7 *The Lay Panel Preliminary Report: UK National Consensus Conference on Plant Biotechnology 2–4 November 1994* (1994), p. 3, Science Museum, London, UK
8 *The Lay Panel Preliminary Report: UK National Consensus Conference on Plant Biotechnology 2–4 November 1994* (1994), p. 8, Science Museum, London, UK
9 *The Lay Panel Preliminary Report: UK National Consensus Conference on Plant Biotechnology 2–4 November 1994* (1994), p. 10, Science Museum, London, UK
10 Mestel, R. (1994) *New Sci.* 144, 4
11 *The Lay Panel Preliminary Report: UK National Consensus Conference on Plant Biotechnology 2–4 November 1994* (1994), p. 12, Science Museum, London, UK
12 *House of Lords Select Committee Report on the Regulation of the UK Biotechnology Industry and Global Competitiveness 13 July 1993* (1993), HMSO, London, UK

Review

Food preservation by hurdle technology*

Lothar Leistner and Leon G.M. Gorris

Hurdle technology was developed several years ago as a new concept for the production of safe, stable, nutritious, tasty and economical foods. It advocates the intelligent use of combinations of different preservation factors or techniques ('hurdles') in order to achieve multi-target, mild but reliable preservation effects. Attractive applications have been identified in many food areas. The present article briefly introduces the concept of hurdle technology, presents potential applications and gives details on a recently concluded study concerned with this topic and to which scientists from 11 European countries have contributed.

The spoilage and poisoning of foods by microorganisms is a problem that is not yet under adequate control, despite the range of preservation techniques available (e.g. freezing, blanching, pasteurizing and canning). In fact, the current consumer demand for more natural and fresh-like foods, which urges food manufacturers to use only mild preservation techniques (e.g. refrigeration, modified-atmosphere packaging and bioconservation), should make this problem even greater. Thus, for the benefit of food manufacturers there is a strong need for new or improved mild preservation methods that allow for the production of fresh-like, but stable and safe foods. The concept of hurdle technology is not new but addresses this need in full[1,2].

Hurdle technology (also called combined methods, combined processes, combination preservation, combination techniques or barrier technology) advocates the deliberate combination of existing and novel preservation techniques in order to establish a series of preservative factors (hurdles) that any microorganisms present should not be able to overcome[1,3–6]. These hurdles may be temperature, water activity (a_w), pH, redox potential, preservatives, and so on. It requires a certain amount of effort from a microorganism to overcome each hurdle. The 'higher' the hurdle, the greater the effort (i.e. the larger the number of organisms needed to overcome it). Some hurdles, like pasteurization, can be high for a large number of different types of microorganisms, whereas others, like salt content, have a less strong effect or the effect is limited in the range of types of microorganisms it affects.

The fact that a combination of preservative factors influences the microbial stability and safety of foods has been known for many centuries. The concept is more or less unconsciously used in many traditional foods, especially in the developing countries. It was re-invented some 15 years ago in the meat industry where the conscious employment of hurdles was found to be highly favourable for the production of shelf-stable sausages[2]. The concept is now ready to be introduced for use with a much wider range of food products, including fruits and vegetables, bakery products, dairy products, fish, and so on. Several novel preservative factors (e.g. gas packaging, bioconservation, bacteriocins, ultrahigh-pressure treatment, edible coatings, etc.) that specifically facilitate this development have been assessed[7].

Hurdle technology is a crucial concept for the mild preservation of foods, as the hurdles in a stable product concertedly control microbial spoilage and food poisoning, leaving desired fermentation processes unaffected. Because of their concerted, sometimes synergistic effect, the individual hurdles may be set at lower intensities than would be required if only a single hurdle were

* Revised version of an article published in 1994 in *Voedingsmiddelentechnologie* 27(21), 15–17 [in Dutch] and *ALITECNA* 4, 17–19 [in Portuguese].

Lothar Leistner is at the Federal Centre for Meat Research, E.C. Baumannstrasse 20, D-95326 Kulmbach, Germany. **Leon G.M. Gorris** (corresponding author) is at the Institute for Agrotechnological Research (ATO-DLO), Bornsesteeg 59, PO Box 17, NL-6700 AA Wageningen, The Netherlands (fax: +31-8370-12260; e-mail: L.G.M.GORRIS@ATO.AGRO.NL).

used as the preservation technique. The application of this concept has proven very successful, as an appropriate combination of hurdles achieves microbial stability and safety and also stabilizes the sensory, nutritive and economic properties of a food[4-6].

Examples of the hurdle effect

A food product is microbiologically stable and safe because of the presence of a set of hurdles that is specific for the particular product, in terms of the nature and strength of their effect. Together, these hurdles keep spoilage or pathogenic microorganisms under control because these microorganisms cannot overcome ('jump over') all of the hurdles present. Examples of sets of hurdles are illustrated by Figs 1a–e. The example shown in Fig. 1a represents a food containing six hurdles: high temperature during processing (F value), low temperature during storage (t value), low water activity (a_w), acidity (pH) and low redox potential (Eh), as well as preservatives (pres.) in the product. Some of the microorganisms present can overcome a number of hurdles but none can jump over all the hurdles used together. Thus the food is stable and safe. This example is only a theoretical case, because all hurdles are depicted as having the same intensity, which is rarely the case in practice. More likely, hurdles are of different intensity, as in the second example (see Fig. 1b), where a_w and preservatives are the main hurdles and storage temperature, pH and Eh are minor hurdles. If there are only a few microorganisms present at the start (see Fig. 1c), fewer different

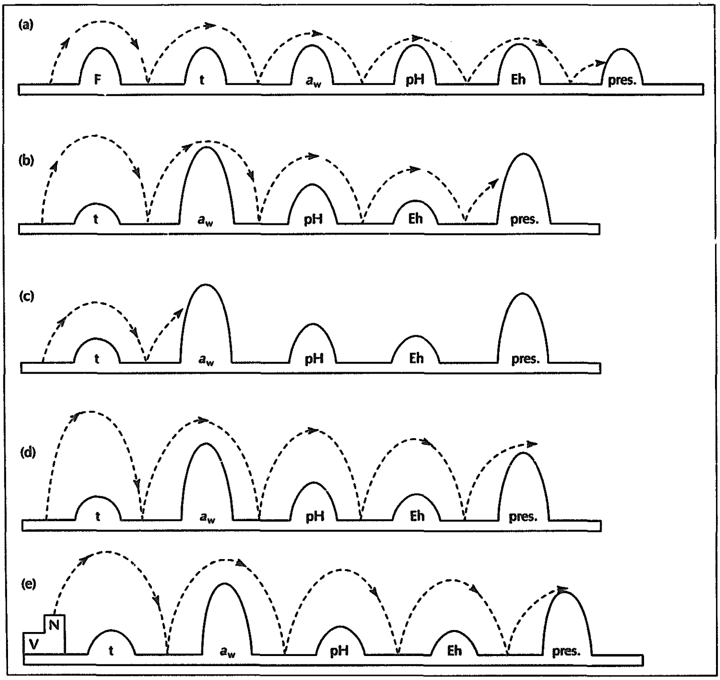

Fig. 1
Five examples of the hurdle effect used in food preservation. The individual hurdles may be encountered simultaneously or sequentially, depending on the type of hurdle and the overall processing. Symbols have the following meaning: F, heating; t, chilling; a_w, low water activity; pH, acidification; Eh, low redox potential; pres., preservatives; V, vitamins; N, nutrients. See text for details.

hurdles or hurdles of lower intensity may achieve microbiological stability. On the other hand, if high numbers of microorganisms are present owing to poor hygienic conditions, the usual set of hurdles may not suffice to prevent spoilage or food poisoning (see Fig. 1d). The example shown in Fig. 1e is a food rich in nutrients and vitamins, which may allow for short-term, strong growth of the microorganisms, and as a result their initial number is increased sharply ('booster effect'). In the examples shown in Figs 1d and 1e, additional or higher hurdles are needed to assure product stability.

Examples of hurdle-preserved foods

Using hurdle technology, salami-type fermented sausages can be produced that are stable at ambient temperature for extended periods of time. The microbial stability is achieved by the use of a combination of hurdles that are important in different stages of the ripening process, leading to a stable final product. Important hurdles in the early stage of the ripening process of salami are the preservatives salt and nitrite, which inhibit many of the bacteria present in the meat batter. However, other bacteria multiply, use up oxygen and thereby cause a drop in Eh, which inhibits aerobic organisms and favours the selection of lactic acid bacteria. The lactic acid bacteria then flourish, causing acidification of the product and a decrease in pH. During long ripening of the salami, the various hurdles gradually become lower: nitrite is depleted, the number of lactic acid bacteria decreases, Eh and pH increase. On the other hand, a_w decreases with time, and thus becomes the main hurdle in long-ripened raw sausage[4]. Increased awareness of the concerted effects of the various hurdles used in combination has made the production of fermented sausages less empirical. Similar combinations of hurdles in other types of fermented foods (e.g. cheese and vegetables) are responsible for the stability and quality of the products.

The hurdle technology approach has also been established for use with non-fermented foods, for instance in the production of tortellini, an Italian pasta product. In this case, reduced a_w and mild heating are the principal hurdles employed during processing, in addition to a modified atmosphere or ethanol vapour in the package and chilling of the product during storage and retail display (Ref. 8 and P. Giavedoni, PhD thesis, University of Udine, Italy, 1994). Ethanol was found to be very effective in inhibiting microbial growth, especially moulds and micrococci.

A recent survey of foods traditionally preserved using hurdle technology, conducted in 10 Latin American countries, identified some 260 different food items derived from fruit, vegetables, fish, dairy products, meat and cereals, which often had a high a_w (sometimes as high as 0.97) and that were stable at ambient temperature (25–35°C) for several months[9]. Based on the increased knowledge of the principles underlying hurdle technology, the Latin American scientists involved in this study are now applying the concept to design shelf-stable, innovative food preparations based on tropical and subtropical fruits (peach, pineapple, mango, papaya, etc.)[10,11].

An overview of combinations of hurdles that have either been studied or already employed, to date, in a range of food products is given in Table 1. In a number of recently developed food products, an almost infinite shelf life can be obtained. An example of this is canned peas marketed in the UK, in which the heat-stable bacteriocin nisin is used as an extra hurdle[12]. Normally, heating and pH reduction are the only two hurdles employed, but these do not suppress the growth of surviving acid-tolerant, spore-forming clostridia, which are completely inhibited by nisin.

Homeostasis and hurdle technology

An important phenomenon that is crucial with regard to hurdle technology is the so-called homeostasis of microorganisms[13]. Homeostasis is the constant tendency of microorganisms to maintain the stability and balance (uniformity) of their internal environment. For instance, although the pH values in different foods may be quite variable, the microorganisms living in them expend considerable effort keeping their internal pH values within very narrow limits[14]. In an acid food, for example, they will actively expel protons against the pressure of a passive proton influx. Another important homeostatic mechanism regulates the internal osmotic pressure (osmohomeostasis). The osmotic strength (which is inversely related to the a_w) of a food is a crucial physical property, which has a great effect on the ability of organisms to proliferate. Cells have to maintain a positive turgor (pressure) by keeping the osmolarity of the cytoplasm higher than that of the environment, and they often achieve this using so-called osmoprotective compounds such as proline and betaine[13,15].

Preservative factors (hurdles) may disturb several or just one of the homeostatic mechanisms of microorganisms, and as a result the microorganisms will not multiply but instead remain inactive or even die[13]. In fact, food preservation is achieved by disturbing the homeostasis of microorganisms in foods, either temporarily or permanently, and the optimal way to do this is to deliberately disturb several of the homeostatic mechanisms simultaneously[6]. This means that any hurdles included in a food should affect the undesired microorganisms in several different ways, for example by affecting the cell membrane, DNA, enzymes, pH, Eh and a_w homeostasis systems. This multi-targeted approach is the essence of hurdle technology[6,7]. Furthermore, this approach is often more effective than single-targeting and enables the use of hurdles of lower intensity, and thereby has less of an effect on product quality. Also, it is possibile that different hurdles in a food will not just have an additive effect on stability, but might act synergistically[1,5–7]. In practical terms this could mean that it is more effective to use a combination of different preservative factors with low intensities that affect different microbial systems or act synergistically than to use a single preservative factor with a high

Table 1. An overview of different types of hurdle-preserved food products[a]

	Cottage cheese	Potato crisps	Ham	Pepper	*Meida-Ya* jam	MAP-packaged salad	Peas, canned using nisin	Cake, packaged using ethanol vapour	Bread, packaged using a flush of CO_2 gas	Cold smoked salmon	Pasta sauce	MAP-packed fresh pasta	Acidified, pasteurized vegetable
Main cause of spoilage													
Microbiological	X		X			X				X			
Biochemical		X	X		X	X		X	X	X	X	X	X
Physical	X				X								
Sensory				X									
Type of hurdle													
High temperature		X	X	X			X				X	X	X
Low temperature	X		X			X					X	X	X
High acidity (low pH)	X				X		X				X		X
Low water activity (a_w)		X	X					X				X	
Low redox potential (Eh)						X			X			X	
Preservative(s)	X		X				X	X		X			
Competitive flora			X							X			
Modified gas atmosphere						X		X	X			X	
Packaging film												X	
Ultrahigh pressure				X	X								
Extrusion				X									
Product origin													
Traditional	X	X	X							X			
Recently developed				X	X	X	X	X	X		X	X	X
Country developed /marketed in	UK, USA		US	UK	Japan	France, UK, USA	UK	Japan		UK, USA	UK	UK, USA	Europe
Shelf life (weeks)	2	>25	>2	∞	12	1	∞	12	12	8	∞	4	>4

[a]These data have been compiled from various industry sources by J.G. Banks of the Campden & Chorleywood Food Research Association, Chipping Campden, UK

intensity. Moreover, in the hurdle technology concept, the objective is to inhibit the growth and proliferation of undesired organisms rather than to actually kill them, thus allowing for the use of hurdles that are not too extreme.

Another phenomenon of practical relevance is referred to as the autosterilization of stable, hurdle-preserved foods. In some ambient-temperature-stable meat products containing clostridia and bacilli spores that had survived the heat treatment applied during processing, it has been observed that some of these spores are able to germinate to form vegetative cells, but that these appear not to be viable and therefore die off. The viable spore count thus shows a gradual decrease during storage[5,16]. The same phenomenon has been observed for several bacteria, yeasts and moulds in hurdle-preserved fruit products stored without refrigeration[10]. A general explanation for the phenomenon might be that, because of the elevated temperature, which favours and probably triggers microbial growth, vegetative cells strain every possible repair mechanism to overcome the various hurdles present. In doing so, they become metabolically exhausted; they completely use up their energy sources and die. Thus, because of such autosterilization, hurdle-preserved foods that are microbiologically stable become even safer during storage, especially at ambient temperatures[6].

Potential hurdles

Up to now, ~50 different hurdles have been identified for use in food preservation (Box 1). The most commonly used important hurdles are high temperature, low temperature, low a_w, acidity, low redox potential, competitive microorganisms (e.g. lactic acid bacteria) and preservatives (e.g. nitrite, sorbate and sulphite). However, many other hurdles are of interest because of their potential for use in food preservation. Recently, a group of scientists from laboratories in 11 different European countries, sponsored by the European Union's FLAIR (Food-linked Agro-industrial Research) programme, studied the traditional and novel hurdles used in food preservation in detail, and compiled a report to document their findings[7]. This report gives an introduction to the application of combined processes in food preservation, presents practical examples of foods preserved by combined processes and describes various preservative factors ('hurdles') that have the potential to be exploited in food preservation. A number of relatively new hurdles are discussed in the form of mini-overviews. Among others, the emerging hurdles include ultrahigh pressure, modified-atmosphere packaging, bacteriocins and edible coatings. The report has been written to assist food processors, scientists and students who are interested in the field of hurdle technology to apply this gentle preservation system to our foods. A copy of the 120-page final report can be obtained free of charge by contacting the corresponding author.

Box 1. Potential hurdles for use in the preservation of foods[a]

Physical hurdles:
High temperature (sterilization, pasteurization and blanching), low temperature (chilling and freezing), ultraviolet radiation, ionizing radiation, electromagnetic energy (microwave energy, radiofrequency energy, oscillating magnetic field pulses and high electric field pulses), photodynamic inactivation, ultrahigh pressure, ultrasonication, packaging film (plastic, multi-layer, active coatings and edible coatings), modified-atmosphere packaging (gas packaging, vacuum, moderate vacuum and active packaging), aseptic packaging and food microstructure.

Physicochemical hurdles:
Low water activity (a_w), low pH, low redox potential (Eh), salt (NaCl), nitrite, nitrate, carbon dioxide, oxygen, ozone, organic acids, lactic acid, lactate, acetic acid, acetate, ascorbic acid, sulphite, smoking, phosphates, glucono-δ-lactone, phenols, chelators, surface treatment agents, ethanol, propylene glycol, Maillard reaction products, spices, herbs, lactoperoxidase and lysozyme.

Microbially derived hurdles:
Competitive flora, protective cultures, bacteriocins and antibiotics.

Miscellaneous hurdles:
Monolaurin, free fatty acids, chitosan and chlorine.

[a] A description of the various hurdles and their applications in food preservation is given by Bøgh-Sørensen[17]

The future of hurdle technology

There has been increasing interest in the design and application of hurdle technology in food preservation over the past few years. It is expected that this development will proceed in the near future, especially as national and international funds have now been established that should allow for (pre-)competitive studies in this field. The Commission of the European Union, for instance, has taken up the area of combined processes as a priority theme (area 3.3.2) in the forthcoming AIR2 ['Agriculture and Agro-industry, including fisheries' (also including food technology, forestry, aquaculture and rural development)] programme that runs under the Fourth Framework initiative from 1994 to 1998.

The combination of various hurdles in the processing and storage of foods has the primary target of obtaining safe foods that are stable with respect to microbial spoilage, using as mild a treatment as possible. However, the concept of hurdle technology may also contribute to improving the organoleptic quality or total quality of foods as perceived by consumers, and developments in this respect are also expected in the near future.

References

1 Leistner, L. (1978) in *Food Quality and Nutrition* (Downey, W.K., ed.), pp. 553–557, Elsevier
2 Leistner, L., Rödel, W. and Krispien, K. (1981) in *Water Activity: Influences on Food Quality* (Rockland, L.B. and Stewart, G.F., eds), pp. 855–916, Academic Press
3 Leistner, L. (1985) in *Properties of Water in Foods in Relation to Quality and Stability* (Simatos, D. and Multon, J.L., eds), pp. 309–329, Martinus Nijhoff Publishers, Dordrecht, The Netherlands
4 Leistner, L. (1987) in *Water Activity: Theory and Applications to Food*

(Rockland, L.B. and Beuchat, L.R., eds), pp. 295–327, Marcel Dekker
5 Leistner, L. (1992) *Food Res. Int.* 25, 151–158
6 Leistner, L. (1995) in *New Methods of Food Preservation* (Gould, G.W., ed.), pp. 1–21, Blackie
7 Leistner, L. and Gorris, L.G.M., eds (1994) *Food Preservation by Combined Processes (EUR 15776 EN)*, Commission of the European Community, Brussels, Belgium
8 Giavedoni, P., Rödel, W. and Dresel, J. (1994) *Fleischwirtschaft* 74, 639–642
9 Aguilera Radic, J.M., Chirife, J., Tapia de Daza, M.S., Welti Chanes, J. and Parada Arias, E. (1990) *Inventario de Alimentos de Humedad Intermedia Tradicionales de Iberoamérica*, Instituto Politécnico Nacional, Unidad Profesional Interdisciplinaria de Biotecnologia, Mexico
10 Alzamora, S.M., Tapia, M.S., Argaiz, A. and Welti, J. (1993) *Food Res. Int.* 26, 125–130
11 Lopéz-Malo, A., Palou, E., Welti, J., Corte P. and Argaiz, A. (1994) *Food Res. Int.* 27, 545–553
12 Gorris, L.G.M. and Bennik, M.H.J. (1994) *Z. Lebensmittelwirtsch.* 45(11), 65–71
13 Gould, G.W. (1988) in *Homeostatic Mechanisms in Microorganisms* (Whittenbury, R., Gould, G.W., Banks, J.G. and Board, R.G., eds), pp. 220–228, Bath University Press, Bath, UK
14 Häussinger, D., ed. (1988) *pH Homeostasis: Mechanisms and Control*, Academic Press
15 Csonka, L.N. (1989) *Microbiol. Rev.* 53, 121–147
16 Leistner, L. and Karan-Djurdjić, S. (1970) *Fleischwirtschaft* 50, 1547–1549
17 Bøgh-Sørensen, L. (1994) in *Food Preservation by Combined Processes (EUR 15776 EN)* (Leistner, L. and Gorris, L.G.M., eds), pp. 7–24, Commission of the European Community, Brussels, Belgium

Review

The development of process flavors

Charles H. Manley and Sajid Ahmedi

The scientific, artistic and regulatory aspects of process flavors are reviewed. The role of the flavorist, as it relates to the creation of process flavors for commercial purposes, is discussed. An overview of the chemistry and analytical techniques used as tools for the artistic approach is also given. In addition, the development of 'building blocks' for flavor creation is discussed, and comparisons are made between the methods used for the creation of classical flavors versus process flavors. Finally, the regulations relating to the safety and labeling of these flavors are considered.

Man's interest in 'cooked' flavors started with the evolution of the human species, and man is the only representative of the animal kingdom that has established the practice of cooking food before eating it. The use of fire, and subsequently other heat sources, to render a raw material palatable is one of man's higher intellectual achievements. The creation of a 'cooked' flavor presents the flavorist with a major challenge.

Chemistry, particularly analytical and natural product chemistry, allows for the further development of our basic understanding of the components that arise during the cooking of foods and the mechanisms involved. Many excellent reviews covering this area of chemistry have already been published[1–3]. This article will explore those areas in which chemistry can assist the flavorist in creating flavors that are developed by the use of the 'process' of cooking.

Charles H. Manley and Sajid Ahmedi are at Takasago International Corp. (USA), Teterboro, NJ, USA (fax: +1-201-288-1692).

The flavorist's approach

The flavorist's approach to flavor development is a creative one, but with a scientific foundation. Let us first review how the flavorist sets about the task of creating flavors from scratch.

The most important step is to first evaluate the target flavor in descriptive terms. A commonly used method is to describe the flavor's character in terms of its top, middle and base 'notes'. The flavorist draws upon experience gained from past work on different flavor blends. An ingredient that might be suitable for providing a certain top note may adversely affect the middle and base notes; therefore, a vast amount of experience as well as a degree of artistry are needed to effectively combine these notes to produce a well-balanced flavor.

Sensory evaluation methods may help define the flavor in terms of its attributes and strength. A small panel of sensory experts (5–8 flavorists) is needed to do this. Efforts are focused on selecting appropriate descriptive terms (usually 6–8) that relate to the character and quality of the flavor or taste.

A more in-depth evaluation may be accomplished by using analytical methods such as the extraction of volatiles, followed by their separation using gas chromatography and aroma evaluation of the separated components (olfactometry). A number of good reviews on such methods for evaluating a flavor can be found in a recent publication[4]. By the use of these methods, the important volatile flavor components can be identified.

Once the basic formula of a flavor has been obtained using the analytical methods, the flavorist is ready to put artistry to work. The aroma components that have

