Quality losses in deep-frozen foodstuffs at cyclically modified storage temperatures

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Abstract

The project “Smart Domestic Appliances in Sustainable Energy Systems (Smart-A)” aims at developing strategies showing how smart domestic appliances can contribute to load management in future energy systems. These systems will have to integrate larger shares of renewable energy, which are partly intermittent, and therefore will require a smarter management of generation and demand.

As household refrigerators and freezers are using a considerable amount of electricity, they are also under investigation how much they can contribute to a smarter energy management. The main area of use in smart systems may be the possibility to store surplus or renewable energy in terms of cold, especially in freezers. Intermittent use would result in increased hysteresis of the temperature of stored food and possible food quality losses due to multiple cooling cycles.

Quality losses in frozen foodstuffs depend not only on the average storage temperature but also on the amplitude of the fluctuations. Aim of this study is to quantify quality changes (weight, texture, sensorial quality and nutritional value) in foodstuff (peppers, bread and minced beef) stored for one year in freezers at different average temperatures and temperature amplitudes (-24°C with temperature amplitude 7.5 K and -19°C with temperature amplitude of 1.5 K).

The results show no significant difference in quality changes between both storage conditions (statistical reliability 95%) with an exception of vitamin C. Consequently, the assumption can be made that the average storage temperature has a greater influence on the range of chemical-physical processes in foodstuffs during frozen storage than the amplitude of temperature fluctuations.
Keywords: frozen storage, temperature fluctuation, moisture migration, texture, weight loss, vitamin C, peroxide value.

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1 Introduction

In times of rising energy prices the question of possible ways of saving energy in private households is growing in importance. Devices with high energy consumption are the first to be targeted. These are primarily refrigerators and freezers which account for 16% of the total energy consumption in households and hence are the largest domestic consumers [1].

The project “Smart Domestic Appliances in Sustainable Energy Systems (Smart-A)” run by Öko-Institute.V. and the University of Bonn is developing strategies for the utilisation of domestic appliances in an environment of fluctuating energy from solar and aeolic energy sources (www.smart-a.org). Possibilities of cold storage in freezers are being investigated which are able to bridge longer interruptions to the energy supply [2]. However, that would mean that foodstuffs would be subject to high fluctuations in temperature which could lead to a loss in quality [1].

1.1 Quality of foodstuffs

Various dimensions must be considered when investigating the quality of foodstuffs. On the one hand, sensorial enjoyment, or sensorial quality, and the health value, or hygienic-toxicological quality, are important. On the other hand, other quality aspects such as the nutritional value (dietary quality) and the usage value play a large role in a comprehensive assessment. However, for consumers the quality of goods represents a certain value. The sensorial value is of prime importance because the individual characteristics can, at least in part, be examined and determined sensorially before purchasing. The health aspect is the next in importance. The quality of frozen foodstuffs is affected primarily by factors such as the type and condition of the original goods, processing conditions, storage temperature, length of storage and packaging [3].

1.2 Storage temperature of foodstuffs in the home

The absolute upper limit for the reproduction of micro-organisms is -10°C, therefore a safe temperature limit would be c. -12°C [4]. GUTSCHMIDT [5] stated in various studies that a temperature of -18°C should be the maximum limit for longer-term food storage. Corresponding minimum requirements for the appropriate production and distribution of frozen foodstuffs in food production and the food trade have been defined in the Ordinance on Frozen Foodstuffs (TLMV) which stipulates a minimum temperature of -18°C.

The speed of chemical reactions is slowed at lower temperatures, but not evenly. For example, in the temperature range of -30°C to -18°C the reaction rate of fruit and vegetables drops by 2 to 3 times (=Q10 value) if the temperature is lowered by 10 K However, in the range above -15°C the Q10 value rises continuously to between 4 and 8 or higher [5]. The Q10 values for fish and meat at temperatures from -20°C to -10°C lie between 1.1 and 2.6, individually as high as 4 or 5, and at temperatures below -20 °C the values lie between 1.05 and 1.1 [6]. Hence the reaction rate is considerably slower in the lower temperature range than in the higher. This behaviour means that particularly sensitive substances such as vitamins are preserved to a large extent. For example, the vitamin C content in frozen vegetables is still preserved to 90 to 100% even after 12 months of storage at a temperature of -30°C [7].

However, in addition to setting the right storage temperature it is reported also as important to keep temperature fluctuations within as narrow a range as possible since the size and shape of the fine ice crystals formed during freezing can change markedly during frozen storage. The growth of ice crystals is speeded up by fluctuations in temperature. Recrystallisation takes place if the vapour pressure is greater around small crystals than around large crystals. Hence a drop in vapour pressure occurs so that large crystals continue to grow at the expense of small ones. Long storage with high fluctuations in temperature is reported to cause a coarser crystal structure to emerge which can lead to cell damage [8].

One study states that the amplitude of temperature fluctuations and the average temperature of frozen storage have a great influence on the extent of recrystallisation and the associated dehydration process in foodstuffs. However, this influence diminishes with lower average temperatures, i.e. the lower the storage temperature, the lower are the overall water and quality losses [9].

Temperature fluctuations may cause gradual dehydration and freezer burns in foodstuffs. If the interior temperature of the freezer drops, the packaging is colder than the frozen food for a short time. This means that vapour sublimates from the product and condenses on the colder inside of the packaging. If the interior temperature rises again, the product is colder than the packaging and the inverse process occurs, but the vapour condenses on the surface of the product and does not re-enter the product. Hence snow forms gradually in the packaging and the foodstuff dehydrates [4].

However, a study with beef products showed very different results after one year of frozen storage with fluctuating and constant temperatures. Samples from storage at a constant temperature of -23°C are compared with samples from storage at temperatures fluctuating between -23°C and -21°C and between -21°C and -18°C. The temperature fluctuations occurred in a 12 hour cycle. After one year of storage no significant quality differences or noticeable weight losses were recorded [10].

1.3 Storage time of foodstuffs in the home

The length of storability of foodstuffs is determined to a great extent by biochemical reactions triggered primarily through enzyme activity. Enzymes are still active at temperatures between -18°C and -20°C, albeit at a highly decelerated rate, thereby causing changes to protein and fats. These changes affect the smell, taste and consistency of foodstuffs considerably [11].

The length of storage is also affected by temperature fluctuations. Standard refrigerator and freezer units use only 2 set-point controllers. The controller activates the compressor (or other electrical parts) at a set upper temperature and de-activates them after cooling to a set lower temperature. This is controlled by preset parameter settings. Hence the temperature will fluctuate between two limits. The type of temperature control is determined by the location of the sensor; a differentiation is made between direct and indirect temperature control. For direct temperature control the sensor is located in the refrigerator-freezer at a point which represents the interior temperature so that the temperature can be recorded as a direct value. For indirect control the sensor is placed at the vaporiser and hence controls the temperature of the vaporiser [12].

1.4 Project remit

The objective of these investigations is to quantify quality changes in stored foodstuffs due to increased amplitude of the storage temperature in freezers. In order to arrive at an overall assessment, the different aspects of quality must be investigated for changes using set indicators. Especial attention will be paid to weight losses and changes in texture of foodstuffs, followed by the nutritional value and sensorial quality. In addition, the energy consumption of the freezer units will be compared for varying storage temperatures and temperature amplitudes.

2 Material and methods

Two identical freezers, model GSP36/A31 from Bosch und Siemens Hausgeräte GmbH with a capacity of 296 l and an ability to freeze of 24 kg in 24 h, were compared. The first unit (Freezer1) was operated at a temperature set on the device of -19°C and a temperature amplitude of 1.5 K, while the second device (Freezer2) was programmed at -24°C with a temperature amplitude of 7.5 K. Thus a maximum temperature of -18°C was ensured in both freezers. Both freezers were stocked with identical foodstuffs which were analysed at set intervals.

Mass and texture analyses, vitamin C content and peroxide values as well as sensory impressions were to be incorporated in the evaluation of quality changes.

Foodstuffs with short storage lives were selected for the evaluation of the two types of frozen storage. Biochemical reactions in vegetables like peppers causing a destruction of vitamins are happening during frozen storage [13]. Bread is representative of changes in texture due to retrogradation during cold and frozen storage [14]. Changes occur in meat through oxidation reactions of fats which can also be analysed [15].

Peppers: Fresh red peppers, grade 1, were bought from one batch at a store for the trial. The peppers were washed, cut and divided between labelled Ziploc® freezer bags. Approximately 50 g of pepper slices were weighed out for each bag. The samples for weight and texture measurements were cut into pieces using a round cutter made of metal with a diameter of 4 cm. The remaining pieces were cut into irregular strips c. 3-4 cm long and packed for the other analyses (vitamin C and sensorial test). The peppers were not blanched before being frozen.

Bread: Fresh rye bread from the same batch with a rye percentage of 30% as sold in standard 500 g packets was used for the bread samples. For the weight and texture measurements two bread slices were packed together in a Ziploc® zipper freezer bag, labelled and weighed. One slice of bread was sufficient for the sensorial tests.

Minced beef: The minced beef was bought frozen and vacuum packed in pre-portioned packs at one time in one shop. The packs were already divided into 4 x 250 g compartments. One sample corresponds to a 250 g compartment. The samples were weighed and labelled.

All cut and packaged samples were distributed equally on 7 shelves in the individual freezers. The products were then frozen for 24 hours using the Superfreeze function (-40°C). Thereafter the temperature was automatically adjusted to the preset level (Freezer1 = -19°C and Freezer2 = -24°C). The positioning of the samples was documented.

Extraction of the samples for analysis was performed in accordance with the EU Commission Directive 92/2/EC of 13 January 1992 [16] laying down the sampling procedure and the Community method of analysis for the official control of the temperatures of quick-frozen foods intended for human consumption.

In order to reflect all temperature areas of a freezer in the analysis, the samples were always taken from three areas (top, middle, bottom). The analyses were performed every four weeks up to the fourth month and thereafter every 3 months (so after 0, 4, 8, 12, 16, 24, 36, 52 weeks).

Measurement method for moisture migration: In order to determine changes in mass, the difference of the final mass to the initial mass of all samples in a thawed out state is measured. The juices that run out during thawing are collected in a 100 ml beaker via a funnel and also weighed in order to verify the accuracy of the measurement.

Measurement method for assessing texture: A texture analyser with various sensors was used to measure the texture. The samples are analysed in a thawed out state. The firmness of the **peppers** is tested in a pressure test according to a testing regulation called “skin puncture strength of different coloured peppers using a cylinder probe” [17]. A stainless steel probe (P/0.5S) is used. The firmness of **bread** is investigated in accordance with the standard AACC (74-09) using a cylinder probe (P/36R). The texture of **minced beef** is tested using a stainless steel cylinder probe (P/0.5S) and the same program as for the peppers [17].The results are expressed as the force required to deform the sample to a certain degree.

Measurement method for vitamin C content: The vitamin C (L-ascorbic acid) content is determined using a colour test from Boehringer Mannheim GmbH Biochemica and a UV VIS spectral photometer with double beam technology [18].

Measurement method for the peroxide value: Fat oxidation is measured using the L 13.00-6 method “Determination of the peroxide number in fats and oils (method as per Wheeler)” from the Official Collection of Analytical Methods of the Federal Republic of Germany in accordance with Art. 35 LMBG (Foodstuffs and Commodities Act).

Measurement method for sensorial quality: The sensory quality is tested in a triangle test according to DIN/ISO 4120 with 12 testers. The results provide information concerning the significance or non-significance of differences between samples [19]. The samples are thawed out and evaluated under laboratory conditions in accordance with the DIN 10962 standard.

Statistical method: In order to compare two independent random samples for significant differences a statistical hypothesis test, or *t*-test, is used [20].The level of significance in these investigations is set at a maximum permissible probability of error $\alpha = 0.05$. Since the test statistic is *t*- distributed with *n* degrees of freedom, the zero hypothesis H_0(= *the foodstuff samples from Freezer1 and Freezer2 do not display any significant differences; hence they are identical)* for the level of significance α is rejected if $|t| > (\alpha;n)$ applies. If the test ratio is smaller than the table value (= *t*-value from the table for the *t*-test which can be found in every statistical formulary) then H_0 cannot be rejected [20].

3 Results and discussion

Moisture migration and changes in texture: The percentage weight losses of the samples after thawing shows that the first instance of foodstuff-specific weight loss occurs when freezing the foodstuff (Fig. 1 and Fig. 2). It increases only slowly with continued length of storage. The vertical bars in the figures

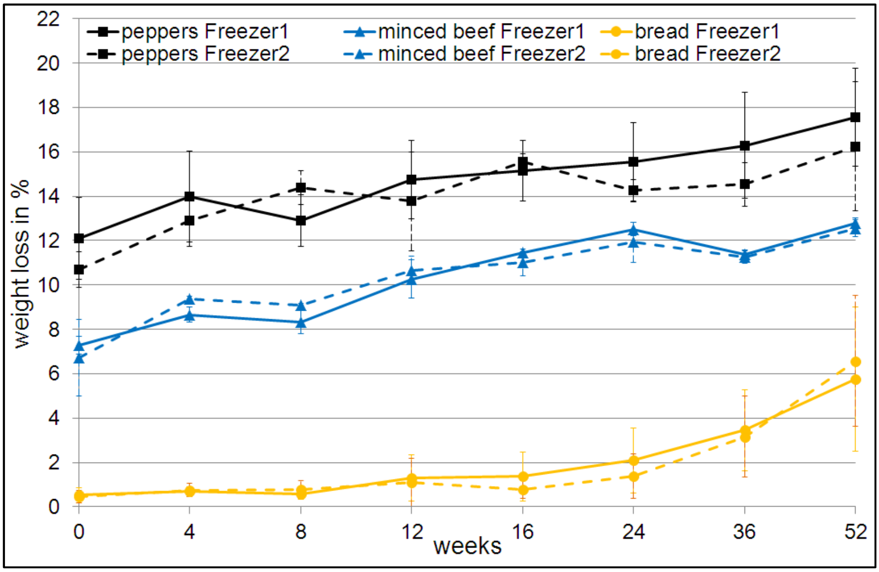

Figure 1: Weight loss in % of the initial weight of peppers, minced beef and bread over 52 weeks of frozen storage (own report).

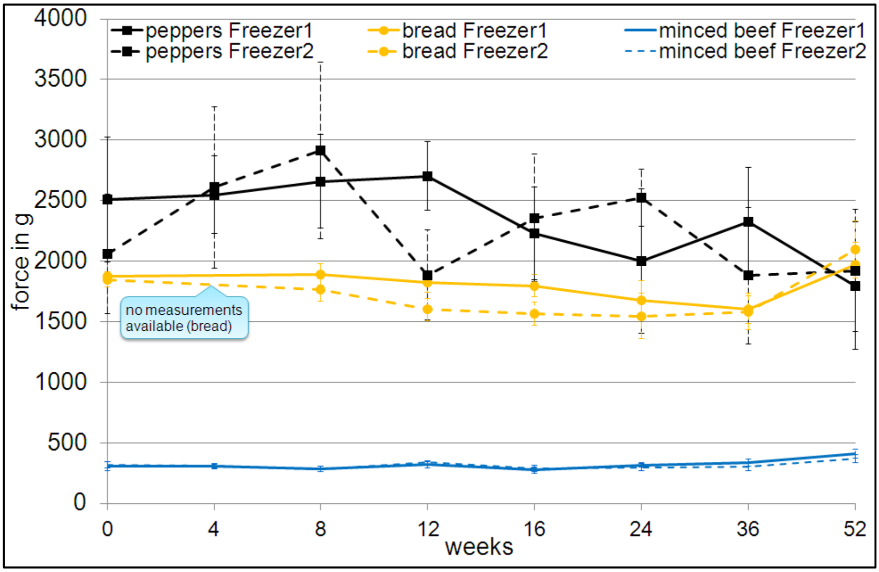

Figure 2: Penetration force for determining texture properties of peppers, bread and minced beef over 52 weeks of frozen storage (own report).

show the standard deviation for samples taken at the same time. The connecting lines are for optical simplification only. The differences in samples are not significant (*t*-test).

Vitamin C content: The vitamin C content of the samples after thawing shows that this decreases only slowly with increasing length of storage and that standard deviations increase (Fig. 3). A significant difference can be detected

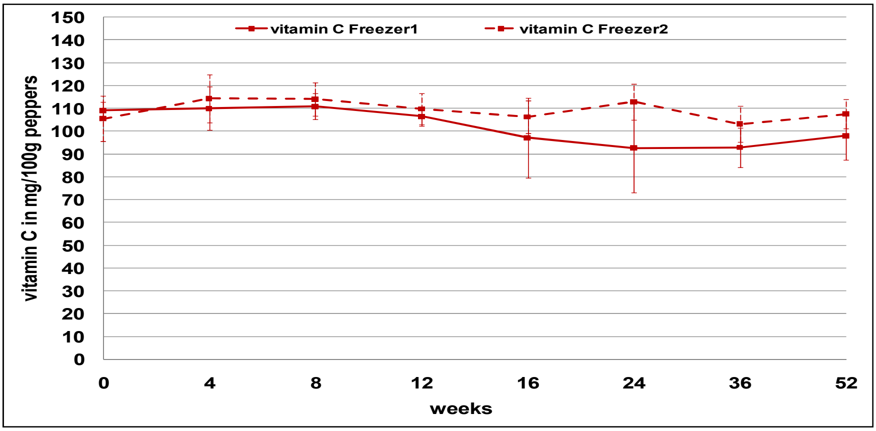

Figure 3: Vitamin C content (peppers) over 52 weeks of frozen storage (own report).

between the samples after 24, 36 and 52 weeks of storage (*t*-test). The vitamin C content in Freezer2 was (109.3 ± 8.8) mg/100 g of peppers after 52 weeks. The vitamin C content in Freezer1 was (104.6 ± 11.0) mg/100 g of peppers.

Changes in peroxide value: The change in peroxide value (POV) in minced beef shows that the values tend to rise over time (Fig. 4). However, the values for both freezers are very close and the standard deviations overlap mostly. No significant difference could be detected between the samples of both freezers (*t*-test).

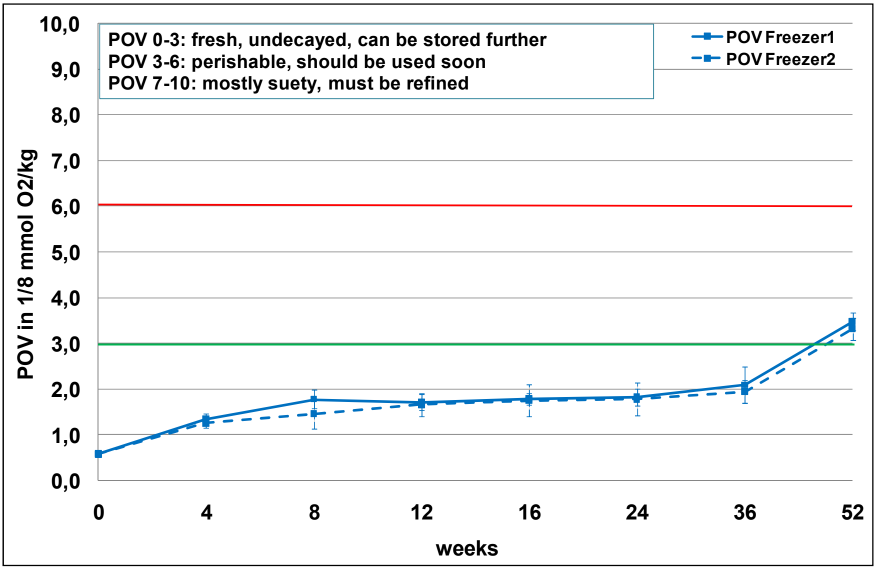

Figure 4: Changes in POV (minced beef) over 52 weeks of frozen storage (own report).

Sensorial quality: In the triangle tests the divergent samples for bread were correctly detected by 7 testers after 0 weeks, for peppers after 9 weeks and for minced beef after 16 weeks. With 7 correct answers from 12 testers and a significance level of $\alpha = 0.1$, a slight differentiation trend was identified between the foodstuff samples of both freezers (Fig. 5). One explanation could be that the samples compared can be differentiated by external characteristics not caused by the storage conditions in the freezer. This occurred with a minced beef sample taken from Freezer1 after 5 weeks and was caused by faulty packaging with a resultant loss of vacuum. The difference between the samples was therefore clearly visible for the testers. This result is classified as a maverick and excluded from further evaluation. At a significance level of $\alpha = 0.05$ the panel did not detect any statistically significant differences in the samples from both freezers.

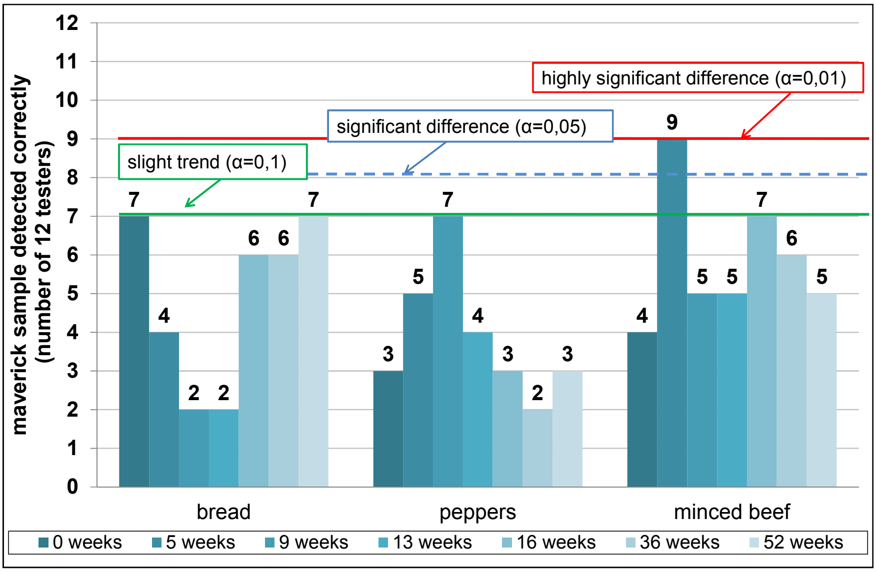

Figure 5: Results of triangle test with a panel of 12 testers (own report).

Energy consumption: In 24 h Freezer1 uses 0.564 kWh and Freezer2 0.627 kWh. If the energy consumption of Freezer2 is set as 100%, the energy consumption of Freezer1 is only 90%. Hence Freezer1 uses around 10% less energy than Freezer2 (Tab. 1).

Table 1: Energy consumption of freezers (365 days=52 weeks) (own report).

Freezer	24 hours (kWh)	365 days (kWh)	Total (%)
Freezer1	0.564	205	90
Freezer2	0.627	228	100

This difference is caused by the differences in the set operating temperatures and the programmed temperature hysteresis. The temperature setting for Freezer1 was -19°C, hence on average the compressor runs a shorter time than the compressor of Freezer2 with a temperature setting of -24°C. The higher energy consumption for Freezer2 is due to higher energy losses, causing longer working time and the resultant greater consumption of energy of its compressor.

4 Conclusions

In view of the results, it is now possible to answer the question as to the extent of quality changes depending on the average storage temperature and temperature amplitude. It can be said in conclusion that for the most part no significant quality differences between the storage temperatures and temperature amplitudes could be identified. The only significant differences were identified after 24, 36 and 52 weeks in the vitamin C content of peppers, which indicates that the average temperature has a greater influence on the complex of chemical and physical processes in foodstuffs during freezing than the amplitude of fluctuations in temperature. However, the difference of average values was only 5 mg/100 g of peppers, which has scarcely any dietary effect on people.

A decisive difference is observable in energy consumption, which is noticeably higher for the freezer with a lower storage temperature and higher temperature fluctuation. Therefore, a frozen storage at the most stable temperature possible is to be preferred, if the electricity consumption is to be kept as low as possible. However, if electricity is not the issue, for example when it is coming from renewable sources and available 'for free' (e.g. photovoltaic), food stuff may be stored at much lower temperatures with high fluctuations without causing significant effects on food quality.

The main area of use in smart systems may be the possibility to store surplus or renewable energy in terms of cold, especially in freezers. An intermittent use would result in an increased hysteresis of the temperature of stored food without causing significant effects on food quality due to multiple cooling cycles.

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