Vinegars of the World
Lisa Solieri • Paolo Giudici
Editors

Vinegars of the World

Preface by Wilhelm Holzapfel
Vinegars can be considered as acidic products of special importance for the enrichment of our diet, and resulting from the desired or controlled oxidation of ethanol containing (liquid) substrates. The traditional use and integration of vinegars in numerous cultures can be traced back to ancient times. In fact, the cultural heritage of virtually every civilization includes one or more vinegars made by the souring action (of micro-organisms) following alcoholic fermentation. It has been documented that the Egyptians, Sumerians and Babylonians had experience and technical knowledge in making vinegar from barley and any kind of fruit. Vinegar was very popular both in ancient Greece and Rome, where it was used in food preparations and as remedy against a great number of diseases. In Asia, the first records about vinegar date back to the Zhou Dynasty (1027-221 BC) and probably China’s ancient rice wines may have originally been derived from fruit, for which (malted) rice was substituted later.

The historical and geographical success of vinegars is mainly due to the low technology required for their production, and to the fact that several kinds of raw materials rich in sugars may easily be processed to give vinegar. In addition, vinegars are well-known and accepted as safe and stable commodities that can be consumed as beverages, health drinks or added to food as preservatives or as flavouring agents. The majority of vinegars, especially from sugary and acidic fruits, are easy to make, and this explains the relatively slow development in their science and technology through time. However, there is an urgent necessity to increase scientific knowledge and improve the technology of vinegar manufacture, and thereby to ensure higher standards of quality and safety in an expanding and increasingly diverse world-wide market.

The quality of wine vinegar is determined by a network of factors, mainly the raw wine substrate, microorganisms involved, and the aceticification process employed in its production. Attempts to characterise vinegars have been based on the control of these three features. When the final products are analysed, it is difficult to evaluate to what extent quality differences are due to the raw material or to differences in production methods and in the microbial starter employed. Thus, it is
necessary to determine the influence of each feature separately. The knowledge, prediction, and integrated control of any of these features constitute the challenge to obtain more efficient and predictable ethanol conversions, thus increasing stability, quality and processing efficiency.

It deserves special mentioning that this book also focuses on recent developments in the molecular characterisation of prokaryotes. The vital information is presented in a concise manner, and includes microbial genomics and multi-locus sequencing techniques. In addition, an unprecedented amount of molecular data is provided which, together with phenotypic information, forms the basis for a new roadmap of acetic acid bacteria systematics.

Recently, nomenclature and classification of acetic acid bacteria have been strongly revised, and new genera and species were recognised from different environment samples. This has culminated into an unexpectedly large group, now encompassing more than ten genera, including about fifty species. Yet, not all the species are involved in vinegar production, and those most frequently reported (still) belong to the genera Acetobacter, Gluconobacter and Gluconacetobacter.

Vinegar technologies could be grouped in three main domains: static, solid state and submerged “fermentation”. The latter represents the most recent quick process, in which the typical parameters of oxidative conversion (temperature, oxygen, alcohol content, and acidity) are strictly controlled. This process requires a strong energy input, and is implemented for industrial vinegar production. By contrast, static and solid state fermentations are mainly applied to traditional vinegar production with a long fermentation phase, and entail low energy consumption.

Within the wide scope of this book, the editors succeeded in bringing together a group of internationally recognised experts as authors for the diverse areas and issues of importance to vinegars worldwide. About forthy scientists from ten countries have contributed to the compilation and preparation of the seventeen chapters, thereby giving a picture of the most representative vinegars in the world. The wide coverage includes both the history and global perspectives on vinegars, innovative and traditional technologies for manufacture, and the microbiology in the inclusive context of ecology and up-to-date taxonomy.

This book is unique in many respects. It can be considered as the most authoritative, documentation, both scientifically and practically, on vinegars hitherto. Its rational approach to vinegar production is based on recent scientific data on food science, technology, engineering and microbiology. The work is coherent, and all the chapters are well integrated and complementary in the context of its overall scope. General aspects regarding vinegar history, acetic acid bacteria, other micro-organisms, and technology were discussed separately in specific chapters. The main vinegars presently produced in the world are clearly exposed in synoptic tables giving evidence to raw materials, micro-organisms involved, and geographical distribution. Single chapters have been devoted to the most important vinegars, thereby providing a wealth of information on the wide variety of vinegars produced and consumed around the world.

It is my pleasure to congratulate the editors, Dr. Lisa Solieri and Prof. Paolo Giudici, with this outstanding achievement. I have no doubt that this book on vine-
gar will be an extremely valuable guide and standard work of reference to all scientists, technologists, engineers and scholars in this field. It will most definitely also provide exciting literature and pleasant reading experience to every consumer and particularly to the highly specialized connoisseurs and gourmets of our time.

November 2008

Wilhelm Holzapfel
Handong Global University
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_Andi Shau-mei Ou and Rei-Chu Chang_

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_Fusheng Chen, Li Li, Jiong Qu and Chunxu Chen_

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1.1 General Overview

The history of vinegar production, which dates back to around 2000 BC, has taught us a great deal about microbial biotransformation. However, vinegar has been always considered a ‘poor relation’ among fermented food products: it is not considered to be a ‘food’, it does not have great nutritional value, and it is made by the transformation of richer and more nutritive fermented foods. Vinegar is used as a flavouring agent, as a preservative and, in some countries, also as a healthy drink. It can be made from almost any fermentable carbohydrate source by a two-step fermentation process involving yeasts as the first agent, followed by acetic acid bacteria (AAB): the most common raw materials are apples, pears, grapes, honey, syrups, cereals, hydrolysed starches, beer and wine.

Since vinegar is generally an inexpensive product, its production requires low-cost raw materials, such as substandard fruit, seasonal agricultural surpluses, by-products from food processing, and fruit waste. However, there are also some very expensive vinegars, produced from regional foods according to well-established methods, although these are the exception to the rule: examples include traditional balsamic vinegar from Modena in Italy, sherry vinegar from Spain, and oxos from Greece. There are also spirit vinegars obtained directly by acetic oxidation of ethanol derived from the distillation of fermented mashes or petrochemical ethanol. In addition, pyroligneous liquor (or ‘wood vinegar’), collected during wood carbonization, is used as an agricultural feedstuff, an animal health product, an ingredient in cosmetics, and a traditional medicine in Japan and East Asia (Mu et al., 2003; 2006). In this book, these distilled solutions have not been considered as vinegars because no fermentative process occurs in their production. Another separate group consists of flavoured vinegars: herbal or fruit vinegars. Herbal vinegars are wine vinegars or white distilled vinegars flavoured with garlic, basil, tarragon, cinnamon, cloves, nutmeg or other herbs. Fruit-flavoured vinegars are wine and white vinegars sweetened with fruit or fruit juice to produce a characteristic sweet-sour taste. In these cases the name ‘X vinegar’ does not indicate the raw materials.
used in vinegar fermentation but the ingredients added to obtain specific taste and flavour characteristics (Figure 1.1).

1.2 Vinegars: Raw Materials and Geographical Distribution

According to the international definition of vinegar, in this book we consider only vinegars derived from a two-stage fermentation process of agriculturally produced raw materials. A list of vinegars is presented in Table 1.1, but cannot be considered exhaustive, since many different varieties of vinegar are produced all over the world, and some of them are unknown outside their area of origin. Most vinegars have a plant origin, with two exceptions: those produced from whey or honey. Whey, which is the milk serum residual of the cheese-making process, is rich in lactose and/or its corresponding hydrolysed sugars, galactose and glucose, depending on the cheese-making technology. Furthermore, sour whey is heavily contaminated with lactic acid bacteria (LAB) and needs to be pasteurized before alcoholic and acetic fermentation. Honey is very rich in sugars (70-80% w/w), mostly sucrose, fructose and glucose, the proportions of which are influenced by the botanical origin of the nectar collected by the bees. Honey is always diluted before alcoholic fermentation occurs; honey wine contains up to 17% (v/v) ethanol (Steinkraus, 1996). This alcoholic beverage is well known around the world by different names, such as mead, ambrosia, metheglin, hydromel, aguamiel, medovukha and ogol, and is also used to produce vinegar.

Figure 1.1 Fermentation of herbal flavoured vinegar in glass demijohns
Table 1.1 Overview of vinegars from around the world: raw materials, intermediate product, vinegar name and geographical distribution

<table>
<thead>
<tr>
<th>Category</th>
<th>Raw material</th>
<th>Intermediate</th>
<th>Vinegar name</th>
<th>Geographical distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetable</td>
<td>Rice</td>
<td>Moromi</td>
<td>Komesu, kurosu (Japanese)</td>
<td>East and Southeast Asia</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Heicu (Chinese)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bamboo sap</td>
<td>Fermented bamboo sap</td>
<td>Bamboo vinegar&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Japan, Korea</td>
</tr>
<tr>
<td></td>
<td>Malt</td>
<td>Beer</td>
<td>Malt vinegar</td>
<td>Northern Europe, USA</td>
</tr>
<tr>
<td></td>
<td>Palm sap</td>
<td>Palm wine (toddy, tari, tuack, tuba)</td>
<td>Palm vinegar, toddy vinegar</td>
<td>Southeast Asia, Africa</td>
</tr>
<tr>
<td></td>
<td>Barley</td>
<td>Beer</td>
<td>Beer vinegar</td>
<td>Germany, Austria, Netherlands</td>
</tr>
<tr>
<td></td>
<td>Millet</td>
<td>Koji</td>
<td>Black vinegar</td>
<td>China, East Asia</td>
</tr>
<tr>
<td></td>
<td>Wheat</td>
<td>Koji</td>
<td>Black vinegar</td>
<td>China, East Asia</td>
</tr>
<tr>
<td></td>
<td>Sorghum</td>
<td>Koji</td>
<td>Black vinegar</td>
<td>China, East Asia</td>
</tr>
<tr>
<td></td>
<td>Tea and sugar</td>
<td>Kombucha</td>
<td>Kombucha vinegar</td>
<td>Russia, Asia (China, Japan, Indonesia)</td>
</tr>
<tr>
<td></td>
<td>Onion</td>
<td>Onion alcohol</td>
<td>Onion vinegar</td>
<td>East and Southeast Asia</td>
</tr>
<tr>
<td></td>
<td>Tomato</td>
<td>–</td>
<td>Tomato vinegar</td>
<td>Japan, East Asia</td>
</tr>
<tr>
<td></td>
<td>Sugarcane</td>
<td>Fermented sugar cane juice</td>
<td>Cane vinegar</td>
<td>France, USA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Basi</td>
<td>Sukang iloko</td>
<td>Philippines</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Kibizu</td>
<td>Japan</td>
</tr>
<tr>
<td>Fruit</td>
<td>Apple</td>
<td>Cider</td>
<td>Cider vinegar</td>
<td>USA, Canada</td>
</tr>
<tr>
<td></td>
<td>Grape</td>
<td>Raisin</td>
<td>Raisin (grape) vinegar</td>
<td>Turkey and Middle East</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Red or white wine</td>
<td>Wine vinegar</td>
<td>Widespread</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sherry wine</td>
<td>Sherry (jerez) vinegar</td>
<td>Spain</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cooked must</td>
<td>Balsamic vinegar</td>
<td>Italy</td>
</tr>
<tr>
<td></td>
<td>Coconut</td>
<td>Fermented coconut water</td>
<td>Coconut water vinegar</td>
<td>Philippines, Sri Lanka</td>
</tr>
<tr>
<td></td>
<td>Date</td>
<td>Fermented date juice</td>
<td>Date vinegar</td>
<td>Middle East</td>
</tr>
<tr>
<td></td>
<td>Mango</td>
<td>Fermented mango juice</td>
<td>Mango vinegar</td>
<td>East and Southeast Asia</td>
</tr>
<tr>
<td></td>
<td>Red date</td>
<td>Fermented jujube juice</td>
<td>Jujube vinegar</td>
<td>China</td>
</tr>
<tr>
<td></td>
<td>Raspberry</td>
<td>Fermented raspberry juice</td>
<td>Raspberry vinegar</td>
<td>East and Southeast Asia</td>
</tr>
<tr>
<td></td>
<td>Blackcurrant</td>
<td>Fermented blackcurrant juice</td>
<td>Blackcurrant vinegar</td>
<td>East and Southeast Asia</td>
</tr>
<tr>
<td></td>
<td>Blackberry</td>
<td>Fermented blackberry juice</td>
<td>Blackberry vinegar</td>
<td>East and Southeast Asia</td>
</tr>
<tr>
<td></td>
<td>Mulberry</td>
<td>Fermented mulberry juice</td>
<td>Mulberry vinegar</td>
<td>East and Southeast Asia</td>
</tr>
<tr>
<td></td>
<td>Plum</td>
<td>Umeboshi&lt;sup&gt;c&lt;/sup&gt; fermented plum juice</td>
<td>Ume-su</td>
<td>Japan</td>
</tr>
<tr>
<td></td>
<td>Cranberry</td>
<td>Fermented cranberry juice</td>
<td>Cranberry vinegar</td>
<td>East and Southeast Asia</td>
</tr>
<tr>
<td></td>
<td>Kaki</td>
<td>Fermented persimmon juice</td>
<td>Persimmon vinegar</td>
<td>South Korea</td>
</tr>
<tr>
<td></td>
<td>Whey</td>
<td>Fermented whey</td>
<td>Whey vinegar</td>
<td>Europe</td>
</tr>
<tr>
<td></td>
<td>Honey</td>
<td>Diluted honey wine, tej</td>
<td>Honey vinegar</td>
<td>Europe, America, Africa</td>
</tr>
</tbody>
</table>

<sup>a</sup> Vegetable is not a botanical term and is used to refer to an edible plant part; some botanical fruits, such as tomatoes, are also generally considered to be vegetables.

<sup>b</sup> Obtained by bamboo sap fermentation.

<sup>c</sup> Umeboshi are pickled ume fruits. ʻUme is a species of fruit-bearing tree of the genus *Prunus*, which is often called a plum but is actually more closely related to the apricot.
<table>
<thead>
<tr>
<th>Common name</th>
<th>Botanical name</th>
<th>Edible part</th>
<th>Main carbon sourcesᵃ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apple</td>
<td>Malus domestica</td>
<td>Fruits (pome)</td>
<td>Fructose, sucrose, glucose</td>
</tr>
<tr>
<td>Apricot</td>
<td>Prunus armeniaca</td>
<td>Fruits (drupe)</td>
<td>Sucrose, glucose, fructose</td>
</tr>
<tr>
<td>Bamboo</td>
<td>Species and genera of the family Poaceae, subfamily Bambusoideae</td>
<td>Bamboo sap</td>
<td>Sucrose</td>
</tr>
<tr>
<td>Bamboo</td>
<td>Species of the genus Musa Hordeum vulgare</td>
<td>Fruits (false berry)</td>
<td>Sucrose, glucose, fructose</td>
</tr>
<tr>
<td>Barley</td>
<td>Hordeum vulgare</td>
<td>Seeds (caryopsis)</td>
<td>Starch</td>
</tr>
<tr>
<td>Carambola</td>
<td>Averrhoa carambola</td>
<td>Fruits</td>
<td>Fructose, glucose</td>
</tr>
<tr>
<td>Cashew</td>
<td>Anacardium occidentale</td>
<td>Fruits</td>
<td>Sucrose, inverted sugars</td>
</tr>
<tr>
<td>Cocoa</td>
<td>Theobroma cacao</td>
<td>Bean mucilage</td>
<td>Glucose</td>
</tr>
<tr>
<td>Coconut</td>
<td>Cocos nucifera and other species of the family Areceae</td>
<td>Coconut water (fibrous drupe)</td>
<td>Glucose, fructose</td>
</tr>
<tr>
<td>Date</td>
<td>Phoenix dactylifera</td>
<td>Fruits (drupe)</td>
<td>Sucrose</td>
</tr>
<tr>
<td>Fig</td>
<td>Ficus carica</td>
<td>False fruit (syconium)</td>
<td>Glucose, fructose</td>
</tr>
<tr>
<td>Grape</td>
<td>Vitis vinifera and other species of the genus</td>
<td>Fruits (berry)</td>
<td>Glucose, fructose</td>
</tr>
<tr>
<td>Oil palm tree</td>
<td>Elaeis guineensis</td>
<td>Sap (xylem fluid)</td>
<td>Sucrose</td>
</tr>
<tr>
<td>Onion</td>
<td>Allium cepa</td>
<td>Bulbs</td>
<td>Fructose, glucose, sucrose</td>
</tr>
<tr>
<td>Panicum</td>
<td>Panicum miliaceum and other species of the subfamily Panicoideae</td>
<td>Seeds</td>
<td>Starch</td>
</tr>
<tr>
<td>Pear</td>
<td>Pyrus communis and other species of the genus</td>
<td>Fruits (pome)</td>
<td>Fructose, sucrose, glucose</td>
</tr>
<tr>
<td>Persimmon</td>
<td>Diospyros kaki and other species of the genus</td>
<td>Fruits</td>
<td>Fructose, glucose, sucrose</td>
</tr>
<tr>
<td>Pineapple</td>
<td>Ananas comosus</td>
<td>False fruit (syncarpel)</td>
<td>Sucrose, glucose, fructose</td>
</tr>
<tr>
<td>Plum</td>
<td>Prunus domestica</td>
<td>Fruits (drupe)</td>
<td>Sucrose, fructose, glucose</td>
</tr>
<tr>
<td>Potato</td>
<td>Solanum tuberosum</td>
<td>Tuber</td>
<td>Starch</td>
</tr>
<tr>
<td>Raphia palm</td>
<td>Raphia hookeri and Raphia vinifera</td>
<td>Sap (xylem fluid)</td>
<td>Sucrose</td>
</tr>
<tr>
<td>Ribes (Blackcurrant, Redcurrant, Gooseberry)</td>
<td>Ribes spp.</td>
<td>Fruits (berry)</td>
<td>Fructose, glucose</td>
</tr>
<tr>
<td>Rice</td>
<td>Oryza sativa and Oryza glaberrima</td>
<td>Seeds (caryopsis)</td>
<td>Starch</td>
</tr>
<tr>
<td>Sorghum</td>
<td>Sorghum bicolor and other species</td>
<td>Seeds (caryopsis)</td>
<td>Starch</td>
</tr>
<tr>
<td>Sugarbeet</td>
<td>Beta vulgaris</td>
<td>Roots</td>
<td>Sucrose</td>
</tr>
<tr>
<td>Sugarcane</td>
<td>Species of the genus Saccharum</td>
<td>Stalks</td>
<td>Sucrose</td>
</tr>
<tr>
<td>Wheat</td>
<td>Triticum aestivum and other species</td>
<td>Seeds (caryopsis)</td>
<td>Starch</td>
</tr>
</tbody>
</table>

ᵃ Listed in order, from the largest to the smallest amount.
1.2.1 Botanical Species

Many botanical species can be used for vinegar production since they only need to have two main basic attributes; first to be safe for human and animal consumption, and second to be a direct or indirect source of fermentable sugars.

A non-exhaustive list of the main botanical species involved and their edible parts used is shown in Table 1.2. General classifications and groupings can be made on the basis of the chemical composition of the edible parts and their ease of fermentation:

- **Acid and easily fermentable**: pH <3.5, with glucose, fructose and sucrose as the main constituents, e.g. berries, grapes, apples, plums.
- **Moderate acid and easily fermentable**: pH 3.5-4.5, e.g. figs, dates.
- **Low acid and easily fermentable**: pH >4.5, e.g. palm sap.
- **Non-fermentable**: hydrolysis required before fermentation, e.g. seeds.

The chemical composition of the raw material exerts a strong selective pressure on microorganisms and determines the dominant species involved in acetification. Specific examples are given for the vinegars described in other chapters of this book.

The critical steps in vinegar production are the preparation and the fermentation of raw materials. Preparation of raw materials includes all the operations required to produce fermentable sugary and protein solutions, such as slicing and/or crushing to obtain fruit juice, enzymatic digestion of starch in cereals, as well as cooking and steaming in some cases. In general, fruits require less preparation than seeds. On the other hand, seeds are more easily stored and preserved, and consequently their use is independent of the harvest. Fruits are highly perishable, rich in water, and need to be processed very quickly; in some conditions, such as at high temperatures or in the case of damaged fruits, this will be immediately after harvest. These differences make seeds easier to transport and process in large factories, whereas fruits can be made into vinegar in small factories, with less technology, close to the production area.

1.2.2 Economic Importance

From an economic point of view, vinegar production is a small industry in the overall economy of industrialized countries (Adams, 1998). Global shares of the different kinds of vinegar in 2005 were balsamic vinegar (34%), red wine vinegar (17%), cider vinegar (7%), rice vinegar (4%), white vinegar (2%) and other vinegars (36%), as shown in Figure 1.2 (Vinegar Institute, 2006).

In the US market, white distilled vinegar has 68% of the unit share, cider vinegar accounts for 20%, and specialty vinegars account for 12%. In the specialty vinegar category, 39% comprises red wine vinegar, 30% balsamic, 13% all other wine, 12% rice vinegar, and 6% all other specialties (Vinegar Institute, 2006).

In Europe, the vinegar market was around $4.9\times10^8$ L in 2001 and $5\times10^8$ L in 2002, with business worth approximately €268.6 million and €234.3 million,
respectively. European vinegar shares are shown in Figure 1.3. The main vinegar-producing countries are France, Italy and Spain.

In China, white fruit and brewed vinegars are popular. Every year, $8.0 \times 10^9$ kg of distilled spirit vinegar and $2.0 \times 10^9$ kg of brewed vinegar are produced (Wei, 2001). There are at least 14 types of traditional brewed vinegars, among which five types are the most widespread: Zhenjiang aromatic vinegar, Sichuan bran vinegar, Shanghai rice vinegar, Jiangzhe rose vinegar and Fujian red rice vinegar (Liu et al., 2004).

In developing countries, where food preservation and technology options are limited, vinegar is an important agent for preserving fresh fruit and vegetables from rapid deterioration. Especially in the tropics, the environmental conditions accelerate food spoilage. Developing and improving small-scale vinegar production, and food fermentation technologies in general, is one of the goals of the FAO (Anonymous, 1995; FAO, 1998).

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**Figure 1.2** Global shares of the different vinegar types in 2005 (from the Vinegar Institute, 2006, available at http://www.versatilevinegar.org/markettrends.html#2)

**Figure 1.3** European vinegar share in 2002 (from Comité Permanent International du Vinaigre, available at http://vinaigre.fr)
1.3 Vinegar Processing: the Role of Fermentation

As for any other food, the global view of vinegar processing from producer to market can be summarized as shown in Figure 1.4. In general, basic safe food operating principles, such as good agricultural practices (GAP), good manufacturing practices (GMP) and good hygiene practices (GHP), should be in place in all the steps, but in particular before starting fermentation, when environmental factors may permit the growth of dangerous microorganisms such as aflatoxin-producing moulds and harmful bacteria, especially since these steps are often carried out at room temperature. After aceticification, there is no real danger of spoilage, since acetic acid has strong antibacterial activity at low pH. Vinegar also requires pack-
<table>
<thead>
<tr>
<th>Vinegars</th>
<th>Moulds</th>
<th>Yeasts</th>
<th>LAB</th>
<th>AAB</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Z. rouxii, Candida spp.,</td>
<td></td>
<td>Ga. intermedius,</td>
<td>Liu et al., 1996;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sc. pombe, S’codes ludwigii,</td>
<td></td>
<td>Ga. kombucha</td>
<td>Boesch et al., 1998;</td>
</tr>
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<td></td>
<td></td>
<td>P. membranaefaciens,</td>
<td></td>
<td></td>
<td>Teoh et al., 2004;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B. bruxellensis</td>
<td></td>
<td></td>
<td>Dutta, Gachhui, 2007</td>
</tr>
<tr>
<td>Beer/malt vinegar</td>
<td>–</td>
<td>Saccharomyces sensu stricto</td>
<td>Lb. brevis, Lb. buchneri,</td>
<td>A. cerevisiae,</td>
<td>White, 1970;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>P. damnosus</td>
<td>Ga. sacchari</td>
<td>Greenshields, 1975a,b;</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>Fleet, 1998;</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cleenwerck et al., 2002</td>
</tr>
<tr>
<td>Coconut water vinegar</td>
<td>nd</td>
<td>Saccharomyces spp.</td>
<td>nd</td>
<td>A. aceti</td>
<td>Steinkraus, 1996</td>
</tr>
<tr>
<td>Nata de coco</td>
<td></td>
<td></td>
<td>nd</td>
<td>Ga. xylinus</td>
<td>Steinkraus, 1996</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Iguchi et al., 2004</td>
</tr>
<tr>
<td>Fruit vinegars</td>
<td>–</td>
<td>S. cerevisiae, Candida spp.</td>
<td>nd</td>
<td>A. acetis,</td>
<td>Maldonado et al., 1975;</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>A. pasteurianus</td>
<td>Uchimura et al., 1991;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Gluconacetobacter spp.</td>
<td>Snowdon, Cliver, 1996;</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Ilha et al., 2000;</td>
</tr>
<tr>
<td>Palm wine vinegar</td>
<td>–</td>
<td>S. cerevisiae, S. uvarum, C. utilis, C. tropicalis, Sc. pombe, K. lactis</td>
<td>Lb. plantarum, Lc. mesenteroides</td>
<td>Acetobacter spp., Zymomonas mobilis</td>
<td>Okafor, 1975;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Uzochukwu et al., 1999;</td>
</tr>
<tr>
<td>Rice vinegar</td>
<td>Komesu</td>
<td>Aspergillus oryzae, Aspergillus soyae, Rhizopus spp.</td>
<td>S. cerevisiae</td>
<td>Lb. casei var. rhamnosus</td>
<td>Hesslerline, 1983;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>A. pasteurianus</td>
<td>Otsuka, 1990</td>
</tr>
</tbody>
</table>

(continued)
<table>
<thead>
<tr>
<th>Vinegars</th>
<th>Moulds</th>
<th>Yeasts</th>
<th>LAB</th>
<th>AAB</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red rice vinegar</td>
<td>Monascus purpureus</td>
<td>S. cerevisiae</td>
<td>nd</td>
<td><em>Acetobacter</em> spp.</td>
<td>Liu et al., 2004</td>
</tr>
<tr>
<td>Sorghum vinegar</td>
<td>nd</td>
<td>S. cerevisiae and other Saccharomyces sensu stricto</td>
<td><em>Lc.</em> meseteroides, heterofermentative LAB</td>
<td><em>Acetobacter</em> spp.</td>
<td>Steinkraus, 1996; Konlani et al., 1996; Naumova et al., 2003</td>
</tr>
<tr>
<td>African sorghum vinegar</td>
<td>nd</td>
<td>Monascus purpureus</td>
<td>nd</td>
<td><em>Acetobacter</em> spp.</td>
<td>Liu et al., 2004</td>
</tr>
<tr>
<td>Chinese sorghum vinegar</td>
<td>Monascus purpureus, Aspergillus oryzae, Monascus spp.</td>
<td>S. cerevisiae, Hansenula spp.</td>
<td>nd</td>
<td><em>Acetobacter</em> spp.</td>
<td>Liu et al., 2004</td>
</tr>
<tr>
<td>Whey vinegar</td>
<td>–</td>
<td>K. marxianus</td>
<td>nd</td>
<td><em>Ga.</em> liquefaciens, <em>A.</em> pasteurianus</td>
<td>Parrondo et al., 2003</td>
</tr>
</tbody>
</table>

aging; intermediate bulk containers and tanks should be manufactured of stainless steel, glass or plastic material resistant to corrosion. After raw material preparation, fermentation plays a key role in vinegar production. Different microbial species are involved at various stages of the fermentation process, such as LAB, yeasts, moulds and AAB, which often colonise vegetables, fruits and other raw materials used in vinegar production. From each microbial group, the main species associated with vinegars are listed in Table 1.3. The great microbial diversity reflects the variety of raw materials, sugar sources and processes, as well as the diversity of the physico-chemical characteristics (e.g. temperature, pH, water activity).

Two steps are common to all vinegars: alcoholic and acetic fermentation, due to yeasts and AAB, respectively, whilst other microorganisms, such as moulds and LAB, are involved only in specific vinegars. Among the yeasts, *Saccharomyces cerevisiae* is the most widespread species in fruit and vegetable vinegars; the lactose-fermenting yeast, *Kluyveromyces marxianus*, is the species responsible for whey fermentation; and a physical association of yeasts, LAB and AAB is involved in the fermentation of kombucha. Even though there are now ten generally recognized genera of AAB (Chapter 3), the majority of the species detected in vinegars belong to the genera *Acetobacter* and *Gluconacetobacter*. However, it is likely that several of the species and genera involved in vinegar production have not yet been described because of the difficulties in cultivating AAB. Furthermore, the taxonomy of the acetic acid bacteria is undergoing extensive revision at present, and many species and genera may soon be reclassified.

### 1.3.1 Spontaneous Fermentation

Fermentation can be induced either by spontaneous fermentation, by back-slopping, or by the addition of starter cultures. In spontaneous fermentation, the raw material is processed and the changed environmental conditions encourage the most appropriate indigenous microflora. The more stringent the growth conditions are, the greater becomes the selective pressure exerted on the indigenous microorganisms.

In a very acidic and sugary environment, such as some fruit juices, only yeast, LAB and AAB can grow. Spontaneous fermentation is suitable for small-scale production and only for very specific juices. However, the method is difficult to control and there is a great risk of spoilage occurring. In most spontaneous fermentations, a microbial succession takes place, and quite often LAB and yeasts dominate initially. These consume sugars and produce lactic acid and ethanol, respectively, which inhibit the growth of many bacteria species, determining prolongation of the shelf life of the goods. Moulds mainly grow aerobically and therefore their occurrence is limited to specific production steps or on crops before and after harvest. Moulds are a big safety concern, since some genera and species are aflatoxin producers. Therefore, the moulds used for starch hydrolysis of seeds should be GRAS (Generally Recognized As Safe). AAB are aerobic whole-cell biocatalysts involved in the conversion of ethanol to acetic acid. AAB are widespread on fruits and in many sugary and acid environments, and their growth is promoted by procedures
that increase the availability of oxygen after yeast fermentation. Examples are sub-
merged culture and solid state fermentations (Chapters 9 and 15).

1.3.2 Back-Slopping Fermentation

Back-slopping uses part of a previously fermented batch to inoculate a new batch. This procedure increases the initial number of desirable microorganisms and

![Figure 1.5 Succession of steps in back-slopping to transfer the AAB film from a vinegar cul-
ture to a new wine barrel. a Tool to collect AAB film b Tool inside the vinegar barrel c Tool
covered with the AAB film d Vinegar barrel after removal of an AAB film portion e,f Film
transferred into wine barrel to start the acetification process (from Giudici et al., 2006)
ensures a more reliable and faster process than spontaneous fermentation. Back-slopping is a primitive precursor of the starter culture method, because the best-adapted species are seeded over the indigenous population (De Vuyst, 2000). Nevertheless, the manufactured goods are still exposed to the risk of fermentation failure, since mould growth or harmful bacteria spoilage can occur.

In general, back-slopping is considered a useful practice because it improves the growth of useful yeasts, while inhibiting the growth of pathogenic microorganisms and reducing spoilage, and in addition the laborious and time-consuming starter selection process is avoided. The back-slopping practice is particularly useful for inoculating AAB cultures, as they are very fastidious microorganisms that need special attention in order to produce true starter cultures. In the semi-continuous submerged acetification process, at least one-third of the vinegar is left in the fermenter to inoculate the new wine (Chapter 6), whereas in surface-layer fermentation a physical transplant of the AAB film can be easily done in order to preserve the integrity of the cell layer, as shown in Figure 1.5. This procedure assures a better implantation of inoculum on the indigenous microbial population in a new barrel.

1.3.3 Starter Culture Fermentation

A starter culture can be defined as a microbial preparation of a large number of cells of a microorganism (in some case more than one), which is added to the raw material to produce a fermented food by accelerating and steering its fermentation process (Leroy and De Vuyst, 2004). Starter culture development is strictly related to the ‘pure culture’ technique, which is a practice originally elaborated by Robert Koch for bacteria (Raineri et al., 2003). By using this approach each microbial colony is made up of cells that all originate from the same single cell. This ensures that the cultures are not a mixture of different unknown individuals and they can therefore be relied upon to produce the desired biochemical reactions.

The use of starter cultures in food production is a well-accepted practice, as it increases the safety, the stability and the efficiency of the process and reduces production losses caused by uncontrolled fermentation, eliminating undesired features. In some Asian vinegars, a mixed starter culture of undefined moulds and yeasts, called koji, is used to saccharify and ferment rice and cereals. However, koji cannot be considered to be a true starter, as its exact microbial composition is often unknown. In other cases, true starter cultures of oenological S. cerevisiae strains, selected for winemaking, are used for producing the alcoholic bases for vinegars, such as beer, wine and cider. S. cerevisiae var. sake, selected for sake production, is mainly used in rice vinegar fermentation.

Regarding acetic fermentation, the use of starter cultures is a long way from being applied on a large scale, for two main reasons: first, the AAB are nutritionally demanding microorganisms, which are difficult to cultivate and maintain in laboratory media, or to preserve as a dried starter; and, second, vinegar is generally an inexpensive commodity and therefore its manufacture does not warrant an expensive starter culture selection.