THE ROUTLEDGE HANDBOOK OF SUSTAINABLE FOOD AND GASTRONOMY

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CONTENTS

Foreword x
Editors’ biography xii
Editorial introduction xiv
Acknowledgements xvii
Notes on contributors xviii

PART 1
Anthropology of food 1

1 “Luxurious simplicity”: self-sufficient food production in Italian ecovillages 3
   Alice Brombin

2 Spirituality, social identity, and sustainability 21
   Peter Varga

3 ‘Sustainable food’: whose responsibility is it anyway? A personal commentary 29
   Clare Hindley

4 Food for thought: culinary heritage, nostalgia, and food history 34
   Paul Cleave
PART 2  

Local food initiatives

5 Does the pursuit of local food destroy our environment? Questions of authenticity and sustainability  
Sean Beer

6 Back to the roots – when hip meets sustainable: a case study of the Kartoffelkombinat in Munich  
Thomas Berron

7 Nutrition in rural India  
Richa Govil

8 Aboriginal food: traditional dishes surviving in the fast food era  
Donald Sinclair and Carolann Marcus

9 Sustaining and spreading local food culture through cooking classes: a case study of Chiang Mai, Thailand  
Wantanee Suntikul, Rodrigues Ng Iris, Ho Weng, Luo Xiao Yan, Lam Iok Cheng and Chan Weng San

10 The use of local culture and sustainability in local food and beverage entrepreneurship: case studies in Cornwall  
John Tredinnick-Rowe and Tim Taylor

PART 3  

Food movements

11 Vegetarianism for public health and for the environment: major F&B implications  
Maryam Fotouhinia Yepes

12 Reducing the food miles: locavorism and seasonal eating  
Jan Arend Schulp

13 Spa cuisine: an opportunity for the hospitality industry?  
Sandra J. Cooper

14 Discussions on Slow Food and San Francisco  
Alissa Folendorf, Colin Johnson and Mehmet Ergul
PART 4
Social pillar/social entrepreneurship 143

15 Ethical employment in the catering industry
   Gaurav Chauela 145

16 The Peruvian cacao value chain’s success: fostering sustainable entrepreneurship, innovation, and social inclusion
   Sandor G. Lukacs de Pereny 157

17 An analysis of the potential restaurant operations have for rehabilitating offenders: a case study of Her Majesty’s Prison, The Verne
   Sonja Beier 187

PART 5
Food innovation/future 197

18 Broadening insect gastronomy
   Afton Halloran, Christopher Münke, Paul Vantomme, Benedict Reade and Josh Evans 199

19 Wild ideas in food
   Christopher Münke, Afton Halloran, Paul Vantomme, Josh Evans, Benedict Reade, Roberto Flore, Roland Rittman, Anders Lindén, Pavlos Georgiadis and Miles Irving 206

20 Foods from aquaculture: varied and growing
   Ricardo Radulovich 214

21 Fermentation art and science at the Nordic Food Lab
   Benedict Reade, Justine de Valicourt and Josh Evans 228

PART 6
A sustainable restaurant system 243

22 Sustainable restaurant concepts, focus on F&B
   Elena Cavagnaro 245

23 Foodservice, health and nutrition: responsibility, strategies and perspectives
   Laure Saulais 253
Contents

24 Sustainable supply chains and environmental and ethical initiatives in restaurants  
Christine Demen Meier, Nicolas Siorak, Stéphanie Bonsch Buri and Clémence Cornuz

25 How self-sufficient can a restaurant be? Introducing the Foodzone model, a managerial tool  
Jaap Peter Nijboer, Peter R. Klosse and Jan Arend Schulp

26 Business model development for a sustainable and responsible restaurant concept: the dimensions and business rationales of CSR and sustainability  
Anders Justenlund

27 The sustainable restaurant: does it exist?  
Charles Barneby and Juline E. Mills

PART 7  
Culinary tourism

28 Local foods: marketing and the destination  
Martyn Pring, Sean Beer, Heather Hartwell and Jeffery Bray

29 Authenticity and experience in sustainable food tourism  
Sonia Ferrari and Monica Gilli

30 The autumn-pear: a symbol for local identity, local specialities, biodiversity and collaborative park management, an Austrian case study  
Ulrike Pröbstl-Haider, Elisabeth Hochwarter and Josef Schrank

31 Tourism, food traditions and supporting communities in Samoa: the Mea’ai Project  
Tracy Berno

32 Foodways of lowland Sariaya: towards a sustainable food tourism  
Shirley V. Guevarra and Corazon F. Gatchalian

33 Gastronomic tourism: development, sustainability and applications – a case study of County Cork, Republic of Ireland  
Clare Carruthers, Amy Burns and Gary Elliott
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Author(s)</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>34</td>
<td>Responsible travel as a means to preserve cultural and natural</td>
<td>Nikki Rose</td>
<td>370</td>
</tr>
<tr>
<td></td>
<td>heritage: initiatives in Crete, Greece</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>PART 8</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>General issues/world food crisis</strong></td>
<td></td>
<td><strong>377</strong></td>
</tr>
<tr>
<td>35</td>
<td>International and national regulations in favour of sustainable</td>
<td>Nicolas Siorak, Christine Demen Meier, Stéphanie Bonsch Buri and</td>
<td>379</td>
</tr>
<tr>
<td></td>
<td>operations in food service</td>
<td>Clémence Cornuz</td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>The political and economic realities of food system sustainability</td>
<td>Christina Ciambriello and Carolyn Dimitri</td>
<td>391</td>
</tr>
<tr>
<td>37</td>
<td>Customer expectations regarding organic and healthy food</td>
<td>Christine Demen Meier, Nicolas Siorak, Stéphanie Bonsch Buri and</td>
<td>408</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Clémence Cornuz</td>
<td></td>
</tr>
<tr>
<td><strong>Index</strong></td>
<td></td>
<td></td>
<td><strong>421</strong></td>
</tr>
</tbody>
</table>
Nordic Food Lab

The Nordic Food Lab (NFL) is a self-governed foundation based in Copenhagen, Denmark. The aim of NFL is to investigate food diversity and deliciousness and to share the results in an open-source format. We combine scientific and cultural approaches with culinary techniques from around the world to explore the edible potential of our region. We are intent on challenging and broadening tastes while generating and adapting practical ideas and methods for those who make food and those who enjoy eating.

Food fermentation, as a highly diverse and complex set of phenomena, is ripe for this sort of interdisciplinary, practical study. Our aim is to understand the science and craft behind the exceptional results obtained by the very best food producers and, by analysing and experimenting with this knowledge, to figure out how it can be reapplied to food production in new ways.

Fermentation definition

A biochemist might define fermentation as ‘a process performed by microorganisms that transforms sugars into energy in the absence of oxygen’. Others adopt broader definitions of fermentation, including both the metabolic processes of microorganisms (with or without oxygen), and also the action of chemicals they produce (particularly enzymes, organic acids, gases and volatile compounds) of either plant or animal origin on a substrate (Nout, 2005). For the good of this text, food fermentation will be broadly defined as the metabolic processes of microorganisms as applied to food substrates for preservative, gastronomic, health and other benefits.

During the production of fermented foods, there are often other physical and chemical transformations that are not directly related to the microbes’ metabolism yet nonetheless affect the outcome of the final product. Examples include hydrolysis of macromolecules by enzymatic activity, oxidation from light or air, transformation by heat, and moisture loss. These processes are important in the production of certain foods, for example Maillard reactions in soy sauce and cured meats, or enzymatic and oxidative processes in various teas. While these processes are not direct results of fermentation itself, it is important to realise that
Figure 21.1  The Nordic Food Lab.
they may both affect and be affected by fermentation kinetics and are often vital to the organoleptic characteristics of the finished food product. A holistic understanding of fermented foods must also include these processes, along with the myriad other factors that affect the fermentation environment and thus the ultimate quality of the food.

Main functions of fermentation with a focus on sustainability

Preservation

This is the function most often cited for the development of fermented food traditions. Many fermentative processes produce organic acids, ethanol or carbon dioxide or other bio-preservatives such as nisin, which help to make the food pathogenically stable (Ross et al., 2002). These compounds make the environment difficult to inhabit for unwanted microorganisms, allowing the desirable microbes to become and remain dominant instead of pathogenic competitors. These fermentative processes often take place ‘spontaneously’ by naturally present microorganisms; many fermentation techniques thus likely began as chance discoveries, and were subsequently developed into more refined practice (McGovern, 2010). Fermenting edible substrates often requires little to no further temperature treatment – such as freezing, refrigeration, dehydration (hot or cold), pasteurisation or sterilisation – for preservation, and therefore fermented foods can often be made with a relatively low energy consumption. Fermentation techniques are thus ideal for remote areas and much of the developing world, and also for lowering energy consumption worldwide – many fermentation processes even generate energy. Fermentative food preparations also have applications during a glut of a certain type of food. A clear example of this is when many cabbages are ready at the same time – if one makes sauerkraut, possibly without even the addition of salt, the cabbages can be eaten all year long.

Flavour

Food fermentations usually contain organic acids. Especially when one considers the origins of fermentation as soured/alcoholic beer prototypes/porridges and early breads (Braidwood et al., 1953), the added sour taste would have served an important role in augmenting an essentially bland diet. During fermentation, the breakdown of complex carbohydrates into sugars, proteins into peptides and free amino acids, and lipids into fatty acids and aromatic molecules gives a much wider range of tastes, aromas and textures than would be available in the ingredients in their unfermented state. As flavour is the body’s way of recognising nutrients in the environment (Morini, 2007), it is unsurprising that this point of flavour development is intrinsically linked to the bioavailability of nutrients – as explored in brief below.

Health

There is an exponentially broadening picture of how microbes and fermented foods affect our health. Microbes break down molecules in the foods we eat, such as lactose in dairy products and inulin and other less-digestible fibres in vegetables. Fermentation can also enhance vitamin and essential amino acid content as well as produce beneficial antimicrobial compounds. This increase in bioavailability of nutrients means that foods that would otherwise be quite poor in nutrients can become very dense, just through the action of microbes and time. They detoxify certain foods like cassava, whose cyanogenic glycosides are rendered
harmless in fermentations. This detoxification leads us to broaden our food choices, as some foods that would otherwise be poisonous can be rid of toxins. Increasing the diversity of our food choices has repeatedly been shown to increase the sustainability of food systems by broadening our reliance on any one food, thus lowering specific pressures on natural resources and bolstering ecological resilience (Burlinghame and Dernini, 2012).

In many cases, fermented foods provide both probiotic and prebiotic functions (Cutting, 2011; Moslehi-Jenabian et al., 2010). The microbes themselves in unpasteurised foods sometimes come to populate our gastrointestinal tract, providing numerous benefits while reproducing and living in our bodies. Having a healthy ecology of bodily microbes is essential to sustaining human health; microbes living in our large intestine outnumber human cells in a healthy human body by around 10:1, providing essential and diverse roles such as heightened immune-responses, digestion and homeostasis (Wallace et al., 2011).

**Classification**

Classification of fermented foods can be done by different means – for example, by substrate, by classical microbial nomenclature, by human culture or geographical origin, by techniques used in production (such as inoculation method) or, as is most frequently done, a mixture of these methods.

At NFL we use a variety of methods to classify our fermentations, but perhaps the most useful is simply the name of the final product that our ferment aims to emulate. However, things quickly become complicated when we start to carry out processes that, at least to our knowledge, have never been carried out before. At this point a small amount of knowledge of the microbiology of similar fermented foods helps. For example, we know a bit about sauerkraut, and we would like to carry out a similar process on some apples. We know that in the sauerkraut we are trying to emulate, the dominant form of fermentation is ‘lactic acid fermentation’, so we call our apples ‘lacto-fermented apples’. This kind of classification removes the problem of identifying the often incredibly complex microbial ecologies inside the food stuff and allows us to describe new products by ‘functional similarity’ to existing techniques and traditions, rather than mainly by specific microbial ecologies.

**Classification by inoculation method**

There are three main ways we can begin the process of fermenting.

**Backslopping**

Backslopping has historically been the principal method for inoculation. Backslopping is the process of using an already successful ferment to inoculate a new one. The assumption is that the existing ‘good’ microbes will colonise the newly available nutrients, reproducing and generating a more-or-less similar culture. Good examples are sourdough bread mothers and some traditional vinegars. Methods of perpetuated ferments such as nuka or various brines into which typically vegetable substrates are submerged are similar in their ecology. This gives rise to mixed, but very stable ecology of microbes in the food (Vogel and Ehrmann, 2010). Some ferments use multi-stage backslopping methods, which can be very complex (Chen et al., 2008). Continual selection of successful ferments means that, over time, microbes are selected for beneficial characteristics. This symbiotic evolution also in turn affects human development (McGovern, 2010). This coevolution is a fascinating area of study.
Wild-type fermentations

Wild-type fermentations use the microorganisms found naturally on the substrate and in the surrounding environment. Often, but not always, these ferments are begun by changing the substrate’s physical and chemical conditions to select for a certain type of microbe that might already be found in its naturally occurring mix. For example, adding salt to cabbage selects for lactic acid bacteria (LAB) and against many pathogens. This method gives the least consistent and most surprising results (Katz, 2013).

Pure strain inoculation

Pure strain inoculation involves the addition of one or more known strains of microbes. This method has only been available since the laboratory cultivation of microbes became a developed and affordable technique. This process is used in almost all industrial-scale food fermentations. Many different species can be used for inoculation, a good summary of which can be found in Bourdichon et al. (2012). Although some results may lack character, this reliability can give the opportunity for perfecting recipes and technique over many batches.

Foods by applied microbial family

Bacteria

Lactic acid fermentation

LAB are a broad category of microbes found in many foods including pickled vegetables like kimchi and sauerkraut, sourdough, salami, soy sauce, and fermented dairy products such as cheese, villi or trahanas. Their unifying characteristic is their ability to produce lactic acid as the main product of their metabolism of glucose thus creating an acidic environment. By lowering pH, lactic acid protects the food against most pathogenic bacteria and gives these foods their characteristic sour flavour.

The fermentation can be homolactic or heterolactic. Homolactic fermentation transforms one molecule of glucose into two molecules of lactic acid, while heterolactic fermentation transforms one molecule of glucose into one molecule of lactic acid, one molecule of ethanol, and one molecule of carbon dioxide. This heterolactic fermentation explains the light effervescence of some acidified foods.

Homolactic fermentation: \( \text{glucose} = 2 \text{lactic acid} + \text{energy} \)
\[ C_6H_{12}O_6 = 2 C_3H_6O_3 + 2 \text{ATP} \]

Heterolactic fermentation: \( \text{glucose} = \text{lactic acid} + \text{ethanol} + \text{energy} \)
\[ C_6H_{12}O_6 = C_3H_6O_3 + C_2H_5OH + CO_2 + 2 \text{ATP} \]

To ferment many vegetables using LAB, little more is needed than to add salt. Salt draws moisture out of the vegetable matter by osmosis, which produces a brine: the submerged vegetables are then in the necessary oxygen-poor (but not completely anaerobic) environment in which LAB thrive. LAB fermentations can occur across a wide range of salinity, from 0 per cent (many dairy products like yoghurt and sour cream) to 25 per cent (certain seafood sauces in East Asia). We have found 2–2.5 per cent salt of the total weight of substrate to be a good minimum salt concentration to experiment with. This can be achieved by
adding 2.5g of salt to 100g of substrate or with brine by adding 5g salt to 100g water, and 200g substrate.

LAB are microaerophiles, meaning that they like to be in the presence of small amounts of oxygen, but not too much. They are also typically mesophilic, meaning that they like to ferment at room temperature or slightly warmer. For this reason we carry out much of our lactic fermentations in vacuum bags, which have been sealed just before reaching full vacuum.

If a heterolactic fermentation occurs, then CO₂ production may cause the bag to explode – keep a close eye! It should also be noted that excessive use of plastic vacuum bags is not a sustainable practice; old-fashioned brining, which we also utilise, is much less wasteful.

As the pathogenic microbe Clostridium botulinum cannot produce toxins below pH 4.2, this is generally regarded as a safe final acidity if it is reached quickly. Ferments can frequently be cooled down to slow or stop the microbial activity at pH 4.6 and the pH will continue to drop for a period, reaching a final pH of 4.2.

While we enjoy lacto-fermenting all manner of vegetables and dairy (Reade, 2013), other exciting experiments involving LAB include various fermented sauces. Incidentally, they are also a perfect example of a mixed microbial culture in action. Fermented sauces such as fish sauce and other protein-rich sauces are made partly through a process of lactic acid and sometimes alcoholic fermentations. These occur alongside the enzymatic breakdown of proteins (proteolysis). In the case of fish sauce, added salt prevents the growth of undesired microbes so halophilic (halo – salt, philic – liking) LAB can dominate the substrate. Through osmosis, the salt draws water from the fish, creating a brine in which proteolysis occurs. Enzymes of the fish’s flesh and digestive tracts flow into the brine and proteolysis causes the solution to become a ‘soup’ of free amino acids giving the sauce its characteristic umami taste.
Acetic acid fermentation

Vinegar, a solution of acetic acid and water and hopefully some residual sugar and aromatic compounds, is often considered a poor cousin in the realm of fermented foods. Yet when made with the right knowledge and aims, vinegar can be a high-quality and valuable product, as in the case of Aceto Balsamico Tradizionale di Modena, which reaches prices in excess of €1/ml.

As ethanol is a product of a first fermentation mostly done by yeast, vinegar is a product of a double and mixed fermentation. Vinegar can be obtained from any raw material that has undergone an alcoholic fermentation. A good vinegar is normally achieved from an alcohol concentration of 5–9 per cent; however both stronger and weaker solutions can produce excellent results. In an acetic fermentation, acetic acid bacteria (AAB) convert ethyl alcohol (ethanol) into acetic acid, the essential characteristic of vinegar. This occurs in the presence of oxygen:

\[ \text{ethanol} + \text{oxygen} = \text{acetic acid} + \text{water} + \text{energy} \]
\[ C_2H_5OH + O_2 = CH_3COOH + H_2O + 8–13 \text{ ATP} \]

Classic vinegars as we know them in the West are made by a number of methods. These can be divided roughly into two groups: slow, traditional techniques where attaining a finished vinegar may take from one month to many years; and rapid techniques, which make vinegar from ‘wine’ in as little as six hours.

AAB will proliferate much more easily if some vinegar is mixed in with the alcoholic ferment, thereby acidifying the wine and creating an environment where the AAB thrive. This addition is normally carried out using a mature batch of unpasteurised vinegar made from the same source (backslopping!). If this is done with unpasteurised vinegar it is also a means by which to inoculate the ‘wine’ with the correct AAB strains. As AAB are ubiquitous, if an alcoholic solution of appropriate concentration is left open to the air, it will eventually turn to vinegar, regardless of inoculation.

The most famous slow method of vinegar production is the Orleans method. Barrels are half-filled with a mixture of around 80 per cent wine and 20 per cent live, unpasteurised vinegar, and fermentation is carried out by the AAB, which, in warm conditions, will metabolise all the alcohol in a 9 per cent ethanol wine in one to three months. When fully acidified, the vinegar is siphoned off, leaving around 12L inside a 225L barrel. This is then again half-filled with fresh ‘wine’, allowing the maximum surface area to be exposed to air. To make sure the AAB have as much oxygen available as possible, holes are drilled through the ends of the barrel which are then covered with muslin. This same process can be carried out at home with a large, wide-mouthed jar covered in muslin – a great way to use leftover wine.

We are experimenting with the traditional method for balsamic vinegar production, except using quinces instead of grapes as the initial substrate. The result is an intense, resinous vinegar that has beautiful notes of dried figs and sherry. Another successful recipe involves elderflower wine macerated with elderberries and then left to oxidise into vinegar, creating a sweeter, layered elder vinegar with good aging potential. We have also experimented with rapid aeration methods that can give us vinegar in four to five days and from less traditional ingredients that have less residual sugar to start with, such as herbs, roots, mushrooms and trees. While the rapid method works well for prototyping and industrial production, the slow methods will invariably yield the most complex and delicious final products.
Alkaline fermentations

A lesser-known group of fermentations, alkaline fermentations involve aerobic endospore-forming bacteria (AEB). These foods provide protein-rich, low-cost condiments for millions of people in south-east Asia and Africa (FAO, 1998). The Bacillus genus, with B. subtilis as the most common species, is capable of hydrolysing proteins into amino acids and ammonia. The ammonia increases the alkalinity up to a pH of 9, protecting the food against bacterial spoilage and giving the characteristic amoniated smell. This type of fermentation normally uses legumes or seeds, as they are rich in proteins (Wang and Fung, 1996; Parkouda et al., 2009). Well-known examples of alkaline fermentations include Japanese natto, the rind on washed-rind cheeses and West African dawadawa or soumbala. NFL has not yet experimented very much with alkaline fermentation – it is a vast world yet to explore.

Fungi

Yeast

Many yeasts are able to produce energy in both aerobic and anaerobic conditions. In food, yeasts are primarily used under anaerobic conditions which will yield ethanol and CO₂. Yeasts thus give rise to almost all alcoholic beverages (the Mexican drink pulque is an exception, as most of its alcohol is produced by a bacterium, Zymomonas mobilis (Steinkraus, 1983)). Leavened bread is also made using yeast (Saccharomyces cerevisiae) – the CO₂ creates the bubbles in the bread, and the alcohol evaporates during baking.
The skins of sugary fruits are typically covered in a thin layer of wild yeasts (and other microbes). This means that as the fruit ripens, these yeasts consume available sugars. To make a wild-fermented alcohol, it is often enough just to leave the juices of sugar-rich fruits in contact with the skins for a while – this brief contact should be enough to initiate alcoholic fermentation. Once the yeasts begin transforming the sugars an airlock system should be used, allowing CO₂ to escape without allowing oxygen to enter.

The most commonly domesticated yeast is *Saccharomyces cerevisiae*, naturally found on fruit skins and other sugar-rich material. Due to their variations in alcohol tolerance and enzyme production, different strains of *S. cerevisiae* produce varying quantities of ethanol and CO₂ and at different speeds, which has given rise to different applications in baking and brewing since ancient times (it is also likely that different human activities have in turn selected for these functional differences, enhancing naturally occurring variation). Yeasts also play a role in the fermentation of dairy products such as kefir, as well as in cacao and coffee (Boekhout and Robert, 2003: 24). The genus *Saccharomyces* also contains other species (e.g., *S. bayanus* and *S. pastorianus*) that play an important part in processes of making bread, beer, wine and other alcohols. There are in addition many other yeasts involved in the fermentation of various other foods and drinks (Querol and Fleet, 2006).

**Filamentous fungi/moulds**

A huge diversity of fungi are involved in fermented dairy production (Ropars et al., 2012). Fermented meat products are similarly complex (Spotti and Berni, 2007) and although we experiment with both meat and dairy, much of our exploration into the realm of filamentous fungi has been elsewhere.

As discussed earlier, fish guts offer one source of proteolytic enzymes for the production of umami-rich, protein-based sauces. Another way of harnessing hydrolytic enzymes comes from filamentous fungi (mould) grown on cooked grains or pulses. *Koji* in Japan, *nuruk* and *meju* in Korea, *qu* in China – these mould-based techniques are loosely but functionally related. The most common fungus used in this technique, and the predominant one in Japanese *koji*, is *Aspergillus oryzae*. *A. sojae*, *Monascus purpureus* and other species are also used (Steinkraus, 2004). The mould produces many hydrolysing enzymes that can break down proteins, fats and starches (Chen et al., 2008). The umami taste arises through the breaking down of proteins into their building blocks of amino acids, thus creating free glutamic acid, the main molecule that bonds with the umami taste buds and enriches the flavour. Umami can also be found in other fermentations where some proteins are hydrolysed, such as in old cheeses, cured meats and fish sauce. Some of our most delicious recipes have been a sauce fermented in the soy sauce style with barley koji and yellow peas; a miso made in a similar fashion; Roman-style garums made with all manner of animal proteins including pheasant, hare, grasshopper and wax moth larvae; and ‘koji-chovies’ – herrings fermented to achieve an effect similar to anchovies. Although their traditional analogues may not have involved koji, at NFL all of these projects do so.

In addition to umami applications, mould-based saccharification processes also form the basis of grain-based wines such as *makgeolli*, *sake*, *amazake* and *li* (Shurtleff and Aoyagi, 2012).

Beyond its use for saccharification and proteolytic breakdown, we have also been experimenting with *koji* technology for its flavour development. Growing koji on barley and other grains yields a range of fruity, nutty and mushroomy flavours. Resulting koji can then be roasted, allowing us to obtain a whole range of toasted flavours akin to chocolate or coffee. We are currently developing versions of these products involving blends of fermented and unfermented Nordic ingredients, which are mixed with roasted *kojis*. 

236
Another application of filamentous fungi involves the mould *Aspergillus niger*, the predominant fungus in Pu-erh tea which gives it many of its mossy, earthy characteristics. We are currently investigating the use of this mould on Nordic plant parts to produce fermented tisanes that evoke Pu-erh in method but have ultimately their own character.

**Very mixed fermentations**

Most traditional food fermentations contain many species of microorganism. These microbial ecologies develop and can be highly stable, such as in the case of sourdough mothers (Vogel and Ehrmann, 2010), or they may fluctuate as populations of different species rise and fall. One example would be the *moromi* stage of a soy sauce ferment. First, the salt in the *moromi* brine kills off species (such as the koji moulds), which are not tolerant to the changed osmotic pressure. Next, halotolerant yeast (*Zygosaccharomyces rouxii*) species that create alcohol begin to thrive, and as they consume available sugars, a species of LAB (*Tetragenococcus halophilus*) begins to acidify the solution as the yeasts subside (Steinkraus, 2004).

A further example of a mixed fermented food is kombucha. Kombucha is a beverage typically made with black tea, sweetened with 5–15 per cent sucrose, and set to ferment at 25–30 °C for 10–12 days with a symbiotic culture of bacteria and yeasts (SCOBY) (Sreeramulu et al., 2000; Dufresne and Farnworth, 2000). Inoculation of new batches uses either about 10 per cent of kombucha from a previous batch, or a piece of the mother. The brewing vessel is covered with a clean, coarsely woven cloth to keep out insects and debris while allowing aeration (Greenwalt et al., 1998).

The jellyfish-like mother produced by *Acetobacter xylinum* is often called ‘tea fungus’ (Mo et al., 2008).

*Figure 21.4* Kombucha mother.
Figure 21.5  Venison Fenalär.
Although much superstition surrounds the presence or absence of the mother, the functional microbes are present also in the liquid and the floating membrane is in fact only a visible manifestation of the yeast–bacteria symbiosis – the zoogloal mat (Jayabalan et al., 2010; Sreeramulu et al., 2000). The cellulose is a secondary metabolite of the fermentation, similar in structure to a ‘mother of vinegar’ (Jayabalan et al., 2010). The exact microbial composition depends on the source, condition and treatment of the kombucha culture (Sreeramulu et al., 2000).

We have experimented quite extensively with kombucha, exploring flavouring agents and different fermentable substrates. Particularly interesting and successful recipes have included kombuchas of juniper wood, boletus mushrooms, lemon verbena and carrot.

**Fenalår**

Fenalår is an old Norwegian tradition for preserving sheep’s leg. We have taken this tradition and elaborated it quite a bit, mixing in mummification techniques and other layers of fermentation to yield a product that is as complex as it is unique and delicious. We undertake the process on a leg of roe deer. The process involves rubbing the venison leg with yoghurt whey; leaving it at 5 °C overnight; rubbing the leg with juniper dust and salt (around 2 per cent of weight); leaving it at 2 °C for seven days; rubbing the leg with spruce resin tincture; hanging the leg at 2 °C for four days; placing the leg in a cold smoker for four days; removing and hanging for two months; dipping into rendered deer fat; leaving a further two months; dipping into melted beeswax; leaving a further two months; then removing the wax, slicing thinly and enjoying. This is a very mixed fermentation that likely involves LAB, yeasts, enzymatic breakdown of proteins and fats, oxidation, moisture loss, surface moulds of varying descriptions and the production of a whole host of secondary metabolites – and is a perfect example of complex microbial ecology in action.

**Conclusion**

Microbes are one of the most powerful tools we have to create foods that are diverse, delicious, nourishing and speak genuinely of their place in the world. We have been evolving alongside microbes since before our emergence as a species and will continue to do so into the future. Engaging in the fermentation of food is one of the most exciting ways to engage directly in this coevolution. Using scientific methods to learn more about the complexity of microbial ecology in fermented foods, paired with a gastronomic sensibility and a desire to eat well, allows us to experiment, keeping food traditions alive and exploring ways to situate them in contemporary food systems and cultures.

We are continually discovering new applications for pure strain microorganisms and wild mixed ecologies, and new techniques to make the most of traditional and innovative tools and techniques. Visit our website, www.nordicfoodlab.org, for more information on all of the above and to follow our ongoing research.

**References**


