ELSEVIER

Journal of Food Engineering **22** (1994) 421–432

0260-8774/94/$7.00

Further Developments in the Utilization of Hurdle Technology for Food Preservation

L. Leistner

Federal Centre for Meat Research, E.-C.-Baumann-Straße 20, D-95326 Kulmbach, Germany

ABSTRACT

In earlier research, we studied the influence of water activity (a_w) *on the stability and safety of meats. It became obvious that in addition to* a_w *other factors (hurdles) determine the microbial stability of foods. From this understanding the hurdle effect was conceived, and later hurdle technology was derived, which was applied to shelf stable products and intermediate moisture foods based on meat. Similar principles are used for the preservation of many other foods, in industrialized as well as in developing countries, especially for foods storable without refrigeration. A linkage of hurdle technology with the hazard analysis critical control points (HACCP) concept has been achieved, and the relationship to predictive microbiology is now being studied. Fundamental issues, such as lipid oxidation in membranes and the homeostasis of microorganisms, are currently being investigated in the light of hurdle technology. This approach is also applicable for quality aspects of foods. To secure the total desired quality of a food, the safety and quality hurdles should be kept within the optimal range.*

INTRODUCTION

Water activity (a_w) is a major factor in the preservation of foods (Scott, 1957; Leistner & Russel, 1991). During the last two decades in the Federal Centre for Meat Research of Germany the influence of a_w on the stability and safety of meats has been studied thoroughly. First, the a_w tolerance of microorganisms and methods for a_w measurement of foods as well as the a_w adjustment and prediction of shelf-life of meats were examined (Leistner & Rödel, 1975), and thereafter the stability of intermediate moisture foods (IMF) as a function of a_w and other hurdles was investigated (Leistner & Rödel, 1976). The benefit of the hurdle effect for energy saving during storage of foods was pointed out (Leistner, 1978), and the concept of shelf stable products (SSP), based on a_w, was introduced (Leistner & Rödel, 1979). The growth, metabolic activity, resistance and survival of microorganisms in relation to a_w were reviewed, and data on the surface a_w of meat as well as the changes of a_w during chilling and freezing of meats were presented (Leistner *et al.*, 1981). Thereafter, from the hurdle effect, hurdle technology was derived, and this concept was applied to SSP of different types (F-SSP, a_w-SSP and pH-SSP) as well as to traditional IMF from Asia and Africa (Leistner, 1985). Later, the sequence of hurdles in fermented sausages was described, and guidelines were defined for safe SSP and IMF (Leistner, 1987). Stiebing and Rödel (1992) introduced the surface water activity of fermented sausages (determined by temperature measurement just beneath the surface of the sausage during ripening) as the leading criterion for an optimization and automation of the ripening process. Further developments also occurred in relation to defining 'hygiene hurdles,' which are important for the aseptic packaging of cooked meats in 'clean-rooms' or, on the other hand, for the production of fermented meats in 'bio-rooms' (Leistner, 1990). Finally, an update was presented on meat preservation by combined methods (hurdle technology), and the concept of Combi-SSP was introduced (Leistner, 1992*a*).

OTHER APPLICATIONS

The hurdle effect and the hurdle technology are now applied widely in industrialized countries, especially for the development of stable and safe food products (food design), not only for meats, but also for a variety of foods, for instance, in mild technologies for fruit processing (Torreggiani *et al.*, 1990) or in the shelf-life extension of fish (Baldrati *et al.*, 1990). In less developed countries too, the significance of hurdle technology for efficient food preservation has been recognized, e.g. in South Africa (von Holy, 1988–1989), Iberoamerica (Aguilera *et al.*, 1990) and in the People's Republic of China (Wang & Leistner, 1991). In Iberoamerica, traditional foods storable without refrigeration were studied in 11 countries, and 246 foods based on fruits, vegetables, milk, fish, cereals and meat were approved as stable. Most of these foods were IMF; however, the stability and safety of many products were due to empirically applied hurdle technology (Aguilera & Parada, 1992). Thus, undoubtedly, hurdle technology is applicable not only for the preservation of meat, but also for other foods of animal and plant origin. At present, in the production of many foods, hurdle technology is empirically used without knowledge of the principles involved. However, it is foreseeable that in the future hurdles will be intelligently applied in food design.

This has been illustrated by the successful stabilization of Paneer and Lup Cheong, two foods of developing countries. Paneer is a cottage cheese type product mixed with tomato sauce, onions and spices, which is frequently consumed in the northern part of India, because of its nutritive value and characteristic taste. However, Paneer spoils within 2 days under the environmental conditions of India (temperatures up to 35°C), and this is a severe drawback. In our laboratories we developed mildly heated Paneer in cans, with the desirable sensory characteristics, which is storable for several weeks without refrigeration. The following combinations of hurdles proved effective with this product: $a_w = 0.97$, $F = 0.8$, pH = 5.0 or $a_w = 0.96$, $F = 0.4$, pH = 5.0 (Rao *et al.*, 1992).

Lup Cheong is a raw but not fermented sausage of China, storable for several weeks without refrigeration. However, the Taiwanese variety of Lup Cheong, because of its desired soft texture (a_w around 0.94), acquires a sour taste as a result of spoilage by lactic acid bacteria, and may be poisoned because of the growth of *Staphylococcus aureus*. In cooperation with a visiting scientist from Taiwan we stabilized Taiwanese Lup Cheong by the addition of 3.5% sodium lactate and 0.1% sodium acetate. The modified product remains tasty and is stable and safe even when stored for several weeks without refrigeration (Kuo, J.C., Dresel, J. & Leistner, L., 1992, unpublished data).

HURDLE TECHNOLOGY FOR ARMY PROVISIONS

In less developed countries, foods storable without refrigeration are in demand, because energy is expensive, and electricity is not continously available. However, for industrialized countries foods stable and safe without chilling have advantages too, because temperature abuse might occur during storage (especially in the home), and under some circumstances refrigeration is absent. The latter is true during military exercises. Therefore, our laboratories received a grant from the medical corps of the German Army for the selection of meat products storable for at least 6 days at 30°C. However, these meats should not be of the conventional army type, because soldiers prefer fresh foods rather than canned rations. As the execution of this army project is a good example of the possible accomplishments of hurdle technology, it will be described here in more detail.

During the initial phase of the project a survey of potentially suitable meat products already on the market was carried out. We asked German meat processors to name for us their meat products which taste like those bought in delicatessen shops, but need no refrigeration. Twenty-four manufacturers named 100 of their products with 'fresh product characteristics,' which they considered stable. However, after incubation we could confirm the stability of only 75 products. These products we scrutinized for their physical, chemical, microbiological and technological characteristics. From the results obtained, eight categories of products were distinguishable (Table 1), because they had a stability and safety based on different principles of hurdle technology.

We then manufactured the promising products under pilot plant conditions, challenged them with spoilage and food-poisoning bacteria, and investigated their stability, safety and quality during and after storage. If necessary, the recipes and technologies were modified and optimized. Finally, we produced the approved products in a medium-sized meat factory, because they should perform well under practical conditions too.

As large and small enterprises must be able to manufacture these rations, the processes had to be described for each product in detail, and therefore 15–20 critical control points for the process of each product group were defined. In this way, for the first time a linkage between hurdle technology (used for food design) and the hazard analysis critical control points (HACCP) concept (employed for process control) was achieved (Hechelmann *et al.*, 1991; Leistner, 1992*b*). If the recommended meat products are manufactured according to the outlined HACCP concepts, they are stable, safe and of high sensory quality, and

TABLE 1
Eight Categories of Meat Products for Army Provisions with 'Fresh-Product Characteristics', Which are Storable Without Refrigeration

1. Quick-ripened fermented sausages
2. Mini-salami (two different types)
3. Brühwurst and liver sausage as F-SSP
4. Dried brühwurst as a_w-SSP
5. Repasteurized brühwurst as a_w-SSP
6. Brawns and brühwurst as pH-SSP
7. Items of brühwurst as Combi-SSP
8. Meats heated in sealed aluminium foil

thus could be used as attractive rations for soldiers during military exercises.

In the processing of the meats recommended in this study, no microbiological tests are necessary; however, other parameters have to be strictly controlled: time, temperature, pH and a_w. By following the suggested HACCP concepts, these controls should be done on-line. Hitherto, to measure the water activity of meats reliably within a few minutes was a problem. Now a new instrument is available which is based on freezing point determination and allows exact a_w measurement of meats within 10–20 min. This instrument was developed in our laboratories by Rödel *et al.* (1989); it is manufactured by NAGY, D-70794 Filderstadt, Germany, and has been named a_w-Kryometer (Fig. 1). Besides a_w, also the temperature, pH and redox potential of foods, could also be measured with this instrument, by employing appropriate sensors, and this should be helpful in the monitoring of foods.

ADDITIONAL HURDLES

Several related concepts for quality assurance of foods are currently under investigation within several FLAIR projects of the European Community: hurdle technology (used for food design), the HACCP

Fig. 1. NAGY a_w-Kryometer type AWK-10 with sample container and sensor.

concept (used for process control), and predictive microbiology (used for process refinement). By considering these different approaches, an overall strategy for securing tasty, stable and safe foods should now be accomplished. The linkage between hurdle technology and HACCP has been achieved recently, as mentioned above.

Predictive microbiology (Gould, 1989) is a promising concept for computer-based and quantitative safety evaluation of foods, and is already advanced for predicting the growth, death and survival of pathogenic and spoilage bacteria in certain food products (McClure *et al.*, 1993). Predictive modelling for the food industry, concerning the most common food-poisoning bacteria in a variety of foods, has been available in the UK since October 1992 under the designation Food Micromodel. However, the models available for predictive microbiology can manage only relatively few parameters (hurdles), i.e. temperature, pH, a_w, aerobic or anaerobic conditions, and some preservatives (e.g. nitrite, lactic acid or carbon dioxide). These are important hurdles, and thus the available models give a good estimate of the behaviour of food-poisoning bacteria in foods. However, there are numerous additional hurdles (Table 2), which are important for the stability and safety of foods. Thus, predictive microbiology cannot be considered to be a quantitative approach to hurdle technology, but only allows reliable predictions of the behaviour of microorganisms in relatively simple food

TABLE 2

Some Potential Hurdles for Foods of Animal or Plant Origin, Which Improve the Stability and/or the Quality of These Products

Temperature (high or low)
pH (low or high)
a_w (low or high)
Eh (low or high)
Oxygen tension (low or high)
MA (modified atmosphere)
Pressure (high or low)
Ultrasound (high)
Radiation (UV, microwaves, ionizing radition)
Competitive flora (lactic acid bacteria, etc.)
Microstructure (e.g. water-in-oil emulsions)
Preservatives (organic acids, sodium lactate, sodium acetate, sodium ascorbate, trisodium phosphate, potassium sorbate, parabens, fatty acids and their esters, glycerol, propylene glycol, ethanol, spices, nitrite, sulfite, smoke, antioxidants, chelating agents, Maillard reaction products, pimaricin and other antibiotics, lysozymes, nisin and other bacteriocines, etc.)

systems, comprising not more than four factors (hurdles). Because several hurdles are not taken into account, the predicted results are fortunately often on the safe side, i.e. the limits indicated for growth of pathogens in foods by the models available are often more prudent ('fail-safe') than the limits in the real food.

Hurdle technology is applicable not only to safety, but also to quality aspects of foods, although this area of knowledge has been much less explored than the safety aspect. Some hurdles (e.g. Maillard reaction products) influence the safety as well as the quality of foods (Stecchini *et al.*, 1991), and this applies to many other hurdles. The possible quality hurdles in foods might influence the sensory, nutritive, technological and economic properties of a product, and the hurdles present might be negative as well as positive for securing the desired total quality of a food. Moreover, the same hurdle could have a positive or a negative effect on food quality, depending on its intensity. For instance, chilling too quickly to a low temperature may cause chill injury in fruits, which could be avoided by cold acclimation. To secure the desired total quality of a food, the safety and quality hurdles should be kept within the optimal range (Fig. 2).

BASIC ASPECTS

Even for fundamental aspects of food preservation, such as the biological membrane deterioration and associated quality losses during the storage of food tissues, hurdle technology could provide a comprehensible illustration. Stanley (1991) suggested that the oxidation of plant and animal membrane lipids is influenced by a number of positive and negative extrinsic and intrinsic factors. Positive hurdles, which keep the membrane lipids in apparently unchanged physiological condition and thus prolong the shelf-life of foods are: relatively low temperature, appropriate relative humidity, absence of light and slight anoxia. Stanley concluded that the hurdle technology approach would seem to be applicable to a wider concept of food preservation than just microbial stability, but that, in order for it to work, a precise knowledge of the effectiveness of each hurdle for a given commodity is required. Hurdles that can be utilized to preserve plant tissue and thus food quality include antioxidants, controlled-atmosphere storage, low temperature, reduced ethylene levels, and effective packaging.

Another fundamental aspect of food preservation by hurdle technology is the synergistic effect of combined processes. This could be due to disturbance of the homeostasis within microorganisms (Gould, 1988).

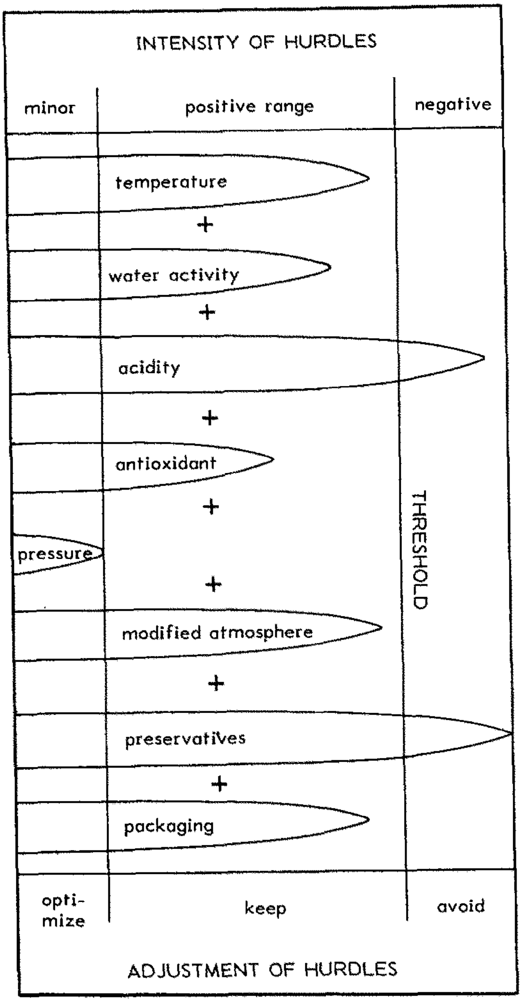

Fig. 2. Example of quality hurdles in a food, which could be, at the same time, safety hurdles and determing in summation the total quality of this product.

It has been suspected for some time (Leistner, 1978) that different hurdles in a food might have an intensifying effect on each other. Hammer and Wirth (1984) reported that several additives which all cause a depression of a_w in meat products do not enhance each other, but have an additive effect only. However, the reason for this finding might have been the fact that all the additives tested lowered only the a_w, and thus had the same target within the bacterial cell. On the other hand, a synergistic effect of hurdles is to be expected if different hurdles (e.g. a_w, pH, Eh, preservatives) in the food have different targets within the microbial cell, and thus disturb the homeostasis in several respects. Therefore, employing different hurdles in the preservation of a particular food should have advantages, because microbial stability could be achieved with a combination of gentle hurdles (Leistner, 1992*b*). In practical terms, this could mean, for instance, that it is more effective to use different preservatives in small amounts in a food than only one preservative in larger amounts, because different preservatives might have different targets in the bacterial cells (e.g. disturbance of cell membrane, DNA, enzyme systems, pH or a_w) and thus act synergistically. Certainly, the interrelationship of hurdle technology and homeostasis warrants further investigation.

INTEGER FOODS

Finally, another challenging aspect of hurdle technology should be mentioned — the use of coatings for integer food pieces. If a food is not comminuted, but consists of large pieces of plant or animal tissue, protection against microbial deterioration might be achieved by a surface layer on the food, which contains and maintains inhibitory substances (hurdles). An example of a traditional food for which an edible surface coating is used to inhibit mould growth on the surface and to inactivate salmonellae inside of food is Pastirma, a raw beef product common in Moslem countries. The applied surface paste (3–5 mm thick) contains a binder, several spices and 35% fresh garlic (El-Khateib *et al.*, 1987; Leistner, 1987). On the other hand, Torres (1987) studied the surface microbial stability of model foods by using coatings which maintain preservatives and the desired low pH, and he demonstrated that a low pH in the surface layer greatly improved the effectiveness of sorbic acid in this coating. Guilbert (1988) used superficial edible layers for the protection of easily perishable tropical fruits, and considered this as an application of hurdle technology without affecting the integrity of food pieces.

Moreover, the so-called osmotic dehydration, a dewatering and impregnation process which consists of soaking foods (fruits, vegetables, meat, cheese and fish) in highly concentrated solutions of sucrose, sodium chloride or other humectants, could generally be employed for solute transfer from a solution into the product (Lerici *et al.*, 1988). It is thus possible to insert not only water activity lowering agents, but also preservatives and nutrients, as well as substances which control the pH, texture and flavour of a food, and thus build up positive hurdles which improve the stability as well as the quality of food products (Raoult-

Wack *et al.*, 1992). Here again, another mode of application of hurdle technology to foods with promising perspectives has been introduced.

CONCLUSION

Chirife *et al.* (1991) have demonstrated that mummification, as practised in ancient Egypt, is a very old example of preservation by the hurdle concept. Because mummification comprises (at least) three hurdles, namely reduced a_w (0.72), increased pH (10.6), and preservatives. The reduction of a_w and at the same time an increase of pH was brought about by natron, a natural mineral salt found in Egypt. The preservatives were spices, plant resins and other aromatic plant substances. Thus, hurdle technology is by no means a novel process, but still one which has a great potential for further research and application.

REFERENCES

Aguilera, J.M. & Parada Arias, E. (1992). CYTED-D AHI: an Ibero American project on intermediate moisture foods and combined methods technology. *Food Research International*, **25**, 159–65.

Aguilera, J.M., Chirife, J., Tapia, M.S., Welti, J. & Parada Arias, E. (1990). *Inventario de Alimentos de Humedad Intermedia Tradionales de Iberoamérica*. Instituto Politécnico Nacional, Mexico, 557 pp.

Baldrati, G., Ambroggi, F., Gola, S., Cassarà, A., Giavedoni, P. & Sensidoni, A. (1990). Modified-atmosphere storage of trout fillets: optimization of the procedure. In *Chilling and Freezing of New Fish Products*. International Institute of Refrigeration, Paris, pp. 193–9.

Chirife, J., Favetto, G., Ballesteros, S. & Kitic, D. (1991). Mummification in ancient Egypt: an old example of tissue preservation by hurdle technology. *Lebensm.-Wiss. u.-Technol.*, **24**, 9–11.

El-Khateib, T., Schmidt, U. & Leistner, L. (1987). Mikrobiologische Stabilität von türkischer Pastirma. *Fleischwirtschaft*, **67**, 101–5.

Gould, G.W. (1988). Interference with homeostasis — food. In *Homeostatic Mechanisms in Micro-organisms*, eds R. Whittenbury, G.W. Gould, J.G. Banks & R.G. Board. FEM Symposium, **44**, 220–8.

Gould, G.W. (1989). Predictive mathematical modelling of microbial growth and survival in foods. *Food Science and Technology Today*, **3**, 89–92.

Guilbert, S. (1988). Use of superficial edible layer to protect intermediate moisture foods: application to the protection of tropical fruit dehydrated by osmosis. In *Food Preservation by Moisture Control*, ed. C.C. Seow. Elsevier Applied Science Publishers, London, pp. 199–220.

Hammer, G.F. & Wirth, F. (1984). Wasseraktivitäts-(a_w-)Verminderung bei Leberwurst. *Mitteilungsblatt Bundesanstalt Fleischforschung Kulmbach*, **84**, 5890–3.

Hechelmann, H., Kasprowiak, R., Reil, S., Bergmann, A. & Leistner, L. (1991). Stabile Fleischerzeugnisse mit Frischprodukt-Charakter für die Truppe. BMVg FBWM 91-11. Dokumentations- und Fachinformationszentrum der Bundeswehr, Bonn, 129 pp.

Leistner, L. (1978). Hurdle effect and energy saving. In *Food Quality and Nutrition*, ed. W.K. Downey. Applied Science Publishers, London, pp. 553-7.

Leistner, L. (1985). Hurdle technology applied to meat products of the shelf stable product and intermediate moisture food types. In *Properties of Water in Foods in Relation to Quality and Stability*, eds D. Simatos & J.L. Multon. Martinus Nijhoff Publishers, Dordrecht, pp. 309-29.

Leistner, L. (1987). Shelf-stable products and intermediate moisture foods based on meat. In *Water Activity: Theory and Applications to Food*, eds L.B. Rockland & L.R. Beuchat. Marcel Dekker, New York, pp. 295-327.

Leistner, L. (1990). Was sind sichere Produkte? In *Sichere Produkte bei Fleisch und Fleischerzeugnissen*, ed. L. Leistner. Bundesanstalt für Fleischforschung, Kulmbacher Reihe Band 10, pp. 1-21.

Leistner, L. (1992*a*). Food preservation by combined methods. *Food Research International*, **25**, 151-8.

Leistner L. (1992*b*). Linkage of hurdle technology with HACCP. *Meat Focus International*, **1**, 233-6.

Leistner, L. & Rödel, W. (1975). The significance of water activity for micro-organisms in meats. In *Water Relations of Foods*, ed. R.B. Duckworth. Academic Press, London, 309-23.

Leistner, L. & Rödel, W. (1976). The stability of intermediate moisture foods with respect to micro-organisms. In *Intermediate Moisture Foods*, eds R. Davies, G.G. Birch & K.J. Parker. Applied Science Publishers, London, pp. 120-34.

Leistner, L. & Rödel, W. (1979). Microbiology of intermediate moisture foods. In *Food Microbiology and Technology*, eds B. Jarvis, J.H.B. Christian & H.D. Michener. Medicina Viva Servizio Congressi, Parma, pp. 35-56.

Leistner, L. & Russel, N.J. (1991). Solutes and low water activity. In *Food Preservatives*, eds N.J. Russel & G.W. Gould. Blackie, Glasgow, pp. 111-34.

Leistner, L., Rödel, W. & Krispien, K. (1981). Microbiology of meat and meat products in high- and intermediate-moisture ranges. In *Water Activity: Influences on Food Quality*, eds L.B. Rockland & G.F. Stewart. Academic Press, New York, pp. 855-916.

Lerici, C.R., Mastrocola, D., Sensidoni, A. & Dalla Rosa, M. (1988). Osmotic concentration in food processing. In: *Preconcentration and Drying of Food Materials*, ed. S. Bruin. Elsevier Applied Science Publishers, Amsterdam, pp. 123-34.

McClure, P.J., Baranyi, J., Boogard, E., Kelly, T.M. & Roberts, T.A. (1993). A predictive model for the combined effect of pH, sodium chloride and storage temperature on the growth of *Brochothrix thermosphacta*. *International Journal of Food Microbiology*, **19**, 161-78.

Rao, J.K., Dresel, J. & Leistner, L. (1992). Anwendung der Hürden-Technologie in Entwicklungsländern, zum Beispiel für Paneer. *Mitteilungsblatt Bundesanstalt Fleischforschung. Kulmbach*, **31**, 293-7.

Raoult-Wack, A.L., Lenart, A. & Guilbert, S. (1992). Recent advances in dewatering through immersion in concentrated solutions. In *Drying of Solids*, ed. A.S. Mujumdar. International Science Publishers, New York, pp. 21-51.

Rödel, W., Scheuer, R. & Wagner, H. (1989). Neues Verfahren zur Bestimmung der Wasseraktivität bei Fleischerzeugnissen. *Fleischwirtschaft*, **69**, 1396–99.
Scott, W.J. (1957). Water relations of food spoilage microorganisms. In *Advances in Food Research*, Vol. 7, eds E.M. Mrak & G.F. Stewart. Academic Press, New York, pp. 83–127.
Stanley, D.W. (1991). Biological membrane deterioration and associated quality losses in food tissues. *Critical Reviews in Food Science and Nutrition*, **30**, 487–553.
Stecchini, M.L., Giavedoni, P., Sarais, I. & Lerici, C.R. (1991). Effect of Maillard reaction products on the growth of selected food-poisoning micro-organisms. *Letters in Applied Microbiology*, **13**, 93–6.
Stiebing, A. & Rödel, W. (1992). Kontinuierliches Messen der Oberflächen-Wasseraktivität von Rohwurst. *Fleischwirtschaft*, **72**, 432–8.
Torreggiani, D., Senesi, E., Maltini, E. e Crivelli, G. (1990). Innovazioni tecnologiche e qualità della frutta trasformata. *Annali dell'Istituto Sperimentale per la Valorizzazione Tecnologica dei Prodotti Agricoli Milano*, **21**, 57–65.
Torres, J.A. (1987). Microbial stabilization of intermediate moisture food surfaces. In *Water Activity: Theory and Applications to Food*, eds L.B. Rockland & L.R. Beuchat. Marcel Dekker, New York, pp. 329–68.
Von Holy, A. (1988–1989). Hurdle technology for shelf-stable foods. *South African Food Review*, (Dec–Jan), 27–31.
Wang W. & Leistner, L. (1991). New developments in the preservation and shelf-life of meat products. South-West Minority College, Chengdu, Sichuan, 30 pp, (in Chinese).