Indulgence in sweet foods and drinks is a human weakness and both are consumed far beyond their value in relieving hunger and thirst. Sucrose – the most widely consumed sweetener in the world – has been criticised for many years for its contribution to obesity, dental caries and other diseases. While glucose and fructose syrups are widely used to replace sucrose in foods, many of the problems associated with ‘sugar’ consumption remain.

Sweeteners and Sugar Alternatives in Food Technology is the leading book on this subject, offering a comprehensive overview of the many sweeteners and sugar alternatives used in food production today. Over the last 30 years a wide range of sugar substitutes have been developed and marketed. The replacement of sugars in foods has given us a new perspective on healthy foods, and claims such as ‘sugar-free’ and ‘no added sugar’ are increasingly being exploited by food manufacturers. The use of ingredients to improve the nutritional status of a food product is one of the major driving forces for new product development, and sugar replacement is still a developing area. This book provides a unique reference for food scientists and technologists with information on sugar replacement options to produce foods that not only taste and perform as well as sugar-based products, but also offer consumer benefits including calorie reduction, dental health benefits, digestive health benefits and improvements in long-term disease risk through strategies such as dietary glycaemic control.

This second edition of Sweeteners and Sugar Alternatives in Food Technology continues in the tradition of the bestselling first edition, with many of the authors returning to contribute the very latest updates in their areas of expertise. New chapters on isomaltulose, trehalose and developments in sweeteners have been added, to reflect the changes in the uses and understanding of sweeteners. References and legislation have been fully updated, making this new edition the most relevant available guide to this constantly evolving subject.

About the Editors
Kay O’Donnell has worked in the food industry for over 20 years, in a variety of senior R&D and commercial roles, for companies including Forum Bioscience, Cadbury, Kraft, GSK and Mars.

Malcolm W. Kearsley was most recently a Principal Scientist with Cadbury at their research centre in Reading, UK. After a career in teaching, research and technical sales in the food industry, he is now retired.
Sweeteners and Sugar Alternatives in Food Technology
Contents

Preface xvii
Contributors xix

PART ONE: NUTRITION AND HEALTH CONSIDERATIONS 1

1 Glycaemic Responses and Tolerance 3
Geoffrey Livesey
1.1 Introduction 3
1.2 Glycaemic response in ancient times 4
1.3 Glycaemic response approaching the millennium 5
1.4 The glycaemic response now and in future nutrition 6
1.5 Glycaemic response and adverse outcomes: both physiological and in response to advice 7
1.6 Measurement and expression of the glycaemic response 7
1.7 The acute glycaemic response to sugars and alternatives 13
1.8 Long-term glycaemic control with sweeteners and bulking agents 15
1.9 Are low glycaemic carbohydrates of benefit in healthy persons? 18
1.10 Gastrointestinal tolerance in relation to the glycaemic response 18
1.11 Conclusion 19
References 20

2 Dental Health 27
Anne Maguire
2.1 Introduction 27
2.2 Dental caries 27
  2.2.1 The problem 27
  2.2.2 Aetiology 28
2.3 Reduced-calorie bulk sweeteners 32
  2.3.1 Erythritol 32
  2.3.2 Isomalt 32
  2.3.3 Lactitol 34
  2.3.4 Malitol 34
  2.3.5 Sorbitol 36
## 6 Aspartame, Neotame and Advantame

Kay O’Donnell

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1 Aspartame</td>
<td>117</td>
</tr>
<tr>
<td>6.1.1 Introduction</td>
<td>117</td>
</tr>
<tr>
<td>6.1.2 Synthesis</td>
<td>117</td>
</tr>
<tr>
<td>6.1.3 Sensory properties</td>
<td>119</td>
</tr>
<tr>
<td>6.1.4 Physicochemical properties</td>
<td>120</td>
</tr>
<tr>
<td>6.1.5 Physiological properties</td>
<td>123</td>
</tr>
<tr>
<td>6.1.6 Applications</td>
<td>125</td>
</tr>
<tr>
<td>6.1.7 Analysis</td>
<td>126</td>
</tr>
<tr>
<td>6.1.8 Safety</td>
<td>126</td>
</tr>
<tr>
<td>6.1.9 Regulatory status</td>
<td>127</td>
</tr>
<tr>
<td>6.2 Neotame</td>
<td>127</td>
</tr>
<tr>
<td>6.2.1 Neotame structure and synthesis</td>
<td>128</td>
</tr>
<tr>
<td>6.2.2 Sensory properties</td>
<td>128</td>
</tr>
<tr>
<td>6.2.3 Physiochemical properties</td>
<td>130</td>
</tr>
<tr>
<td>6.2.4 Physiological properties</td>
<td>131</td>
</tr>
<tr>
<td>6.2.5 Applications</td>
<td>131</td>
</tr>
<tr>
<td>6.2.6 Safety</td>
<td>132</td>
</tr>
<tr>
<td>6.2.7 Regulatory</td>
<td>132</td>
</tr>
<tr>
<td>6.3 Advantame</td>
<td>132</td>
</tr>
<tr>
<td>6.3.1 Synthesis</td>
<td>133</td>
</tr>
<tr>
<td>6.3.2 Sensory properties</td>
<td>133</td>
</tr>
<tr>
<td>6.3.3 Stability</td>
<td>133</td>
</tr>
<tr>
<td>6.3.4 Solubility</td>
<td>133</td>
</tr>
<tr>
<td>6.3.5 Safety</td>
<td>134</td>
</tr>
<tr>
<td>6.3.6 Regulatory</td>
<td>134</td>
</tr>
<tr>
<td>References</td>
<td>134</td>
</tr>
</tbody>
</table>

## 7 Saccharin and Cyclamate

Grant E. DuBois

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1 Introduction</td>
<td>137</td>
</tr>
<tr>
<td>7.2 Current understanding of sweetness</td>
<td>137</td>
</tr>
<tr>
<td>7.3 Saccharin</td>
<td>139</td>
</tr>
<tr>
<td>7.3.1 History, manufacture and chemical composition</td>
<td>139</td>
</tr>
<tr>
<td>7.3.2 Organoleptic properties</td>
<td>140</td>
</tr>
<tr>
<td>7.3.3 Physical and chemical properties</td>
<td>144</td>
</tr>
<tr>
<td>7.3.4 Physiological properties</td>
<td>146</td>
</tr>
<tr>
<td>7.3.5 Applications</td>
<td>147</td>
</tr>
<tr>
<td>7.3.6 Safety</td>
<td>149</td>
</tr>
<tr>
<td>7.3.7 Regulatory status</td>
<td>151</td>
</tr>
<tr>
<td>7.4 Cyclamate</td>
<td>151</td>
</tr>
<tr>
<td>7.4.1 History, manufacture and chemical composition</td>
<td>151</td>
</tr>
<tr>
<td>7.4.2 Organoleptic properties</td>
<td>154</td>
</tr>
<tr>
<td>7.4.3 Physical and chemical properties</td>
<td>156</td>
</tr>
<tr>
<td>7.4.4 Physiological properties</td>
<td>158</td>
</tr>
</tbody>
</table>
8 Sucralose 167
Samuel V. Molinary and Mary E. Quinlan

8.1 Introduction 167
8.2 History of development 167
8.3 Production 168
8.4 Organoleptic properties 168
8.5 Physico-chemical properties 170
8.6 Physiological properties 174
8.7 Applications 175
8.7.1 Beverages 175
8.7.2 Dairy products 178
8.7.3 Confectionery 178
8.7.4 Baked products 178
8.7.5 Pharmaceuticals 179
8.8 Analytical methods 179
8.9 Safety 179
8.10 Regulatory status 181
References 181

9 Natural High-Potency Sweeteners 185
Michael G. Lindley

9.1 Introduction 185
9.2 The sweeteners 187
9.2.1 Thaumatin 187
9.2.2 Steviol glycosides 191
9.2.3 Lo han guo (mogroside) 197
9.2.4 Brazzein 200
9.2.5 Monatin 201
9.3 Conclusions 203
References 204

PART THREE: REDUCED-CALORIE BULK SWEETENERS 213

10 Erythritol 215
Peter de Cock

10.1 Introduction 215
10.1.1 History 215
10.1.2 General characteristics 215
10.1.3 Manufacturing process 217
## Contents

10.2 Organoleptic properties 218
  10.2.1 Sweetness intensity 218
  10.2.2 Sweetness profile 218
  10.2.3 Cooling effect 219
  10.2.4 Synergy with other sweeteners 219

10.3 Physical and chemical properties 219
  10.3.1 Stability 219
  10.3.2 Solubility 220
  10.3.3 Melting point and other thermal characteristics 220
  10.3.4 Viscosity 220
  10.3.5 Hygroscopicity 220
  10.3.6 Boiling point elevation and freezing point depression 220
  10.3.7 Water activity at various concentrations versus sucrose 220

10.4 Physiological properties and health benefits 221
  10.4.1 Digestion of carbohydrates 221
  10.4.2 Metabolic fate of erythritol 222
  10.4.3 Caloric value 225
  10.4.4 Digestive tolerance 225
  10.4.5 Glycaemic and insulinaemic response 225
  10.4.6 Dental health 226
  10.4.7 Anti-oxidant properties 227

10.5 Applications 228
  10.5.1 Table-top sweeteners 228
  10.5.2 Beverages 230
  10.5.3 Chewing gum 231
  10.5.4 Chocolate 234
  10.5.5 Candies 235
  10.5.6 Fondant 236
  10.5.7 Lozenges 236
  10.5.8 Bakery (pastry) products 237

10.6 Safety and specifications 239
10.7 Regulatory status 239
10.8 Conclusions 240
References 240

11 Isomalt 243
  Anke Sentko and Ingrid Willibald-Ettle

11.1 Introduction 243
11.2 Organoleptic properties 244
  11.2.1 Sweetening potency versus sucrose 244
  11.2.2 Sweetening profile versus sucrose 245
  11.2.3 Synergy and/or compatibility with other sweeteners 245

11.3 Physical and chemical properties 245
  11.3.1 Stability 245
  11.3.2 Solubility 247
  11.3.3 Viscosity 247
  11.3.4 Heat of solution 247
11.3.5 Boiling point elevation 248
11.3.6 Melting range 249
11.3.7 Hygroscopicity – moisture uptake at various relative humidities 249
11.3.8 Water activity at various concentrations versus sucrose 250

11.4 Physiological properties 252

11.5 Applications 254
11.5.1 Hard candies 254
11.5.2 Chocolates 259
11.5.3 Low boilings 261
11.5.4 Chewing gum 263
11.5.5 Pan coating with ISOMALT GS 264
11.5.6 Compressed tablets 266
11.5.7 Baked goods 267
11.5.8 Fruit spreads 268
11.5.9 Breakfast cereals, cereal bars and muesli 268
11.5.10 Overview – further applications 270

11.6 Safety 270

11.7 Regulatory status: worldwide 271

11.8 Conclusions 271

References 272

12 Lactitol 275

Christos Zacharis 275

12.1 History 275

12.2 Organoleptic properties 275

12.3 Physical and chemical properties 276
12.3.1 Stability 276
12.3.2 Solubility 277
12.3.3 Viscosity 278
12.3.4 Heat of solution 279
12.3.5 Boiling point elevation 280
12.3.6 Hygroscopicity 280
12.3.7 Water activity 280

12.4 Physiological properties 281
12.4.1 Metabolism 281

12.5 Health benefits 282
12.5.1 Lactitol as a prebiotic 282
12.5.2 Lactitol to treat hepatic encephalopathy 285
12.5.3 Lactitol and diabetes 285
12.5.4 Tooth-protective properties 285

12.6 Applications 287
12.6.1 Chocolate 287
12.6.2 Baked goods 288
12.6.3 Chewing gum and confectionery 289
12.6.4 Ice cream and frozen desserts 289
12.6.5 Preserves 290
12.6.6 Tablets 290
Contents

12.7 Regulatory status 291
12.8 Conclusions 291
References 292

13 Maltitol Powder 295
Malcolm W. Kearsley and Ronald C. Deis
13.1 Introduction 295
13.2 Production 296
13.2.1 Alternative methods of maltitol manufacture 296
13.3 Structure 297
13.4 Physical and chemical properties 297
13.4.1 Chemical reactivity 298
13.4.2 Compressibility 298
13.4.3 Cooling effect (heat of solution) 298
13.4.4 Humectancy and hygroscopicity 298
13.4.5 Molecular weight 298
13.4.6 Solubility 299
13.4.7 Sweetness 299
13.5 Physiological properties 299
13.5.1 Calorific value 299
13.5.2 Dental aspects 300
13.5.3 Diabetic suitability 300
13.5.4 Glycaemic index 301
13.5.5 Laxative effects 301
13.6 Applications in foods 302
13.6.1 The main food applications of maltitol 303
13.7 Labelling claims 305
13.8 Legal status 306
13.9 Conclusions 306
References 307

14 Maltitol Syrups 309
Michel Flambeau, Frédérique Respondek and Anne Wagner
14.1 Introduction 309
14.2 Production 310
14.2.1 Maltitol syrups 310
14.2.2 Polyglycitols 310
14.3 Hydrogenation 311
14.4 Structure 312
14.5 Physico-chemical characteristics 312
14.5.1 Chemical reactivity 313
14.5.2 Cooling effect (heat of solution) 313
14.5.3 Humectancy 313
14.5.4 Hygroscopicity 313
14.5.5 Molecular weight 314
14.5.6 Solubility 315
14.5.7 Viscosity 316
Contents

14.6 Physiological properties 316
  14.6.1 Calorific value 316
  14.6.2 Dental aspects 317
  14.6.3 Glycaemic index 318
  14.6.4 Toleration 319
  14.6.5 Sweetness 321
  14.6.6 Conclusions 322
14.7 Applications in foods 323
  14.7.1 Hard candy 324
  14.7.2 Aerated confectionery 324
  14.7.3 Caramels 325
  14.7.4 Sugar-free panning 326
  14.7.5 Chewing gum 327
  14.7.6 Other sugar-free or reduced-sugar confectionery 327
  14.7.7 Dairy applications 327
  14.7.8 Bakery applications 328
  14.7.9 Ketchup 328
14.8 Legal status 329
14.9 Safety 329
14.10 Conclusions 329
References 330

15 Sorbitol and Mannitol 331
Ronald C. Deis and Malcolm W. Kearsley

15.1 Introduction 331
15.2 Production 331
  15.2.1 Sorbitol powder 332
  15.2.2 Sorbitol syrups 333
  15.2.3 Mannitol 333
15.3 Hydrogenation 335
15.4 Storage 335
15.5 Structure 335
15.6 Safety 336
15.7 Physico-chemical characteristics 337
  15.7.1 Chemical reactivity 337
  15.7.2 Compressibility 337
  15.7.3 Cooling effect 338
  15.7.4 Humectancy 338
  15.7.5 Hygroscopicity 338
  15.7.6 Molecular weight 338
  15.7.7 Solubility 339
  15.7.8 Viscosity 339
15.8 Physiological properties 339
  15.8.1 Calorific value 339
  15.8.2 Dental aspects 340
  15.8.3 Diabetic suitability 340
  15.8.4 Glycaemic response 340
Contents

15.8.5 Tolerance 341
15.8.6 Sweetness 341

15.9 Applications in foods 342
15.9.1 Gum 342
15.9.2 Hard candy 343
15.9.3 Tabletting 343
15.9.4 Surimi 343
15.9.5 Cooked sausages 343
15.9.6 Baked goods 344
15.9.7 Panning 344
15.9.8 Over-the-counter products 344
15.9.9 Chocolate 344

15.10 Non-food applications 344
15.10.1 Sorbitol 344
15.10.2 Mannitol 345

15.11 Legal status 345
15.12 Conclusions 346
References 346

16 Xylitol 347
Christos Zacharis

16.1 Description 347
16.2 Organoleptic properties 348
16.2.1 Sweetness 348
16.2.2 Sweetness synergy 349
16.3 Physical and chemical properties 350
16.3.1 Heat of solution 350
16.3.2 Stability 351
16.3.3 Solubility 351
16.3.4 Viscosity 352
16.3.5 Boiling point elevation 352
16.3.6 Water activity 354
16.3.7 Hygroscopicity 354
16.4 Physiological properties 354
16.4.1 Metabolism 354
16.4.2 Suitability for diabetics 355
16.4.3 Tolerance 356
16.4.4 Caloric value 356
16.4.5 Health benefits 357
16.4.6 Other health benefits associated with xylitol 364
16.5 Applications 366
16.5.1 Confectionery 366
16.5.2 Chewing gum 367
16.5.3 Hard coating applications 367
16.5.4 Chocolate 368
16.5.5 Dairy products and frozen desserts 368
16.5.6 Baked goods 368
16.5.7 Non-food applications 369
16.6 Safety 369
16.7 Regulatory status 370
References 371

PART FOUR: OTHER SWEETENERS 383

17 New Developments in Sweeteners 385
Guy Servant and Gwen Rosenberg

17.1 Sweet taste modulators 385
17.2 Sweet modulator targets 385
17.3 Industry need for reduced-calorie offerings 385
17.4 Sweet taste receptors 386
  17.4.1 Sweet taste modulator mechanism of action 386
  17.4.2 Identification and evaluation of sweet taste modulators 387
  17.4.3 Optimisation of sweet taste modulators 388
17.5 Commercially viable sweet taste modulators 390
17.6 Regulatory approval of sweet taste modulators 390
17.7 Commercialisation of sweet taste modulators 391
17.8 Future sweet taste modulators and new sweeteners 392
17.9 Modulators for other taste modalities 392
17.10 Savoury flavour ingredients 393
17.11 Bitter blockers 393
17.12 Cooling flavours 393
17.13 Salt taste modulators 394
17.14 Conclusions 394
References 394

18 Isomaltulose 397
Anke Sentko and Ingrid Willibald-Ettle

18.1 Introduction 397
18.2 Organoleptical properties 397
18.3 Physical and chemical properties 398
  18.3.1 Physical properties 398
  18.3.2 Chemical properties 400
18.4 Microbiological properties 401
18.5 Physiological properties 402
  18.5.1 Dental health 403
  18.5.2 Effect on blood glucose and insulin 403
  18.5.3 Effect on fat oxidation 405
  18.5.4 Gastrointestinal tolerance 405
18.6 Toxicological evaluations 406
18.7 Applications 406
  18.7.1 Beverage applications 406
  18.7.2 Confectionery applications 410
  18.7.3 Other applications 411
Preface

Indulgence in sweet foods and drinks is a human weakness and both are consumed far beyond their value in relieving hunger and thirst. Sweetness is most commonly associated with sucrose, and this is the most widely consumed sweetener in the world although it has been criticised for many years by some with regard to its contribution to obesity, dental caries and other diseases. While glucose (and fructose) syrups are widely used to replace sucrose in foods, this is largely a cost-saving exercise and does not address many of the problems associated with ‘sugar’ consumption.

Over the last 30 years, a wide range of sugar replacers have been developed and marketed. These include the bulk sweeteners – the polyols, which replace sucrose and glucose on a weight for weight basis, and the high-potency sweeteners where a kilogram of sugar in a food product might be replaced by a few grams of a very sweet material. In the case of high-potency sweeteners, this has led to the development of a parallel industry to provide ingredients, which can be used in conjunction with the sweetener to retain the ‘bulk’ of the traditional product. More recently, sugars with many of the properties of bulk sweeteners and sweet taste enhancers that increase the potency of sweet compounds have been new additions to the market.

Replacement of sugars in foods has given us a new perspective on healthy foods where claims such as ‘sugar-free’, ‘no-added-sugar’ and ‘reduced calorie/sugar’ are being exploited by food manufacturers.

The use of ingredients to improve the nutritional status of a food product is one of the major driving forces for new product development, and sugar replacement is still seen as an area for development. This book provides a unique reference for food scientists and technologists with information on sugar replacement options to produce foods that not only taste and perform as well as sugar-based products but also offer consumer benefits including calorie reduction, dental health benefits, digestive health benefits and improvements in long-term disease risk through strategies such as dietary glycaemic control.

This second edition of *Sweeteners and Sugar Alternatives* follows the same basic layout as in the successful first edition with many of the same authors contributing to their relevant areas of expertise. New chapters on isomaltulose, trehalose and developments in sweeteners have been included to reflect changes in the use and understanding of sweeteners and sweet taste. For ease of reference, the book is set out as follows:

*Part One: Nutrition and Health Considerations.* This part considers the physiological effects and subsequent health benefits of sweeteners and sugar alternatives. Subjects include improved glycaemic control, dental health, digestive health and the role of these products in calorie control and weight management.

*Part Two: High-Potency Sweeteners.* This part describes the properties and applications of the most commonly used sweeteners. These products are unique in that they provide high sweetness without bulk and without any major impact on calories.
Preface

*Part Three: Reduced-Calorie Bulk Sweeteners.* This part describes both the properties and applications of polyols and includes reference to polyglycitols, hydrogenated glucose syrups containing less than 50% maltitol. Bulk sweeteners provide the physical characteristics of sugar and glucose but with reduced calories and other physiological benefits.

*Part Four: Other Sweeteners.* This part describes new developments in sweeteners and specifically how they elicit a sweet taste when consumed. Also included are chapters on isomaltulose and trehalose that, although classed as sugars, exhibit many of the properties of the bulk sweeteners.

*Part Five: Bulking Agents – Multi-Functional Ingredients.* This chapter focuses on the oligo- and polysaccharide materials that are most applicable as sugar alternatives and that have sugar-like properties in food applications and, often, prebiotic properties. They allow greater flexibility when replacing sugar in formulations and complement the use of all types of sweeteners in foods.

The summary tables at the end of each chapter and the extensive references are meant to inspire those who wish to learn more.

A sincere thanks to all the contributors to the book.

Kay O’Donnell and Malcolm W. Kearsley
Contributors

Michael Auerbach  
Regulatory Advisor  
Active Nutrition, DuPont Nutrition & Health  
NY, USA

Peter de Cock  
Cargill  
Vilvoorde, Belgium

Anne-Karine Dedman  
Technical Manager  
Active Nutrition, DuPont Nutrition & Health  
Paris, France

Ronald C. Deis  
Corn Products International  
Newark, DE, USA

Grant E. DuBois  
Sweetness Technologies, LLC  
Roswell, GA, USA

Michel Flambeau  
Application and Technical Support Director  
Tereos Syral  
Marckolsheim, France

Takanobu Higashiyama  
Hayashibara International Inc.  
Broomfield, CO, USA

Malcolm W. Kearsley  
Reading, UK

Christian Klug  
Head of Quality Management and Regulatory Affairs  
Nutrinova Nutrition Specialities and Food Ingredients GmbH  
Sulzbach, Germany

Michael G. Lindley  
Lindley Consulting  
Crowthorne, UK

Geoffrey Livesey  
Independent Nutrition Logic Ltd  
Wymondham, UK

Anne Maguire  
Centre for Oral Health Research  
School of Dental Sciences  
Newcastle University, UK

Samuel V. Molinary  
Consultant  
Scientific & Regulatory Affairs  
Beaufort, SC, USA

Kay O’Donnell  
Weybridge  
UK

Arthur C. Ouwehand  
Active Nutrition, DuPont Nutrition & Health  
Kantvik, Finland

Mary E. Quinlan  
Tate & Lyle  
London, UK

Frédérique Respondek  
Scientific and Regulatory Affairs Manager  
Tereos Syral  
Marckolsheim, France

Alan B. Richards  
Hayashibara International Inc.  
Broomfield, CO, USA

Gwen Rosenberg  
Senomyx Inc  
San Diego, CA, USA
Contributors

Henna Roytio
Active Nutrition, DuPont Nutrition & Health
Kantvik, Finland

Michele Sadler
Consultant Nutritionist
MJSR Associates
Kent, UK

Anke Sentko
BENEO GmbH
Mannheim, Germany

Guy Servant
Senomyx Inc.
San Diego, CA, USA

Julian D. Stowell
Vice President, Scientific Affairs
Active Nutrition, DuPont Nutrition & Health
Reigate, UK

Kirsti Tiihonen
Active Nutrition, DuPont Nutrition & Health
Kantvik, Finland

Gert-Wolfhard von Rymon Lipinski
MK Food Management Consulting GmbH
Bad Vilbel, Germany

Anne Wagner
Vice President
Innovation and Quality
Tereos Syral
Marckolsheim, France

Ingrid Willibald-Ettle
BENEO GmbH
Mannheim, Germany

Christos Zacharis
Technical Manager Functional Sweeteners
Active Nutrition, DuPont Nutrition & Health
Surrey, UK
Part One
Nutrition and Health Considerations
1 Glycaemic Responses and Toleration

Geoffrey Livesey
Independent Nutrition Logic Ltd, Wymondham, UK

1.1 INTRODUCTION

Sugars and sweeteners have an important role in the human diet and choosing the right ones in the right amounts can influence health. Knowledge will enable good choices, and further research and understanding of the literature will confirm or deny how good our choices are, and where improvements are possible. Choice is not simply a matter of which is the healthier or healthiest, since the technological properties and economics of sugars and sweeteners impact on which of them can be used suitably in a particular food.

A wide range of potential influence on health is offered by sugars and sweeteners when selected appropriately, as will be evident in detail from other chapters. These include the following:

- A reduced risk of dental caries.¹
- Potential for improved restoration of the early carious lesions.²
- A reduction in caloric value that may contribute towards a lower risk of overconsumption, obesity and improved survival.³,⁴
- Substrate for butyrate production, and potentially reduced risk of colon cancer.⁵
- The formation of osmolytes efficacious for laxation and lower risk of constipation or accumulation of toxic metabolites.⁶
- Substrate for saccharolytic and acidogenic organisms in the colon that contribute to prebiotics and ‘digestive health’ potentially including improved immunological function.⁷,⁸

Each of these can influence the choice of sugars and sweeteners. Of particular relevance is their impact on glycaemic response and potential to contribute to low glycaemic index (GI) or glycaemic load (GL) diets.

Lowering post-prandial glycaemia and insulinaemia through an appropriate choice of sugars⁹ and sweeteners, together with other low-glycaemic carbohydrates, fibre, protein, lower energy intake and exercise,¹⁰ can each improve glycaemic control. In turn, this appears to lower the prevalence or risk of developing metabolic diseases including metabolic syndrome, diabetes (and associated complications), heart disease, hypertension, stroke, age-related macular degeneration and certain cancers.¹²⁻¹⁶
In those who are susceptible, lower glycaemic carbohydrate foods may also benefit appropriate weight gain during pregnancy, limit insulin requirements in gestational diabetes, potentially allow favourable foetal growth patterns and fat accretion, reduce neural tube defects and aid recovery from surgery.

Meta-regression of interventional studies of lower GI or GL diets show a time-dependent lower body weight over a 1-year period and supports weight maintenance after weight loss. Reduced food intake in humans may be partly responsible for weight loss and maintenance. Lowering of body weight improves survival among newly diagnosed diabetes patients, and may contribute to longer survival beyond old age as seen in animal studies while lowering glycaemia with isomalt.

The converse of all aforementioned is that, given the right circumstances, a poor choice of type and amount of all carbohydrates, including sugars and sweeteners, could augment ill health. Attributes of sugars and sweeteners affecting health via the glycaemic response are nutritional and need to be seen in the context of the whole diet. It is appropriate, therefore, to consider the glycaemic aspect of diet and health from ancient to the present and future times – so far as these can be ascertained, explained and envisaged.

1.2 GLYCAEMIC RESPONSE IN ANCIENT TIMES

It is often argued that our genes might not cope with diets that are substantially different from those eaten by our ancestors. Quite what these diets were or how tolerant ancient genes have become are matters of uncertainty. Successful genes were in existence for both herbivorous and carnivorous diets prior to humankind; however, no early diet appears to have been high glycaemic. Those peoples who would normally consume ‘early’ or rudimentary diets, such as recent hunter–gatherers, experience low levels of diabetes and respond adversely to diets we may now consider high glycaemic. This is consistent with the notion that early genes were unadapted to high-glycaemic responses, and also consistent with a notion of adaptation having occurred in the people of today’s relatively more glucose-tolerant ‘western’ cultures, at least among a large proportion of them. Those not having adapted, contribute to prevalent diabetes and other conditions mentioned that are currently experienced, which is far higher than in either hunter–gatherers or rudimentary horticulturalists or simple agriculturalists or pastoralists. For the people of these ‘basic’ cultures and for ‘unadapted’ westerners (easterners or southerners or northerners), a high-glycaemic response remains a health hazard, for which a variety of strategies exist to help them cope. Europe has a rich culture and a documented history of its foods, and so we can obtain some idea of how the glycaemic character of diets may have developed over time.

Generally, we may assume diets to partly reflect the foods that can be found or are made available to eat. If this is so, examination of the inventory of foods identified in European history may shed some light on what was eaten and what might now be eaten for optimal health. Such an inventory is provided by Toussaint-Samat from which an assessment of the development in the glycaemia character of contemporary diets has been made taking account of the protein, fat, fibre and sources of carbohydrate (Figure 1.1). The picture cannot be accurate but what is clear is a progressive increase in the GL, with a markedly rapid increase in this GL following industrialisation. We cannot be sure of the prevalence of disease in Europe throughout the whole of this timescale, but we would not likely dispute that the prevalence of obesity and metabolic disease is as high now as ever.
Evolutionary adaptation to ancient diets of low glycaemic load may have left mankind genetically predisposed to non-communicable diseases provoked by today’s high-glycaemic diets. Based on the history of foods in Europe,\textsuperscript{32} with calculations by this author (A, agricultural revolution; B, industrial revolution). Open symbols show values post the industrial revolution.

Such a trend is argued to also have occurred throughout more recent times in the United States,\textsuperscript{25} with recent emphasis on reducing the fat content of the diet, a doubling of flour consumption during the 1980s and an increase overall in sugar, corn syrup and dextrose consumption prior to the end of the millennium.\textsuperscript{33–35} These together with a lower dietary fibre content of foods\textsuperscript{34} imply exposure to diets eliciting a high-glycaemic response.

### 1.3 Glycaemic Response Approaching the Millennium

Much of our understanding of the interplay between health and the glycaemic response to foods has arisen from investigations into the dietary management of diabetes. Whereas very low-glycaemic carbohydrate foods such as Chana dahl were used in ancient India for a condition now recognised as diabetes,\textsuperscript{36} nineteenth century recommendations in western cultures were for starvation diets, which were, of course, non-glycaemic. The drawback of such is obvious and in 1921, high-fat (70%) low-carbohydrate (20%) diets were recommended,\textsuperscript{37} which by definition would be low glycaemic. A gradual reintroduction of carbohydrate into recommendations for diets for diabetic patients arose as carbohydrate metabolism came under some control using drugs, but mainly because ‘dietary fat’ was recognised to have a causal role in coronary heart disease, to which diabetics and glucose intolerant individuals succumb, more readily in some cases than others.\textsuperscript{38–41} The metabolic advantages of replacing dietary fat (saturated fat) with high-fibre high-carbohydrate was lower fasting glycaemia, lower total-, HDL- and LDL-cholesterol and lower triglycerides.\textsuperscript{42–46} Such benefits may in part be related to dietary fibre or its influence on the glycaemic response.\textsuperscript{47,48} Certainly, the non-digestible carbohydrate in these diets would ensure some degree of lower glycaemia for a given carbohydrate intake and support beneficial effects from lower saturated fat intake.
6 Sweeteners and Sugar Alternatives in Food Technology

During these times, the adverse influence of higher glycaemia or more dietary carbohydrate was either unrecognised or the risk was accepted by the medical profession in fear of (or compromise for) the adverse effects of ‘dietary fat’. The adverse influence of higher glycaemia may also have been overlooked due to the apparent benefits of the non-digestible carbohydrate in the high-carbohydrate foods. Indeed, the Institute of Medicine has recommended high-fibre diets to combat coronary heart disease, and this builds upon the dietary fibre hypothesis that proposed higher prevalence of diabetes, heart disease and other conditions associate with diets deficient of fibre. An absence of fibre in high-sugar products left sugar (sucrose) vulnerable; nevertheless, this sugar remained preferable among nutritionists to high (saturated) fat, which it might displace from the diet, giving rise to the concept of the ‘sugar–fat-seesaw’ discussed elsewhere.

Throughout the whole of these times, the primary purpose of recommending energy from carbohydrate was to displace the intake of energy as fat. In part, this is because carbohydrate supplies energy, but also because carbohydrate counters the insulin desensitising influence of both mobilised body fat and dietary fat. This purpose for carbohydrate was retained in the GI concept, whereby carbohydrate of low-glycaemic response further improved glycaemic control in diabetes patients, and possibly the plasma lipid profile.

However, it must be considered whether carbohydrates have a long-term future as a means to displace fats from the diet. It is noteworthy that the increasing carbohydrate content of diets throughout European history, which partly explains the higher GL (Figure 1.1), has not adequately displaced ‘fats’ from the diet or prevented obesity. Excess of carbohydrate prevents the use of fat stores and encourages dietary fat to be stored. In general, elevating the consumption of monounsaturated and polyunsaturated (bar trans) fats is considered beneficial in respect of diabetes, coronary heart disease and a variety of conditions and is consistent with early diets. In addition, there is little or no evidence that carbohydrate ingestion can selectively limit the ingestion of saturated fats. Proponents of the Mediterranean diet (high in mono- and polyunsaturated fats) would hold that the use of carbohydrate for the purpose of limiting fat intake is unsound.

1.4 THE GLYCAEMIC RESPONSE NOW AND IN FUTURE NUTRITION

The general picture now for glycaemic control is that a high-fibre, low-glycaemic and low-saturated fat diet is optimal. With obesity being a major problem and a risk factor for type-2 diabetes and heart disease, an appropriate energy balance has become of major importance. Weight loss has for some time been recognised as important to the survival of newly diagnosed type-2 diabetes patients and improvement in prognosis for cardiovascular disease. These are practical examples of how caloric restriction improves survival in at-risk groups. Of course, caloric restriction implies here a diet reduced in energy via lower saturated fat and lower GL than is generally consumed.

It is clearly preferable to limit the intake of both saturated fat and high-glycaemic carbohydrate as energy sources to facilitate weight reduction, rather than simply to exchange energy sources. Prior nutritional debates of ‘fat versus carbohydrate’ might now be viewed as too imprecise in both the description of the food components and how the components are pitched against each other. A similar concern arises when it is argued that low-GI foods should find automatic favour over low-GL foods when in communication with the consumer.
Choosing low-GI foods does not automatically mean maintaining a lower fat intake since approximately 50% of the variance in the GI of foods can be attributed to their fat content. The nutrition debate still needs to provide greater scope for consideration of the adverse influence of ‘saturated fats plus high-GL’ together in general nutrition.

Sugars and sweeteners provoke a range of glycaemic responses related to the carbohydrate structure without the need to ask whether the glycaemic response is actually brought about by co-ingested dietary fat, and so may variably promote, defer or help prevent ill health. Various research groups indicate at the time of writing that ‘the concepts and methods regarding the GI [or GL] are sufficiently mature to recommend preparing the population to use GI as a way to help choose healthier foods...’ This is a position consistent with that over a decade ago in the WHO/FAO recommendations to primary producers and processors of foods: ‘Consider how existing and new technologies can be used to help meet dietary goals regarding the quantity and nutritional properties of food carbohydrates...’ and to ‘provide appropriate information to the consumer on food labels.’

1.5 Glycaemic Response and Adverse Outcomes: Both Physiological and in Response to Advice

Advice to consume a diet of low-, in exchange for high-glycaemic foods has raised consideration about whether this would detract from other nutritional advisory messages. There are, however, no known adverse effects of choosing a diet including low-glycaemic carbohydrate foods instead of high-glycaemic ones, other than for occasionally temporal gastrointestinal discomfort whenever this is accompanied by excessive low digestible carbohydrate ingestion (discussed in Section 1.10).

Occasionally claims are made that the benefits of low GI can be achieved by selecting whole grain foods, fruits and legumes, and that low-glycaemic advice would interfere with this whole food advice. However, such benefit of whole foods is hardly ever likely to be achieved optimally because the glycaemic indices of foods in these food categories cover wide ranges of GI values (Figure 1.2). Intervention choosing low instead of high-GI fruits is shown to be of benefit to diabetes patients, for example.

1.6 Measurement and Expression of the Glycaemic Response

By 1929, the potential of carbohydrate to raise plasma glucose, some of which may spill over into urinary losses in diabetes patients, was indicated by its available carbohydrate content, for which a direct assay to determine the composition of foods was later refined. Fibre was suitable for diabetes patients as it provided no glucose, to either elevate plasma glucose concentrations or urinary losses. Another measure of the glycaemic potential became known as the GI. Later, the quantity called GL, the product of available carbohydrate and GI, was introduced and validated as a measure of the glycaemic response. GL can be assayed directly and without need for knowledge of the available carbohydrate content, about which assumptions are too often made. The GI became widely known, and many GI testing centres have opened. Meanwhile, GI has received criticism as it is said to not meet...
many useful criteria for inclusion in conventional food tables or in communication with the consumer, though tabulation is possible and finds application nonetheless.

The precision of the GI assay, initially examined in a study among five laboratories based on capillary blood sampling using high-carbohydrate foods, has since been the topic of discussion with the aim of standardisation, has subsequently been assessed among 28 different laboratories, and now has Australian and International standardisation. The standardised protocol is only a little different now from that used in the first inter-laboratory study in particular, with regards to the precision achieved. An outstanding question is whether the methods for assessing GI and GL are adequately reproducible for communication with the consumer.

A useful point of reference when assessing a method’s adequacy is one often used in regulatory enforcement for substantiation of reported or declared values in food labelling. Tests need to be able to assess whether a reported value is compliant with regulations specifying boundaries of accuracy required for labelling purposes. Such enforcement often finds it generally practical to ‘accept’ an ‘error’ of no more than 20% in a nutrient value reported on a food label in comparison with an officially analysed (or assessed) value. Such an apparently large ‘permitted’ discrepancy ensures that differences between reported and official values do not arise simply by chance due to imprecision of the test method. However, this particular approach of using a nutrient value as the reference amount that defines the absolute size of the 20% value has limitations. One is that the 20% of nutrient value is extremely onerous when nutrient values are low, because as the value approaches zero, the percentage error approaches infinity. The second is that the ‘permissible error’ differs according to the nutrient amount; 20% of 1 g is 0.2 g, but 20% of 100 g is 20 g, which is 100 times higher. The third is that a constant 20% of nutrient value fails to follow the real error structure in the analytical data except if the error size is an exact proportion of the measurement size, which for biological tests is practically never. For a test such as GI, a basal