Wine Flavour Chemistry
SECOND EDITION
Jokie Bakker & Ronald J. Clarke

Wine Flavour Chemistry brings together a vast wealth of information describing components of wine, their underlying chemistry and their possible role in taste, smell and overall perception. It includes both table wines and fortified wines, such as Sherry, Port and the newly added Madeira, as well as other special wines. This fully revised and updated edition includes new information on retsina wines, rosés, organic and reduced alcohol wines, and has been expanded with coverage of the latest research. Both EU and non-EU countries are referred to, making this book a truly global reference for academics and enologists worldwide.

Wine Flavour Chemistry is essential reading for all those involved in commercial wine making, whether in production, trade or research. The book will be of great use and interest to all enologists, and to food and beverage scientists and technologists working in commerce and academia. Upper level students and teachers on enology courses will need to read this book: wherever food and beverage science, technology and chemistry are taught, libraries should have multiple copies of this important book.

Praise for the first edition of Wine Flavour Chemistry:
“An absolute must for anyone involved professionally in the wine industry, scientist or otherwise.”
Chemistry World

“This book contains a wealth of information on the chemistry of wine flavour as well as on sensory evaluation methods. The content of the book is based on recent published studies, well organized, focused and easy to read.”
Chronica Horticulturae

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Wine Flavour Chemistry

Second edition

Jokie Bakker
Ronald J. Clarke

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# Contents

Preface to the Second Edition  xv
Preface to the First Edition  xvii

1 Introduction  1
   1.1 Scope of the book  1
   1.2 Historical background  2
   1.3 Wine flavour  3
   1.4 Wine colour  6
   1.5 Vinification  6
      1.5.1 Vinification process  8
      Pre-fermentation  9
      Fermentation  15
      Post-fermentation  17
   1.5.2 Red wines  22
      Pre-fermentation  22
      Fermentation  23
      Post-fermentation  24
   1.5.3 White wines  25
      Pre-fermentation  26
      Fermentation  27
      Post-fermentation  28
   1.5.4 Specialized wines  28
      Rosé wines  28
      Wines made from organically farmed grapes  29
      Wines with added resin  30
      Wines with low alcohol content  31
      Sweet wines  31
      Sparkling wine in Champagne  32
      Sparkling wine by other methods  33
      Wines by carbonic maceration  34
      Wines by thermovinification  34
      Wines matured Sur Lie  35
   1.5.5 Fortified wines  35
      Port wine  36
Contents

Sherry 38
Madeira 40

1.6 Physiological effects 42
1.6.1 Attributed negative effects 43
1.6.2 Wine ethyl alcohol (ethanol) 43
1.6.3 Effects of phenols 45
Resveratrol 46
Bibliography 48

2 Grape Varieties and Growing Regions 53
2.1 Wine grapes 53
2.2 Vine plant characteristics 56
2.3 Soil, climate and ripeness 57
2.3.1 Soil 57
2.3.2 Climate 58
2.3.3 Ripeness 64
2.4 Grape growing regions of the world 65
2.4.1 World wine production 65
2.4.2 Regions 66
2.5 Chemical composition of grapes, must and finished wines 71
2.5.1 Grapes and must 71
2.5.2 Finished wine 79
2.6 Quality control and classification of wines 79
2.6.1 France 79
2.6.2 Germany 82
2.6.3 Italy 83
2.6.4 Spain 84
2.6.5 Australia 84
2.6.6 USA 85
2.6.7 Quality control systems in the European Union 86
Bibliography 87

3 Basic Taste and Stimulant Components 89
3.1 Introduction 89
3.2 Basic taste perception 90
3.2.1 Role of taste 90
3.2.2 Taste perception mechanism 91
3.3 Ethyl alcohol 92
3.3.1 Measurement of ethyl alcohol content in wines 93
3.3.2 Measurement of sugar content in musts and wines
Brix scale 94
Baumé and Oeschele scales 96
Prediction of alcohol content in the finished wine 96
3.3.3 Sugar content of grapes and must 97
3.3.4 Chaptalization 98
3.4 Acidity
   3.4.1 Contents of organic acids 100
   3.4.2 Measurement of acid content 104
   3.4.3 Acid taste 105
3.5 Sweetness 109
   3.5.1 Chemical structure of sugars 109
   3.5.2 Content/sweetness 109
3.6 Bitterness, astringency and mouthfeel 113
   3.6.1 Basic chemistry 113
      Non-flavanoids 113
      Flavan-3-ols 114
      Flavonoids 116
      Anthocyanins 117
   3.6.2 Basic technology 118
      Location of polyphenols in grapes 118
      Use of the term ‘tannins’ and their classification 119
      Grape tannins 120
      Quantifying methods 121
      HPLC measurements 122
      Other methods 123
      Analyses in grapes and during wine-making 124
   3.6.3 Bitter constituents 127
      White wines 127
      Red wines 127
   3.6.4 Astringency 127
   3.6.5 Mouthfeel 128
3.7 Colouring matter 129
   3.7.1 Colour of red wines 129
   3.7.2 Colour of white wines 132
3.8 Other constituents 134
   3.8.1 Sulfur dioxide 134
      Basic chemistry 135
      Technical use 135
      Taste effects 136
   3.8.2 Carbon dioxide 136
      Formation and handling of CO₂ 137
      Sensory factors 137
   3.8.3 Oxygen 138
      Basic chemistry 138
      Oxygen content in wines 139
      Effect of oxygen on wine 141
3.9 Changes in maturation 142
   3.9.1 ‘In-barrel’ ageing 143
      Vats 143
      Extraction from barrels 144
      Oxidation in barrels 145
3.9.2 ‘In-bottle’ ageing 146  
3.9.3 Oxidation-reduction (redox) potential 146  
   General 147  
   Nernst equation 147  
   Redox potentials in wine 148  
   Redox potentials during vinification 149  

Bibliography 150

4 Volatile Components 155  

4.1 General 155  
   4.1.1 Sensory perception 156  
   4.1.2 Partition coefficients 158  
   4.1.3 Threshold flavour/odour levels 161  
      Units 163  
      Consistency of threshold odour levels 164  
      Threshold level difference between  
      sniffing and tasting 164  
      Threshold levels in solutions of dissolved  
      substances in water and in beverages 166  
      Relationship of threshold values  
      to partition coefficients 168  
      Volatile compound concentration in the vapour phase 170  
   4.1.4 Flavour/odour descriptions 173  
      Use of word descriptions 173  
      Intensity of flavour/odour 175  

4.2 Volatile compounds detected in wines 175  
   4.2.1 Types of aroma in volatile compounds 178  
   4.2.2 Stereochemical effects in aroma volatile compounds 180  

4.3 Contents and sensory evaluation data 180  
   4.3.1 Esters 180  
      Structure 181  
      Presence in wines 181  
      Flavour characteristics 182  
   4.3.2 Aldehydes 189  
      Presence in wine 189  
      Flavour characteristics 190  
   4.3.3 Ketones 190  
      Presence in wines 190  
      Flavour characteristics 190  
   4.3.4 Acetals 196  
   4.3.5 Alcohols 197  
      Presence in wines 197  
      Flavour characteristics 201  
   4.3.6 Lactones and furanones 201  
      Molecular structures 201
Contents

4.3.7 Acids 207
   Presence in wines 207
   Flavour characteristics 207
4.3.8 Nitrogenous compounds 208
4.3.9 Phenols 209
   Presence in wines 209
   Flavour characteristics 209
4.3.10 Terpenes 209
   Chemical structure 209
   Presence in grapes/wines 213
   Flavour characteristics 215
4.3.11 Pyrazines 216
   Chemical structure 216
   Presence in grapes/wines 216
   Flavour characteristics 216
4.3.12 Sulfur compounds 219
   Chemical structure 219
   Presence in wines 219
   Flavour characteristics 220
4.4 Changes during maturation 221
   4.4.1 Fermentation and storage of wines ‘in-vat (tank)’ and ‘in-barrel (cask)’ 221
   Fermentation 221
   Storage 222
   4.4.2 ‘In-bottle’ ageing 224
   Changes in ester content 225
   Substances produced by carbohydrate degradation 225
   Sulfur compounds 225
   Changes in terpenoids 225
   Formation of substances from carotene breakdown 226
4.5 Aroma detection and quantification 227
   4.5.1 Gas chromatography 227
   4.5.2 Sample preparation 228
   4.5.3 Olfactometry 230
4.6 Chemical structure and physical properties 231
Bibliography 231

5 Wine Tasting Procedures and Overall Wine Flavour 239
   5.1 Wine tasting 239
   5.2 Wine tasting procedure 241
   5.2.1 Tasting glass 241
   5.2.2 Serving 243
   5.2.3 Visual 243
5.2.4 Smell 244
5.2.5 Flavour 246
5.2.6 Interactions 247
5.2.7 Astringency 248
5.2.8 Judging the wine 249
5.2.9 Reasons for wine tasting 250
   Sensory analysis 250
   Quality tastings 251
   Identifying wines by tasting 251
   Sensory analyses used in research 252
   Consumer tasting 252
   Analytical tasting 253
5.2.10 Wine tasting information and analysis 254
   Statistical analysis 254
5.3 Factors influencing sensory perception 256
5.3.1 Threshold and sensitivity 257
5.3.2 Vocabulary 258
5.4 Balance of taste sensations in wine 258
5.5 Wine aromas 259
5.5.1 Odour/aroma classification 261
5.5.2 Aroma/odour characteristics of wines from particular grape varieties 262
5.5.3 Variants in Cabernet Sauvignon wine flavour 270
5.5.4 Variants of Chardonnay wine flavour 271
5.5.5 Flavour description of some other commercial wines 273
5.5.6 Off-odours and taints 274
   Cork taint 275
   Mousiness 278
   Ethylphenols 279
5.6 Wine and food flavour 279
5.7 Aroma indices and statistical methods 282
5.7.1 Flavour unit concept 282
5.7.2 Odour activity unit 284
5.7.3 Multivariate and other statistical procedures 285
Bibliography 288

6 Sherry, Port and Madeira 291
6.1 Introduction 291
   6.1.1 Sherry introduction 291
   6.1.2 Port introduction 292
   6.1.3 Madeira introduction 292
   6.1.4 Comparisons between fortified wines 293
   6.1.5 Ethyl alcohol - sensory effect 294
### Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1.6</td>
<td>Ethyl alcohol - chemical effect</td>
<td>295</td>
</tr>
<tr>
<td>6.1.7</td>
<td>Sweetness</td>
<td>295</td>
</tr>
<tr>
<td>6.2</td>
<td>Sherry</td>
<td>295</td>
</tr>
<tr>
<td>6.2.1</td>
<td>Wine producers</td>
<td>296</td>
</tr>
<tr>
<td>6.2.2</td>
<td>Commercial wine styles</td>
<td>296</td>
</tr>
<tr>
<td>6.2.3</td>
<td>Wine writers' comments</td>
<td>297</td>
</tr>
<tr>
<td>6.2.4</td>
<td>Grapes and must</td>
<td>297</td>
</tr>
<tr>
<td>6.2.5</td>
<td>Base wine</td>
<td>298</td>
</tr>
<tr>
<td>6.2.6</td>
<td>Maturation</td>
<td>299</td>
</tr>
<tr>
<td>6.2.7</td>
<td>Maturation changes under flor</td>
<td>299</td>
</tr>
<tr>
<td>6.2.8</td>
<td>Maturation changes without flor</td>
<td>301</td>
</tr>
<tr>
<td>6.2.9</td>
<td>Maturation with and without flor</td>
<td>302</td>
</tr>
<tr>
<td>6.2.10</td>
<td>Volatile compounds</td>
<td>302</td>
</tr>
<tr>
<td>6.2.11</td>
<td>Changes during maturation in phenolic compound content</td>
<td>309</td>
</tr>
<tr>
<td>6.3</td>
<td>Port wine</td>
<td>311</td>
</tr>
<tr>
<td>6.3.1</td>
<td>Port wine producers</td>
<td>311</td>
</tr>
<tr>
<td>6.3.2</td>
<td>Commercial Port wine styles</td>
<td>312</td>
</tr>
<tr>
<td>6.3.3</td>
<td>Wine writers' comments</td>
<td>313</td>
</tr>
<tr>
<td>6.3.4</td>
<td>Grapes and must</td>
<td>314</td>
</tr>
<tr>
<td>6.3.5</td>
<td>Fermentation and base Port wine</td>
<td>315</td>
</tr>
<tr>
<td>6.3.6</td>
<td>Port wine compared to red table wine</td>
<td>317</td>
</tr>
<tr>
<td>6.3.7</td>
<td>Maturation</td>
<td>318</td>
</tr>
<tr>
<td>6.3.8</td>
<td>Colour changes during maturation</td>
<td>318</td>
</tr>
<tr>
<td>6.3.9</td>
<td>Volatile changes during maturation</td>
<td>322</td>
</tr>
<tr>
<td>6.4</td>
<td>Madeira</td>
<td>327</td>
</tr>
<tr>
<td>6.4.1</td>
<td>Madeira wine producers</td>
<td>327</td>
</tr>
<tr>
<td>6.4.2</td>
<td>Commercial Madeira wine styles</td>
<td>327</td>
</tr>
<tr>
<td>6.4.3</td>
<td>Wine writers' comments</td>
<td>328</td>
</tr>
<tr>
<td>6.4.4</td>
<td>Sensory properties</td>
<td>328</td>
</tr>
<tr>
<td>6.4.5</td>
<td>Grapes and must</td>
<td>328</td>
</tr>
<tr>
<td>6.4.6</td>
<td>Base wines maturation</td>
<td>329</td>
</tr>
<tr>
<td>6.4.7</td>
<td>Volatile compounds</td>
<td>330</td>
</tr>
</tbody>
</table>

### Bibliography

335

---

### 7 Formation Pathways in Vinification

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1</td>
<td>Introduction</td>
<td>341</td>
</tr>
<tr>
<td>7.2</td>
<td>Process variables in vinification</td>
<td>342</td>
</tr>
<tr>
<td>7.2.1</td>
<td>Grapes</td>
<td>342</td>
</tr>
<tr>
<td>7.2.2</td>
<td>Yeast strain</td>
<td>344</td>
</tr>
<tr>
<td>7.2.3</td>
<td>Malo-lactic organisms</td>
<td>347</td>
</tr>
<tr>
<td>7.2.4</td>
<td>Temperature</td>
<td>347</td>
</tr>
<tr>
<td></td>
<td>Standard operating temperature</td>
<td>347</td>
</tr>
<tr>
<td></td>
<td>Thermovinification</td>
<td>348</td>
</tr>
<tr>
<td>7.2.5</td>
<td>Clarification procedures</td>
<td>349</td>
</tr>
</tbody>
</table>
Contents

7.2.6 Nutrient medium in fermentation 349
7.2.7 Maceration 351
7.3 Production of ethyl alcohol 351
7.4 Production of individual groups of compounds 352
  7.4.1 Esters 352
  7.4.2 Aldehydes 353
  7.4.3 Ketones 354
  7.4.4 Acetals 354
  7.4.5 Higher alcohols 355
  7.4.6 Furanones and lactones 356
  7.4.7 Acids 357
  7.4.8 Amines 357
  7.4.9 Phenols (volatile) 357
  7.4.10 Terpenes 359
  7.4.11 Pyrazines 360
  7.4.12 Sulfur compounds 360
7.5 Noble Rot 362
Bibliography 364

Appendix I 367
  I.1 Chemical formulae nomenclature 367
     I.1.1 Nomenclature for a homologous series of compounds (Greek number/word system) 367
     I.1.2 System for substituent groups (derivatives) 368
     I.1.3 System for substituting in long-chain compounds 368
     I.1.4 System for characterizing esters 368
     I.1.5 System for characterizing unsaturated compounds 369
     I.1.6 Systems for esters, thiols and thio-compounds 369
     I.1.7 Miscellaneous IUPAC recommendations 369
     I.1.8 Alternative chemical names 369
     I.1.9 Numbering systems for ring compounds 370
     I.1.10 Trivial and common names for derivative alkanes and other compounds 370
     I.1.11 General 371
  I.2 Stereochemistry 371
     I.2.1 Enantiomers 371
        Optical activity 372
        Chirality 373
        Occurrence of enantiomers 375
     I.2.2 Geometrical (stereo-) isomers 375
     I.2.3 Tautomerism 376
  I.3 Chemistry of the oxidation of organic compounds 377
     I.3.1 Auto- and enzymatic oxidation of lipids 378
     I.3.2 Oxidation-reduction of alkyl alcohols and aldehydes 379
     I.3.3 Oxidation of phenolic compounds 380
Oxidation of procyanidins 383
Oxidation of non-flavanoid phenolic compounds 383
General 384
1.3.4 Oxidation-reduction (redox) potentials 384
I.4 Estimation of partition coefficients
of volatile compounds in air/water 386
I.5 Grape varieties and cultivars 389

Appendix II 395
II.1 Units 395
II.2 Data sources
Tables of molecular formulae, weight and physical
properties for each group of volatile compounds
found in wine
- Volatile esters 396
- Volatile aldehydes 399
- Volatile ketones 400
- Volatile alcohols 401
- Volatile furanones/lactones 402
- Volatile acids 403
- Volatile phenols 404
- Volatile terpenes 404
- Volatile methoxy pyrazines 405
- Volatile sulfur compounds 405

Index 407
Preface to the Second Edition

Wine is primarily consumed for pleasure, and despite some attributed health benefits, it does not form an essential part of our diet. Therefore the sensory properties of wines are considered very important and the appreciation of its flavour arguably gives the wine drinker most pleasure. The wine is bought for its appeal in the bottle, for the knowledge the wine drinker has about the sensory properties and the anticipated enjoyment of consuming the wine. After evaluating the colour of the wine in the glass, most wine consumers will smell the wine, and judge its qualities. The release of flavours from wine continues when drinking the wine, and gives further flavour sensations in addition to the perception of many other taste and mouthfeel compounds that should be present in balanced amounts in the wine. There is a very wide range of well made wines available, so if a wine does not deliver the flavour the wine drinker desires and appreciates, a different choice can be made for the next occasion. Since wine flavour plays such a crucial role in wine, this makes a book devoted to *Wine Flavour Chemistry* particularly relevant.

The technological advances in viticulture, wine-making and the resulting improved wine flavours have been based upon the scientific exploration of vines, grapes and wines, their constituents, their chemistry and all aspects of the wine-making process by scientists in many disciplines in research establishments world-wide. The understanding of flavour chemistry and its perception is determined by numerous scientific disciplines, ranging from chemistry and laws of physics to human physiology. Since the first edition of *Wine Flavour Chemistry* more research has become available on wine flavours, with new compounds still being identified. In addition, scientists place much emphasis on determining the potential sensory contributions of flavour compounds in wine, making flavour information as relevant as possible. Advantageous in all research dealing with flavours is the increased scientific understanding of the perception of volatiles and the award of the Nobel Prize for Physiology and Medicine in 2004 to Richard Buck & Linda Axel for their pioneering research on the genetics of the perception of odour (ref. in Chapter 4) has given great impetus to this research field.

Although aspects of wine-making may always remain an art, such as the numerous choices to be made in the wine production process in order to optimize the wine flavour, science has definitely got a very sound and well deserved foothold in the wine making industry. Many highly trained and skilled wine makers work in the wine industry, helping to adapt advances in wine science in order to successfully influence wine making and ultimately
Preface

Wine flavour. All wine drinkers benefit from the well made wines with a wide range of wine flavours available nowadays. This updated book, Wine Flavour Chemistry may attract many different readers interested in wine, ranging from wine consumers, students, academics and people working in the wine industry. Information has been gathered from scientific research, review papers and books to update this comprehensive overview of the subject.

I wish to express my grateful thanks to all the scientists who have kindly shared their research information, which was of invaluable help in preparing this updated book.

Jokie Bakker MSc (Wageningen), PhD (Bristol)
Preface to the First Edition

This volume on wine flavour chemistry has been in gestation for many years; an original draft was started some ten years ago. A number of events led to our renewed interest in getting this book published. First, in the UK, wine has become a drink enjoyed by many consumers at numerous occasions, whereas previously, wine tended to be a drink shrouded by mystique and enjoyed mainly by more knowledgeable people. In contrast, in countries where wine production has been established for a long time, a long-standing culture of wine consumption, mainly with meals, has been established. Since there are now many people in the UK as well as in other areas of the world interested in consuming wines there is also an increased quest for knowledge about wine, making a book focused on the flavour and its chemistry particularly pertinent. Second, during the last two decades, there has been an enormous development in knowledge about viticulture and the technology of wine making worldwide. This has resulted in a much-improved wine quality. Third, many ‘new’ wine regions have been established. These have not been inhibited by cultural preconceptions about wine production, and have experimented in many different ways, pushing the boundaries of both viticulture and wine making. Fourth, financial investments in vineyards and wineries, hand in hand with generally vastly improved wine production skills, have given an array of wine flavours from grapes, which wine-makers in the past could barely have believed possible. The cultivation and production of single variety/cultivar wines have given consumers an insight into the many flavours possible in wines. Of course, the technological advances in viticulture and wine making have been based upon the scientific exploration of grapes and wines, their constituents and their chemistry, by scientists in many disciplines worldwide. Advances in analytical laboratory instruments have proven to be a great help. For example, mass spectrometers have, over the last ten years, become much more sensitive, much smaller, much cheaper and easier to use. This has resulted in an explosion of new data regarding the volatile compounds of wine. Numerous other advances in analytical techniques have aided the quest for knowledge about wine flavour, colour and taste. Interestingly, alongside these technological advances has been the development of sensory science. There is now an array of scientifically based sensory analytical techniques allowing scientists to determine our perception of wine, including the measurements of differences between wines and descriptions of sensory properties.

Two recently published scientific books on wines summarize much of the wine information available. In 1994, Jackson in Canada published his excellent
and wide-ranging book, *Wine Science*, with a second edition in 2000. This was followed in 2000 by the equally excellent *Handbook of Enology* from Ribéreau-Gayon and his colleagues in France. This new book on the chemistry of wine flavours draws together aspects of wine making pertinent to wine flavour, and tries to link chemistry, flavour composition and sensory properties. Our volume draws much information from these antecedent books for which due acknowledgement is readily made. We make similar grateful acknowledgement to several highly perceptive and entertaining, but not overtly scientific, books on wines by British wine writers and journalists. Of course, information from many scientific papers is also used to give a comprehensive overview of the subject. This book, *Wine Flavour Chemistry*, differs from all the foregoing in that it is uniquely devoted to the subject of the flavour of the wine. It is based on the chemistry of the compounds, both volatile and non-volatile, together with the application of the techniques of modern sensory analysis.

The quantities of volatile compounds in head-space air, that is, the air above a glass of wine, are determined by *partition coefficients*, which express the ratio between the amount of those compounds in the liquid and in the air above, both amounts often only in parts per million or much less. The quantities present have to be above *threshold levels of detection and recognition* in order for them to be perceived effectively by the olfactory organs of the nose. There are also threshold levels for non-volatile compounds present in much larger quantities in wines (several grams per litre), and detected only by the taste buds of the tongue, which detect the basic tastes of acidity, sweetness, bitterness and saltiness. Signals from these two highly sensitive organs (the olfactory epithelium and taste buds) are transported through nerve fibres to the brain. Certain other elements of sensory analysis, such as colour, appearance and tactile sensations in the mouth, including astringency, contribute to the overall flavour assessment. Perhaps it is the naming of all the different flavour sensations in all the different wines that is of the greatest intellectual and aesthetic interest, together with their association by scientists with particular chemical substances or groups of substances.

This volume, therefore, attempts to bring together in a readable and accessible form the most recent research from this rapidly developing field. It is aimed to be of interest to consumers with an inquisitive mind about wine, and to all those involved with the production of and trade in wines with an interest in the chemical and technical aspects of wine flavour.

A considerable amount of threshold flavour/odour and other flavour compound information has been recently compiled by Flament in his comprehensive book, *Coffee Flavor Chemistry* (2002). Many wine odour compounds, now known to number around 400, are also to be found among the much larger number of volatile compounds (about 800) in green and roasted coffee brews. In wines, alkyl esters from the fermentation of the must and unchanged terpenes from the grapes are particularly characteristic, though they may undergo change during subsequent ageing; in coffee, many distinctive compounds develop from the roasting process.
Reference to coffee flavour, indeed that of other beverages, should not be surprising since one of the authors (RJC), whilst an enthusiastic wine bibber, spent some forty years in the scientific study and industrial manufacture of coffee, and is the author or co-editor of several books on that subject. The other author of this book (JB) brings a wealth of knowledge and experience directly from her research into wine, especially within fortified wines, with numerous scientific research papers published on this subject.

We wish to express our grateful thanks to all those who have helped us with this book, in particular Professor Clifford of the University of Surrey, UK, and Professor André Charrier, ENSA M, France.

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Chapter 1
Introduction

1.1 Scope of the book

The primary meaning of the word ‘wine’ is the product of the aqueous fermentation by yeasts of the sugars in the juice of grapes. The fermented juices of many other fruits are sometimes also called wines, though they do not enjoy the same popularity or prestige as the grape wines. Fermented liquids from materials containing starch or cereals are usually called ‘beers’. The term wine is incorrectly used, for example, in rice wines, since the sugars in rice are stored as starch. Since fermenting yeasts can only convert sugars into alcohol, raw materials containing starch need to be processed so that, first, sugars are generated, for example, by hydrolytic cleavage of the starch. Uniquely, grapes contain tartaric acid, which has preservative qualities, and which, in addition to the presence of fermentable sugars, gives wines both a relatively high acid and alcohol content.

This book is solely concerned with wine from grapes. The focus is on the chemistry and flavour of table wines, which are normally consumed with meals. These wines have an alcohol content of 9-15% v/v (percent by volume), typically 11.5-14% v/v for red wine. Many red wines from hot wine regions exceed this percentage since the grapes are picked more mature with higher sugar levels. Wines consumed before a meal (aperitifs) are usually ‘dry’ (low sugar content) and often fortified to raise the alcohol content to about 20% v/v. Wines consumed after a meal tend to be sweet, for example, made by fortification with alcohol before the yeasts have converted all the sugar into alcohol, giving fortified wines such as Port as made in the Douro region in northern Portugal. Such fortified sweet wine styles are also made in other regions, and will be referred to as Port style. Fortification of dry wine followed by a special maturation process gives Sherry, as made in the Jerez region in Spain. Some other wine regions also use variants of this production to make Sherry style wines. Sherry can either be kept dry to be served before a meal or sweetened to be served after
a meal. The wine-making process of the classic wines Port, Sherry and the
less popular Madeira will be described separately.

There is a very wide range of types of table wines, from sweet to dry and
from still to sparkling, including its most famous example, Champagne. Table
wines can be red, rosé or white, the colours depending on the choice of grapes
and the wine-making processes used. The wines can be sweet or dry, although
red wines tend to be always dry, while white wines are produced from dry to
to very sweet, with a range of different sweetness levels in between. A most
remarkable sweet white wine is made from grapes infected by Noble Rot that
is caused by a mould (Botrytis cinerea). The term ‘wine’ will be restricted to
the main species of the vine plant, Vitis vinifera, which covers about 98% of
the total wine production from grapes.

1.2 Historical background

There is much historical information on wine, for example, Johnson’s (1989)
excellent writing and McGovern (2003). It is generally considered that vines
originated from the Caucasus area of Russia, between the Baltic and the
Caspian Seas. After the Stone Age, some 6000 years ago, settled agricultural
practices developed in the ‘Fertile Crescent’ of Mesopotamia and Egypt. Wild
vines, botanically known as Vitis vinifera sylvestris, became domesticated and
strictly speaking became the so-called Vitis vinifera L. sativa.

The Vitis genus contains many similar species, with other names such as
Vitis labrusca (see the next paragraph). From those very early origins in
Mesopotamia and Egypt, vines and wine-making methods were exported to
the Greek- and Latin-speaking world of the Mediterranean. After the decline
of these civilizations, wine production in Europe was not established until late
medieval times. Wines were shipped in barrels and even countries with little or
no wine production could enjoy drinking wine. Fortified wines such as Sherries
(the Sack of Shakespeare’s Falstaff) developed as a result of the Arabian
invention of distillation, which gave the required skills to prepare fortifying
spirit that could be added to wines. In the late nineteenth century wine
production was fully established in France. France, Italy and Spain are still the
three largest wine producers.

Speculation remains, however, about the flavour of these early wines compared
with the wines we know today. Grape juice is fairly easily fermented by ubiquitous
yeasts, and the fermented product can be reasonably stable due to its relatively
high alcohol and acid content. However, there are longer-term storage problems
and it is likely that wine spoilage was a frequent problem. This was due to a lack
of understanding of the actual processes involved in vinification and their
effective application. For example, it was not until the days of Louis Pasteur in the
1860s that the role of yeasts in wine fermentation, in addition to the role of some
lactic acid bacteria in wine spoilage, was uncovered. The scientific achievements
of Pasteur regarding the discovery of the microbiological processes involved in
wine-making laid the foundations for the modern wine industry.
As late as the eighteenth century, wines were mostly sweet, although even from these more recent times we have little information regarding the sensory properties of the wines. Roman wines are thought to have been more like syrups. Wines were stored and transported in amphorae, which were long earthenware vessels fitted with stoppers, often made of waxy materials. The Romans used glass decanters to bring wine to the table but glass was too fragile for storing wine. An especial boost came with the invention of glass bottles in the early seventeenth century that were sufficiently strong to allow the transport and storage of wine. Once corks started to be generally used to seal wine bottles, it was a relatively small step to mature the wine in bottles, which had to lie at a fairly even temperature to prevent leaking. Wines have long been imported to the UK, where there was an appreciative market for so-called fine wines. For example, there was a marked interest in red wines from Bordeaux in the early twentieth century, to accompany the lengthy Edwardian dinners.

The native vine plant is confined to certain latitudes of the world and its domesticated version similarly requires favourable growing conditions. In particular, vines thrive in a climate with the right combination of sun and rain, although varieties/cultivars have been adapted to suit various climatic conditions. The type of soil is important, with adequate drainage being a prerequisite for successful vine cultivation. The areas of growth include North and South America, outside the tropics and excluding the very temperate zones. The commercial production of wines in many regions outside Europe did not really develop until the late nineteenth century. White settlers in Australia and New Zealand were interested in wine-making but only after World War II did the wine industry really develop. The spread of vine and wine is probably also closely linked to social and cultural aspects of communities.

Viticulture in Europe and elsewhere, like the production of other domesticated plants cultivated for food and drink, has been closely associated with the activities of plant breeders. Hence, over the centuries many varieties/cultivars of the species *Vitis vinifera* have been selected, e.g. *Vitis vinifera* Pinot Noir, and are responsible for the various wines that are available in the market place. An important part of the history of wine is the disease caused by *Phylloxera*, a root louse pest accidentally imported from America that struck nearly all vines in Europe in the 1870s, devastating many vineyards by killing the vines and thereby ruining the wine industry. It was not until the discovery that grafting local European vines onto American imported root-stocks conferred resistance to the disease that the wine industry in Europe started to recover. Ironically, *Phylloxera* eventually attacked vines in California around 1980, damaging many vineyards.

### 1.3 Wine flavour

The smell and taste of a wine are directly associated with the chemistry of the entire wine-making process. The word flavour usually indicates the combination of smell (or odour) and taste. However, when assessing the
sensory properties of wine, the word ‘tasting’ is used to indicate that the flavour of the wine is being judged. The flavour of wine originates from (1) the grapes, (2) the treatment of the must (grape juice) and its fermentation and (3) the maturation process of the wine. The chemistry of the flavour compounds derived from these three sources will be discussed in some detail for both non-volatile (Chapter 3) and volatile (Chapter 4) compounds.

Wine writers in numerous books and articles, many in the English language, have dealt with the subject of wine flavour. Some texts are aimed at the marketing aspects of wine and emphasize the opinions of expert wine tasters. Other texts are more critical, such as Barr (1988). Of course, there are also numerous texts in French and German, dealing with all aspects of wine. The number of technical texts which directly relate the flavour of the wine to its chemistry is much more limited, though there are some chapters in books on food and beverage flavour in general (see Bibliography). Many scientific papers describe only individual aspects of wine flavour and its chemistry. None of these texts are complete; they omit to raise many questions and fail to answer many others. An exception is the comprehensive scientific book of Jackson (1994, revised for the second and third edition in 2000 and 2008 respectively), which discusses in detail the three interrelated topics of wine science: grapevine growth, wine production and wine sensory analysis. Ribéreau et al. (2006) have published a similar work in two volumes (in English).

The term ‘wine tasting’ is often used and suggests ignorance of the essential nature of wine flavour, which is a combination of (a) the five taste sensations (sweet, salt, sour, bitter, umami) from non-volatile substances perceived on the tongue and (b) the aroma (or smell) sensation from volatile substances perceived by the olfactory organs behind the nose. Volatile substances reach the olfactory organs by two routes, sometimes referred to as the nasal and retronasal routes. Nasal means that volatile compounds will reach the olfactory organ through the nostrils of the nose during the period of ‘nosing’ the wine from the glass. Nosing is the traditional sniffing of the air space above the glass of wine, before any sample is placed in the mouth. Once in the mouth, the wine is warmed up, moved around in the mouth and there is the option of noisily sucking air through the mouth. All these actions help the volatile compounds to escape from the wine and to travel retronasally via the back of the mouth to the olfactory organ. Volatile compounds detected during nosing are often described separately, and may or may not be similar or identical to those detected on the palate. Wine tasting will be discussed in Chapter 5.

There is no consensus in the use of terms like bouquet, aroma, etc. and different wine writers may use them with different meanings. The term ‘aroma’ is most commonly used to describe the smell of the wine derived from the grapes, while the term ‘bouquet’ tends to refer to the smell of the wine formed as part of the development during maturation.

The quality and quantity of colour as well as the clarity of the wine are assessed entirely by eye, usually before the tasting. Next, our sense of smell
and taste are used to assess the flavour of the wine. The depth of intensity and the multicomponent detection of flavour notes in wines (usually described in terms of flavour notes from other fruit/vegetable/mineral/animal sources) that are used to describe wine attributes by many expert wine tasters is surprising to the non-expert wine-drinker, and at times stretches credulity. In addition to flavour recognition and description, there are also the perceptions of mouthfeel, temperature, bubbles, etc., which all are registered and assessed by our senses. Over and above the enjoyment of the wine flavour, wine is also drunk for its stimulant properties, derived from up to 15% v/v ethyl alcohol, formed by the fermentation of sugars in the must by fermenting yeasts.

The flavour of wine is determined by the grape variety (or varieties), in combination with the growing conditions, such as climate, agronomic factors during growth and harvest, and these are reflected in the composition and organic chemistry of the must. Perhaps equally important is the process of vinification used; in particular, must treatment, temperature, yeast strain, use of fermentation aids, filtration and other processes used, together with any maturation (ageing) process. The relative importance of these factors is a moot point, but they are all determined by chemical causes. Interestingly, for example, French wines are essentially characterized by the region in which they are produced, as referred to in the Appellation d’Origine Contrôlée (AC), usually without mention of the grape varieties used (although some French wines nowadays list the grape(s) used on the label). Although the grape varieties are defined in the AC, the proportions used may vary from year to year. As from 1 May 2009 the term ‘Appellation d’Origine Contrôlée AOC or AC’ has, with resistance from some producers, been progressively replaced with the new European standard, Appellation d’Origine Protégée (AOP). In contrast wine makers in many other countries, especially in the ‘New World’, make a feature of characterizing their wines by the grape variety used. In short, currently the French emphasize the ‘terroir’, while in many relatively new wine-making countries the emphasis is on grape variety. A particular grape variety (e.g. Chardonnay, Cabernet Sauvignon) can, evidently, produce a rather different wine flavour as a result of the method of vinification and maturation, even though, usually, the characteristics of the wine flavour for the grape variety remain recognizable. A given variety grown in a certain region is also claimed to give a different wine than when grown in another region, even though the process of vinification is essentially the same. This subject is further explored in Chapter 5.

Therefore the flavour of the wine derived from the grape has to be considered in terms of its complex chemical composition, which is detailed in subsequent chapters. Current wine-making practice is outlined in Section 1.5 to give a better understanding of the background in which chemical changes related to flavour occur. Formation pathways of flavour compounds during vinification are discussed in Chapter 7. Some physiological aspects of wines related to wine chemistry will be described briefly.
Wine Flavour Chemistry

1.4 Wine colour

Wines are primarily distinguished by their colour and fall into three groups: (1) white wines, which include most sparkling wines, (2) red wines, including most fortified Port style wines and (3) rosé wines, essentially an intermediate between white and red wines. A wine's colour is determined by the choice of grape and the vinification process. White grapes, which usually have pale yellow skins, give white wines, while black grapes, which have blue, red or even black skins, depending on the amount of colouring matter in the skins, give mostly red wines. Red grapes can give a range of wine colours, from deep red to rosé, depending on the wine-making process, and by careful handling they can even yield white wines, for example the 'blanc de noirs' in Champagne production. Since most of the colour is in the grapes' skin, the choice of the vinification technique for red grapes allows a lesser or greater extraction of colour into the wine.

Within each colour, however, there will be differences between wines, which are easily perceived in the wine glass. The clarity may also differ, due to very small amounts of very finely suspended insoluble matter (not desired), although nowadays most wines are clarified before reaching the consumer. The changes in colour that occur during ageing, whether the wine is stored in-bottle or in-cask, are determined by chemical composition; the colour of red wines depends on the content and composition of anthocyanins. Colour and the chemistry of the changes in colour during maturation will be discussed briefly in Chapter 3.

1.5 Vinification

Traditionally good wines were made in regions where the conditions were frequently just right to give healthy, ripe grapes, with somewhat cooler weather during vinification. Although undoubtedly much knowledge was collected over many years, there was limited control over the process and wine-making was, to an extent, considered to be an art. With the advance of our scientific knowledge of many aspects of wine-making and the improvements of technology used in wine-making, in particular the use of refrigeration at various stages, there is now much control over the process. Nonetheless, the wine maker still faces many choices that determine the properties of the wine, and so the art still remains in making the best possible wine that is typical for the grapes and the region. The use of modern technology has also enabled good quality wines to be made in many more regions, including ones once thought to be too warm.

A basic understanding of the wine-making process ('vinification') is necessary in any study of wine chemistry and wine flavour. Grapes are the key ingredients, and they should be healthy, mature and in good condition. The choice of grape variety will influence the wine flavour and colour and to an
extent depends on the region. Grape varieties and some of the main growing regions are discussed in Chapter 2. In essence the grapes are picked, crushed to form a ‘must’ (grape juice) and fermented by yeasts to convert the sugars present into alcohol. There are three stages in wine-making, all of which can influence the flavour and colour of the wine:

(1) Pre-fermentation, during which various pre-fermentation treatments of the grapes or must can be given (such as sulfur dioxide addition, sugar or acid adjustments, nitrogen contents and possible addition, clarification of must, contact time with the skins or ‘maceration’ and cooling).

(2) Fermentation of the must, during which several factors have to be managed (such as choice of fermenting yeast, fermentation temperature, maceration time and pressing conditions).

(3) Post-fermentation, during which several different treatments are available. Some are probably essential (such as racking to remove the spent yeast or ‘lees’), while others are optional, depending on the desired characteristics of the wine (such as filtration, cold stabilization). Wines can be made to drink when young, or after maturation (or ageing) in different types of vessels (such as old vats, new oak barrels or bottles).

Several general rules of modern wine-making have emerged. The production of both red and white quality wines requires attention to the following, as emphasized in many wine-making publications:

(1) Grapes should be picked at optimum ripeness, in sound and healthy condition, at as low a temperature as possible (in very warm conditions, they should be cooled) and transported to the winery with minimal delay for immediate processing. The must for white wines should be cooled both before and during fermentation.

(2) Strict adherence to cleanliness of all wine-making equipment; to prevent the growth of spoilage organisms on the grapes, in the must or in the wine at all stages of fermentation and maturation. A particular risk are Acetobacter bacteria, which convert alcohol into acetic acid, hence spoiling the wine into vinegar.

(3) Non-oxidizing atmospheres should be used, especially in the early stages of vinification of white wines, for example by blanketing the must or wine with inert gas and/or by addition(s) of sulfur dioxide.

(4) The temperature of the fermentation should be controlled. Heat produced during fermentation (an exothermic process) in stainless steel tanks should be removed by efficient cooling and refrigeration. This is usually done by cooling the outside of the tank or sometimes by pumping the must through an external heat exchange unit. Fermentation in barrels may lose heat through the relatively larger surface area; however, barrels are difficult to cool, though ice is sometimes used.
The success of wines produced in regions such as Australia, California and South Africa has been attributed to careful attention in controlling the vinification process, especially to the factors listed above. Of course, great care is also given to planning the vineyard (site selection, considering soil, climate and choice of the most appropriate grape) and vineyard management (pruning, fertilization, preventing disease and picking at grape maturity). Modern scientific methods of wine-making analysis and control have also been adopted. Nevertheless, traditional wine makers in Europe have not been slow to adopt modern practices and the overall quality of wine now available to consumers has improved significantly.

The equipment used for fermentation and details of that used for both pre- and post-fermentation stages have been well described in detail (Jackson, 2008; Ribéreau-Gayon et al., 2006), while Robinson (1995) has given a good account for the general reader. The actual equipment used differs between wineries, depending on local conditions and the style of wine that is made.

Spoilage of wine is what all wine-makers want to avoid. This risk is present at all stages of wine-making, and can be both microbiological and chemical in nature. Under the wrong conditions, Acetobacter bacteria can change wine into vinegar in a very short time. Yeasts also pose a risk, as reviewed by Loureiro & Malfeito-Ferreira (2003), pointing out that understanding the ecosystems of wineries is crucial in prevention of spoilage. Excess air is also a known enemy, possibly causing chemical spoilage by oxidation of the wine, and enhancing the risk of microbial spoilage.

1.5.1 Vinification process

The basic wine-making process described here, highlighting those parts that greatly influence the resulting end product, covers many components that are common to both red and white wines. Recent textbooks by Jackson (2008) and by Ribéreau-Gayon et al. (2006) offer the reader a more in-depth treatment. The formation of specific flavour compounds during vinification (Chapter 7, devoted to reaction pathways) and volatile compounds (Chapter 4) are discussed elsewhere. A recent review on red wine-making reviews steps of wine-making affecting colour (Sacchi et al., 2005), and interestingly cold soaks and the addition of sulfur dioxide tended to have an effect on the wine only over a short time, after some maturation the differences became minimal. Other parameters, such as yeast selection and carbonic maceration showed that the grape varieties affected the results.

Flow charts for both the production of red and white wines (Figs. 1.1 and 1.2 respectively) give a helpful overview of the various wine-making steps. Figures 1.1 and 1.2 reflect the headings below, as appropriate. Specific information for the production of red (Section 1.5.2) and white (Section 1.5.3) wines is included below. These brief descriptions focus on the differences from the general vinification process and, therefore, not all captions will be used in Sections 1.5.2 and 1.5.3.