANGRED, W., KONDO, T., NEGORO, S., SHINMYO, A. AND OKADA, H. (1983). Molecular cloning of the genes for xylan degradation of *Bacillus pumilus* and their expression in *Escherichia coli*. *Molecular and General Genetics* **192**, 335–341.

PEDROSA, F.O. AND ZANCAN, G. (1974). L-Arabinose metabolism in *Rhizobium japonicum*. *Journal of Bacteriology* **119**, 336–338.

PETERSON, W.H., HENDERSHOT, W.F. AND HAJNY, G.J. (1958). Factors affecting production of glycerol and D-arabitol by representative yeasts of the genus *Zygosaccharomyces*. *Applied and Environmental Microbiology* **6**, 349–357.

POLAINA, J., WIGGS, M., LASTICK, S., VILLET, R.H. AND GROHMANN, K. (1982). Recombinant DNA technology for ethanolic xylose fermentation. *Abstracts of the Annual Meeting of the American Chemical Society* **1982**, CARB 29.

POSTMA, P.W. AND ROSEMAN, S. (1976). The bacterial phosphoenolpyruvate: sugar phosphotransferase system. *Biochimica et biophysica acta* **457**, 213–257.

POULSEN, P.B. (1984). Current applications of immobilized enzymes for manufacturing purposes. In *Biotechnology and Genetic Engineering Reviews* (G.E. Russell, Ed.), volume 1, pp. 121–140. Intercept, Newcastle upon Tyne.

POWELL, J.F. AND HUNTER, J.R. (1956). Adenosine deaminase and ribosidase in spores in *Bacillus cereus*. *Biochemical Journal* **62**, 381–387.

PRIMROSE, S.B. AND RONSON, C.W. (1980). Polyol metabolism by *Rhizobium trifolii*. *Journal of Bacteriology* **141**, 1109–1114.

PRINCE, R. AND REICHSTEIN, T. (1937). Synthese des d-Xylonsäure. *Helvetica chimica acta* **20**, 101–109.

REBERS, P.A. AND HEIDELBERGER, M. (1959). The specific polysaccharide of type VI *Pneumococcus*. I. Preparation, properties and reactions. *Journal of the American Chemical Society* **81**, 2415–2419.

REBERS, P.A. AND HEIDELBERGER, M. (1961). The specific polysaccharide of type VI *Pneumococcus*. II. The repeating unit. *Journal of the American Chemical Society* **83**, 3056–3059.

REICHSTEIN, T. (1934). l-Adonose (1-Erythro-2-keto-pentose). *Helvetica chimica acta* **17**, 996–1002.

ROBERTS, W.K., BUCHANAN, J.G. AND BADDILEY, J. (1963). The specific substance from *Pneumococcus* type 34(41). The structure of a phosphorus-free repeating unit. *Biochemical Journal* **88**, 1–7.

SAIER, M.H., JR (1977). Bacterial phosphoenolpyruvate: sugar phosphotransferase systems: structural, functional, and evolutionary interrelationships. *Microbiological Reviews* **41**, 856–871.

SAITO, N. AND SUGIYAMA, S. (1964). Production of dihydroxyacetone and other ketoses by *Brevibacterium fuscum*. *Agricultural and Biological Chemistry* **28**, 48–55.

SAITO, N. AND SUGIYAMA, S. (1966). D-Ribose formation by *Pseudomonas reptilivora*. *Agricultural and Biological Chemistry* **30**, 841–846.

SAKAI, T., WATANABE, T. AND CHIBATA, I. (1968). Metabolism of pyrimidine nucleotides in bacteria. *Journal of Fermentation Technology* **46**, 202–213.

SAKAI, T., WATANABE, T. AND CHIBATA, I. (1971). Metabolism of pyrimidine nucleotides in a microorganism. III. Enzymatic production of ribose 5-phosphate from uridine 5′-monophosphate by *Pseudomonas oleovorans*. *Applied and Environmental Microbiology* **22**, 1085–1090.

SANCHEZ, S. AND SMILEY, K.L. (1975). Properties of D-xylose isomerase from *Streptomyces albus*. *Applied and Environmental Microbiology* **29**, 745–750.

SANDERSON, K.E. AND ROTH, J.R. (1983). Linkage map of *Salmonella typhimurium*, Edition VI. *Microbiological Reviews* **47**, 410–453.

SANO, K., YOKOZEKI, K. AND MITSUGI, K. (1977a). Enzymatic production of 5-amino-4-imidazole-carboxamide from 5-amino-4-imidazole-carboxamide-riboside by *Bacillus thiaminolyticus*. Optimal conditions for the enzyme formation and the enzymatic reaction. *Agricultural and Biological Chemistry* **41**, 2331–2334.

SANO, K., YOKOZEKI, K. AND MITSUGI, K. (1977b). Screening of micro-organisms producing 5-amino-4-imidazole-carboxamide and D-ribose from 5-amino-4-imidazole-carboxamide-riboside. *Agricultural and Biological Chemistry* **41**, 2463–2464.

SASAJIMA, K. (1976). D-Ribose. In *Microbial Production of Nucleic Acid-Related Substances* (K. Ogata, S. Kinoshita, T. Tsunoda and K. Aida, Eds), pp. 199–204. Kodansha Ltd., Tokyo and John Wiley & Sons, New York, London, Sydney, Toronto.

SASAJIMA, K. AND KUMADA, T. (1979). Deficiency of D-glucose transport in transketolase mutant of *Bacillus subtilis*. *Institute for Fermentation Research Communications* **9**, 17–26.

SASAJIMA, K. AND KUMADA, T. (1981a). Change in the regulation of enzyme synthesis under catabolite repression in *Bacillus subtilis* pleiotropic mutant lacking transketolase. *Agricultural and Biological Chemistry* **45**, 2005–2012.

SASAJIMA, K. AND KUMADA, T. (1981b). Cell surface change of *Bacillus subtilis* pleiotropic mutant lacking transketolase. *Institute for Fermentation Research Communications* **10**, 3–9.

SASAJIMA, K. AND KUMADA, T. (1983a). Cell surface change of *Bacillus subtilis* mutant lacking transketolase: properties of various revertant strains. *Institute for Fermentation Research Communications* **11**, 3–9.

SASAJIMA, K. AND KUMADA, T. (1983b). Deficiency of flagellation in a *Bacillus subtilis* pleiotropic mutant lacking transketolase. *Agricultural and Biological Chemistry* **47**, 1375–1376.

SASAJIMA, K. AND SINSKEY, A.J. (1979). Oxidation of L-glucose by a pseudomonad. *Biochimica et biophysica acta* **571**, 120–126.

SASAJIMA, K. AND YONEDA, M. (1971). Carbohydrate metabolism mutants of a *Bacillus* species. Part II. D-Ribose accumulation by pentose phosphate pathway mutants. *Agricultural and Biological Chemistry* **35**, 509–517.

SASAJIMA, K. AND YONEDA, M. (1974). D-Sedoheptulose 7-phosphate: D-glyceraldehyde 3-phosphate glycolaldehyde transferase and D-ribulose 5-phosphate 3-epimerase mutants of a *Bacillus* species. *Agricultural and Biological Chemistry* **38**, 1305–1310.

SASAJIMA, K., KUMADA, T. AND YOKOTA, A. (1977). A pleiotropy in carbohydrate metabolism of *Bacillus subtilis* mutant lacking transketolase. *Institute for Fermentation Research Communications* **8**, 69–77.

SASAJIMA, K., NOGAMI, I. AND YONEDA, M. (1970). Carbohydrate metabolism mutants of a *Bacillus* species. Part I. Isolation of mutants and their inosine formation. *Agricultural and Biological Chemistry* **34**, 381–389.

SCALLET, B.L., SHIEH, K., EHRENTHAL, I. AND SLAPSHAK, L. (1974). Studies in the isomerization of D-glucose. *Die Stärke* **12**, 405–408.

SCANGOS, G.A. AND REINER, A.M. (1978). Ribitol and D-arabitol catabolism in *Escherichia coli*. *Journal of Bacteriology* **134**, 492–500.

SCHLENK, F. AND SMITH, R.L. (1953). The mechanism of adenine thiomethylriboside formation. *Journal of Biological Chemistry* **204**, 27–34.

SHAMANNA, D.K. AND SANDERSON, K.E. (1979a). Uptake and catabolism of D-xylose in *Salmonella typhimurium* LT2. *Journal of Bacteriology* **139**, 64–70.

SHAMANNA, D.K. AND SANDERSON, K.E. (1979b). Genetics and regulation of D-xylose utilization in *Salmonella typhimurium* LT2. *Journal of Bacteriology* **139**, 71–79.

SHAPIRO, S.K. AND BARRETT, A. (1981). 5-Methylthioribose as a precursor of the carbon chain of methionine. *Biochemical and Biophysical Research Communications* **102**, 302–307.

SHAPIRO, S.K. AND SCHLENK, F. (1980). Conservation of 5′-methylthioadenosine into *S*-adenosylmethionine by yeast cells. *Biochimica et biophysica acta* **633**, 176–180.

SHIMAMURA, M., YOSHITAKE, J. AND IMAI, T. (1971). Gluconate metabolism by a thiamine-requiring species of *Corynebacterium*. Part IV. Accumulation of D-ribulose. *Agricultural and Biological Chemistry* **35**, 899–904.

SHIMAMURA, M., YOSHITAKE, J. AND IMAI, T. (1973). D-Ribulose production by a

thiamine-requiring *Corynebacterium* species. *Agricultural and Biological Chemistry* **37**, 2245–2249.

SHINMYO, A., EPIFANIO, E.C., PANBANGRED, W. AND OKADA, H. (1983). Expression and regulation of xylanase and β-xylosidase genes of *Bacillus pumilus* in *Escherichia coli* and *Bacillus subtilis*. In *Abstracts of the Annual Meeting of the Society of Fermentation Technology, Osaka, Japan, 7–9 November 1983* (H. Taguchi *et al.*, Eds), p. 56. Society of Fermentation Technology, Osaka.

SIDORCZYK, Z., ZÄHRINGER, U. AND RIETSCHEL, E.T. (1983). Chemical structure of the lipid A component of the lipopolysaccharide from a *Proteus mirabilis* Re-mutant. *European Journal of Biochemistry* **137**, 15–22.

SIMONART, P. AND GODIN, P. (1951). Production de pentoses, d'acide 2-ceto gluconique et d'acide glucuronique. *Bulletin des Sociétés chimiques Belges* **60**, 446–447.

SIMPSON, F.J., WOLIN, M.J. AND WOOD, W.A. (1958). Degradation of L-arabinose by *Aerobacter aerogenes*. *Journal of Biological Chemistry* **230**, 457–472.

SLECHTA, L. AND JOHNSON, L.E. (1976). A new metabolite from *Streptomyces hygroscopicus*. I. Fermentation and isolation. *Journal of Antibiotics* **XXIX**, 685–687.

SLEIN, M.W. (1955). Xylose isomerase from *Pasteurella pestis*, strain A-1122. *Journal of the American Chemical Society* **77**, 1663–1667.

SMIT, J., KAMIO, Y. AND NIKAIDO, H. (1975). Outer membrane of *Salmonella typhimurium*: chemical analysis and freeze-fracture studies with lipopolysaccharide mutants. *Journal of Bacteriology* **124**, 942–958.

SMITH, F. (1939). The constitution of arabic acid. Part I. The isolation of 3-d-galactosido-l-arabinose. *Journal of the Chemical Society* **1939**, 744–753.

SPENCER, J.F.T. AND SALLANS, H.R. (1956). Production of polyhydric alcohols by osmophilic yeasts. *Canadian Journal of Microbiology* **2**, 72–79.

SPENCER, J.F.T., ROXBURGH, J.M. AND SALLANS, H.R. (1957). Factors influencing the production of polyhydric alcohols by osmophilic yeasts. *Journal of Agricultural and Food Chemistry* **5**, 64–67.

STANIER, R.Y., PALLERONI, N.J. AND DOUDOROFF, M. (1966). The aerobic pseudomonads: a taxonomic study. *Journal of General Microbiology* **43**, 159–271.

STRANDBERG, G.W. AND SMILEY, K.L. (1971). Free and immobilized glucose isomerase from *Streptomyces phaeochromogenes*. *Applied and Environmental Microbiology* **21**, 588–593.

SUZUKI, T. AND HOCHSTER, R.M. (1965). On the extracellular accumulation and isolation of D-ribulose in cultures of *Agrobacterium tumefaciens*. *Biochemical and Biophysical Research Communications* **19**, 637–642.

SUZUKI, T. AND ÖNISHI, H. (1967). The production of xylitol and D-xylonic acid by yeast. *Agricultural and Biological Chemistry* **31**, 1233–1236.

SUZUKI, T. AND ÖNISHI, H. (1973). Oxidation and reduction of D-xylose by cell-free extract of *Pichia quercuum*. *Applied and Environmental Microbiology* **25**, 850–852.

SUZUKI, T., TANAKA, N., TOMITA, F., MIZUHARA, K. AND KINOSHITA, S. (1963). Bacterial accumulation of ribose and ribose 5-phosphate. *Journal of Applied and General Microbiology* **9**, 457–458.

TABUCHI, T. AND HARA, S. (1973). Conversion of citrate fermentation to polyol fermentation in *Candida lipolytica*. *Journal of the Agricultural and Chemical Society of Japan* **47**, 485–490.

TAKAGI, Y. AND HORECKER, B.L. (1957). Purification and properties of a bacterial riboside hydrolase. *Journal of Biological Chemistry* **225**, 77–78.

TAKAHASHI, M. AND KUTSUMI, S. (1979). Purification and properties of xylanase from *Gliocladium virens*. *Journal of Fermentation Technology* **57**, 434–439.

TAKASAKI, Y. (1966). Studies on sugar-isomerizing enzyme. Production and utilization of glucose isomerase from *Streptomyces* sp. *Agricultural and Biological Chemistry* **30**, 1247–1253.

TAKASAKI, Y. AND TANABE, O. (1962a). Studies on the isomerization of sugar by bacteria. Part I. Identification and cultural conditions of glucose isomerizing bacteria. *Journal of the Agricultural and Chemical Society of Japan* **36**, 1010–1013.

TAKASAKI, Y. AND TANABE, O. (1962b). Studies on the isomerization of sugar by bacteria. Part II. Enzymatic properties of glucose isomerase. *Journal of the Agricultural and Chemical Society of Japan* **36**, 1013–1016.

TAKASAKI, Y., KOSUGI, Y. AND KANBAYASHI, A. (1969). Studies on sugar-isomerizing enzyme. Purification, crystallization and some properties of glucose isomerase from *Streptomyces* sp. *Agricultural and Biological Chemistry* **33**, 1527–1534.

TAKENISHI, S. AND TSUJISAKA, Y. (1975). On the modes of action of three xylanases produced by a strain of *Aspergillus niger* van Tieghem. *Agricultural and Biological Chemistry* **39**, 2315–2323.

TERADA, M., TATIBANA, M. AND HAYAISHI, O. (1967). Purification and properties of nucleoside hydrolase from *Pseudomonas fluorescens*. *Journal of Biological Chemistry* **242**, 5578–5585.

THARANATHAN, R.N., WECKESSER, J. AND MAYER, H. (1977). Structural studies on the D-arabinose-containing lipid A of *Rhodospirillum tenue*. *Hoppe-Seyler's Zeitschrift für Physiologische Chemie* **358**, 314.

THARANATHAN, R.N., WECKESSER, J. AND MAYER, H. (1978). Structural studies on the D-arabinose-containing lipid A from *Rhodospirillum tenue* 2761. *European Journal of Biochemistry* **84**, 385–394.

THÉRISOD, M., FISCHER, J.-C. AND ESTRAMAREIX, B. (1981). The origin of the carbon chain in the thiazole moiety of thiamine in *Escherichia coli*: incorporation of deuterated 1-deoxy-D-*threo*-2-pentulose. *Biochemical and Biophysical Research Communications* **98**, 374–379.

TOMOYEDA, M. AND HORITSU, H. (1964). Pentose metabolism by *Candida utilis* Part I. Xylose isomerase. *Agricultural and Biological Chemistry* **28**, 139–143.

TOUSTER, O. AND SHAW, D.R.D. (1962). Biochemistry of the acyclic polyols. *Physiological Reviews* **42**, 181–225.

TSUMURA, N. AND SATO, T. (1960). Conversion of D-glucose to D-fructose by a strain of soil bacteria. *Agricultural and Biological Chemistry* **24**, 326–327.

TSUMURA, N. AND SATO, T. (1961a). Enzymatic conversion of D-glucose to D-fructose. Part I. Identification of active bacterial strain and confirmation of D-fructose formation. *Agricultural and Biological Chemistry* **25**, 616–619.

TSUMURA, N. AND SATO, T. (1961b). Enzymatic conversion of D-glucose to D-fructose. Part II. Some properties concerning fructose accumulation activity of *Aerobacter cloacae*, strain KN-69. *Agricultural and Biological Chemistry* **25**, 620–625.

TSUMURA, N. AND SATO, T. (1965a). Enzymatic conversion of D-glucose to D-fructose. Part V. Partial purification and properties of the enzyme from *Aerobacter cloacae*. *Agricultural and Biological Chemistry* **29**, 1123–1128.

TSUMURA, N. AND SATO, T. (1965b). Enzymatic conversion of D-glucose to D-fructose. Part VI. Properties of the enzyme from *Streptomyces phaeochromogenes*. *Agricultural and Biological Chemistry* **29**, 1129–1134.

UCHIDA, K. AND SUZUKI, Y. (1975). Production of D-galactonic acid, 2-keto-D-galactonic acid, L-arabonic acid, and D-xylonic acid by *Erwinia milletiae*. *Journal of the Agricultural and Chemical Society of Japan* **49**, 257–262.

UCHINO, F. AND NAKANE, T. (1981). A thermostable xylanase from a thermophilic acidophilic *Bacillus* sp. *Agricultural and Biological Chemistry* **45**, 1121–1127.

UEHARA, K. AND TAKEDA, M. (1962). L-Xylose dehydrogenase in baker's yeast. *Journal of Biochemistry* **52**, 461–463.

VAN ALPHEN, W., LUGTENBERG, B. AND BERENDSEN, W. (1976). Heptose-deficient mutants of *Escherichia coli* K12 deficient in up to three major outer membrane proteins. *Molecular and General Genetics* **147**, 263–269.

VOLK, W.A., GALANOS, C. AND LUDERITZ, O. (1970). Isolation of 4-amino-4-deoxy-L-arabinose from S and R form bacterial lipopolysaccharides. *FEBS Letters* **8**, 161–163.

WALLER, C.W., ERYTH, P.W., HUTCHINGS, B.L. AND WILLIAMS, J.H. (1953). Achromycin. The structure of the antibiotic puromycin. I. *Journal of the American Chemical Society* **75**, 2025.

WANG, P.Y., JOHNSON, B.F. AND SCHNEIDER, H. (1980). Fermentation of D-xylose by

yeasts using glucose isomerase in the medium to convert D-xylose to D-xylulose. *Biotechnology Letters* **2**, 273–278.

WANG, P.Y., SHOPSIS, C. AND SCHNEIDER, H. (1980). Fermentation of a pentose by yeasts. *Biochemical and Biophysical Research Communications* **94**, 248–254.

WARD, J.B. (1981). Teichoic and teichuronic acids: biosynthesis, assembly, and location. *Microbiological Reviews* **45**, 211–243.

WARREN, S.C. (1968). Sporulation in *Bacillus subtilis*. Biochemical changes. *Biochemical Journal* **109**, 811–818.

WATSON, J.D. AND CRICK, F.H.C. (1953). Molecular structure of nucleic acids. A structure for deoxyribose nucleic acid. *Nature* **171**, 737–738.

WECKESSER, J., ROSENFELDER, G., MAYER, H. AND LÜDERITZ, O. (1971). The identification of 3-*O*-methyl-D-xylose and 3-*O*-methyl-L-xylose as constituents of the lipopolysaccharides of *Myxococcus fulvus* and *Rhodopseudomonas viridis*, respectively. *European Journal of Biochemistry* **24**, 112–115.

WECKESSER, J., DREWS, G., ROPPEL, J., MAYER, H. AND FROMME, I. (1974). The lipopolysaccharides (O-antigens) of *Rhodopseudomonas viridis*. *Archives of Microbiology* **101**, 233–245.

WECKESSER, J., DREWS, G., INDIRA, R. AND MAYER, H. (1977). Lipophilic O-antigens in *Rhodospirillum tenue*. *Journal of Bacteriology* **130**, 629–634.

WEIMBERG, R. (1961). Pentose oxidation by *Pseudomonas fragi*. *Journal of Biological Chemistry* **236**, 629–635.

WEIMBERG, R. AND DOUDOROFF, M. (1955). The oxidation of L-arabinose by *Pseudomonas saccharophila*. *Journal of Biological Chemistry* **217**, 607–624.

WESSELY, F. AND WANG, S. (1938). Über ein Vorkommen von Adonit. *Monatshefte für Chemie* **72**, 168.

WILKINSON, S.G. (1981). Isolation of D-*threo*-pent-2-ulose from the lipopolysaccharide of *Pseudomonas diminuta* N.C.T.C. 8545. *Carbohydrate Research* **98**, 247–252.

WILKINSON, S.G., GALBRAITH, L. AND ANDERSON, W.J. (1983). Lipopolysaccharides from *Pseudomonas maltophilia*: composition of the lipopolysaccharide and structure of the side-chain polysaccharide from strain N.C.I.B. 9204. *Carbohydrate Research* **112**, 241–252.

WILLIAMS, A.G. AND WITHERS, S.E. (1983). *Bacillus* spp. in the rumen ecosystem. Hemicellulose depolymerases and glycoside hydrolases of *Bacillus* spp. and rumen isolates grown under anaerobic conditions. *Journal of Applied Bacteriology* **55**, 283–292.

WOOD, W.A., MCDONOUGH, M.J. AND JACOBS, L.B. (1961). Ribitol and D-arabitol utilization by *Aerobacter aerogenes*. *Journal of Biological Chemistry* **236**, 2190–2195.

WOVCHA, M.G., STEUERWALD, D.L. AND BROOKS, K.E. (1983). Amplification of D-xylose and D-glucose isomerase activities in *Escherichia coli* by gene cloning. *Applied and Environmental Microbiology* **45**, 1402–1404.

YAMANAKA, K. (1958). Studies on the pyruvate and carbohydrate metabolisms by lactic acid bacteria. Part IX. Formation of ketopentoses by lactic acid bacteria. *Agricultural and Biological Chemistry* **22**, 299–308.

YAMANAKA, K. (1962). Studies on the pentose isomerases from lactic acid bacteria. Part VIII. Separation of D-xylose and L-arabinose isomerases. *Agricultural and Biological Chemistry* **26**, 175–179.

YAMANAKA, K. (1963a). Sugar isomerases. Part I. Production of D-glucose isomerase from heterolactic acid bacteria. *Agricultural and Biological Chemistry* **27**, 265–270.

YAMANAKA, K. (1963b). Sugar isomerases. Part II. Purification and properties of D-glucose isomerase from *Lactobacillus brevis*. *Agricultural and Biological Chemistry* **27**, 271–278.

YAMANAKA, K. AND TAKAHARA, N. (1977). Purification and properties of D-xylose isomerase from *Lacobacillus xylosus*. *Agricultural and Biological Chemistry* **41**, 1909–1915.

YAMANAKA, K., GINO, M. AND KANEDA, R. (1977). A specific NAD-D-xylose

dehydrogenase from *Arthrobacter* sp. *Agricultural and Biological Chemistry* **41**, 1493–1499.

YAMANAKA, K., KANEDA, R. AND SAKAI, S. (1977). Production of a new specific D-xylose dehydrogenase by *Arthrobacter* sp. No. 588 isolated from soil. *Journal of the Agricultural and Chemical Society of Japan* **51**, 87–93.

YOKOTA, A. AND SASAJIMA, K. (1981). Derepressed syntheses of sporulation marker enzymes in a *Bacillus* species mutant. *Agricultural and Biological Chemistry* **45**, 2417–2423.

YOKOTA, A. AND SASAJIMA, K. (1983). Enzymatic formation of a new monosaccharide, 1-deoxy-D-*altro*-heptulose phosphate, from DL-acetoin and D-ribose 5-phosphate by a transketolase mutant of *Bacillus pumilus*. *Agricultural and Biological Chemistry* **47**, 1545–1553.

YOKOTA, A. AND SASAJIMA, K. (1984). Formation of 1-deoxy-D-*threo*-pentulose and 1-deoxy-L-*threo*-pentulose by cell-free extracts of microorganisms. *Agricultural and Biological Chemistry* **48**, 149–158.

YOKOTA, A., SASAJIMA, K. AND HORII, S. (1978). Accumulation of a new monosaccharide, 1-deoxy-D-*altro*-heptulose (1-deoxy-sedoheptulose) by transketolase mutants of *Bacillus pumilus*. *Agricultural and Biological Chemistry* **42**, 2245–2252.

YOKOTA, A., SASAJIMA, K. AND YONEDA, M. (1979). Reactivation of inactivated D-glucose dehydrogenase of a *Bacillus* species by pyridine and adenine nucleotides. *Agricultural and Biological Chemistry* **43**, 271–278.

YOSHIHARA, O. AND KAJI, A. (1983). An endo-1,5-α-L-arabinase, which can disintegrate potato tissue. *Agricultural and Biological Chemistry* **47**, 1935–1940.

YOSHIMURA, S., DANNO, G. AND NATAKE, M. (1966). Studies on D-glucose isomerizing activity of D-xylose grown cells from *Bacillus coagulans*, strain HN-68. Part I. Description of the strain and conditions for formation of the activity. *Agricultural and Biological Chemistry* **30**, 1015–1023.

YOSHITAKE, J., SHIMAMURA, H. AND IMAI, T. (1973). Xylitol production by a *Corynebacterium* species. *Agricultural and Biological Chemistry* **37**, 2251–2259.

YOSHITAKE, J., SHIMAMURA, M. AND IMAI, T. (1976). L-Arabitol and ribitol production by a *Corynebacterium* species. *Agricultural and Biological Chemistry* **40**, 1485–1491.

YOSHITAKE, J., OHIWA, H., SHIMAMURA, M. AND IMAI, T. (1971). Production of polyalcohol by a *Corynebacterium* sp. Part I. Production of pentitols from aldopentoses. *Agricultural and Biological Chemistry* **35**, 905–911.

YOSHITAKE, J., ISHIZAKI, H., SHIMAMURA, M. AND IMAI, T. (1973). Xylitol production by an *Enterobacter* species. *Agricultural and Biological Chemistry* **37**, 2261–2267.

YOSHITAKE, J., SHIMAMURA, M., ISHIZAKI, H. AND IRIE, Y. (1976). Xylitol production by *Enterobacter liquefaciens*. *Agricultural and Biological Chemistry* **40**, 1493–1503.

YUNG, K.H., YANG, S.F. AND SCHLENK, F. (1982). Methionine synthesis from 5-methylthioribose in apple tissue. *Biochemical and Biophysical Research Communications* **104**, 771–777.