Increasing storage temperature of frozen foods: effect on sustainability and food quality

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Increasing storage temperature of frozen foods: effect on sustainability and food quality

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ABSTRACT

An extensive study has been performed to the effect of storage temperature and time on the quality of frozen foods to investigate to what extend freezing temperatures can be increased in the frozen food supply chain to increase sustainability by reducing energy use. Different commercial food categories and relevant quality indicators are studied as a function of storage time t_s (up to 18 months) and set storage temperatures T_s (-18°C, -15°C, -12°C , and -9°C), as well as energy use of the freezers. Experimental data showed that an increase of 3°C in storage temperature would save about 7% of energy. Furthermore, for a majority of quality attributes, including microbial, storage temperature could be increased from -18°C to -15°C, without the attribute exceeding the acceptance limit. Sensory properties show a clear trend with t_s and T_s and could be well modelled using a Weibull or Logistic model that allows defining combinations of storage temperature and best-before date for each product. For the majority of products the sensory quality attributes are within the acceptability limits before the used by dates when the products are stored at -15°C. From this study it could be concluded that to increase sustainability in the frozen food supply chain by increasing storage temperature without a loss in food quality, the supply chain should be able to store different products at an increased temperature that is proven to be safe and retains product quality.

1 INTRODUCTION

Freezing is a common world-wide applied method to preserve and increase shelf life of foods. At low temperature molecular motion and reaction kinetics are significantly reduced. Therefore freezing limits growth of bacteria, yeasts, and moulds, limits structural deterioration, preserves nutritional and sensory value without the need of preservatives [1] [2]. The international standard freezing temperature in the frozen food supply chain is -18°C, which was set about a century ago to ensure sufficient food safety over a shelf-life of months. A significant amount of energy and greenhouse gas emissions is globally involved in the frozen supply chain. The current carbon foodprint is estimated at about 260 mega ton CO_2-equivalents per year [3]. Food industry and logistic companies investigate to what extend the freezing temperature could be increased while maintaining food safety, quality, and shelf life, to reduce energy consumption and increase sustainability [4]. An increase from -18°C to -15°C could reduce the environmental impact with about 10% [5] [6].

To successfully implement such a change in the frozen food supply chain, it is important to understand the effects of increased storage temperature on energy consumption and food quality. Food quality includes properties like microbial safety, nutritional content, physical stability, and sensory characteristics, during storage. Various studies have been performed to increase insights in this, focusing on specific quality attributes and food categories [7] [8] [9] [10] [11] [12] [13] [14] [15] [16]. Effects of pretreatments on quality of deep frozen storage of vegetables were studied [17], preservation techniques in general were reviewed [18], and innovative preservation techniques, alternative to freezing, refrigeration and canning were summarized [19]. The effect on food safety was reviewed [20] [21]. Quantitative models were developed allowing for optimizing between energy usage and important quality indicators [22], [23].

Despite the number of published studies, quantitative knowledge is lacking about the relations between frozen storage temperature, time, relevant food quality indicators, and carbon foodprint that allows to increase storage temperature and set a new international standard for the frozen food supply chain. To decrease this knowledge gap and to identify the potential to increase storage temperature, without reformulating products, we performed an extensive study where we followed the most important quality attributes of nine different savoury frozen products, frozen storage temperature, and energy usage, during storage at four different set temperatures up to 18 months generating a large dataset. The results of this study are presented here.

2 MATERIALS AND METHODS

Ten savoury frozen, commercially available products were included in the study; poultry, coated fish, fish, vegetables, plant-based meat alternatives, and pizza. Samples were stored for 18 months in 8 different freezers (Model HCE519F, Haier, Qingdao, Shandong, China) set at 4 different storage temperatures, being -18°C, -15°C, -12°C, and -9°C (2 freezers for each set temperature). At specific times, about once each month, samples were taken from the freezers, randomly chosen, and characterized for key quality indicators, like microbiological, sensory, texture, oxidative rancidity, drip loss, and nutrition. In addition, temperature and energy usage of the freezers were monitored. The products and measured key attributes are summarized in Table 1.

The study was conducted between November 2022 and December 2024. As can be seen in Table 1**Error! Reference source not found.**, the start of the experiment does not correspond to the month of production. Depending on the product the lag between the production date and the start of the experiment was 1 to 8 months.

Table 1 Product categories, product names, product sources, measured attributes, month of production, starting dates of the experiments, and best before dates. The product name is used in the text and figures in this paper. The vegetable mix refers to Birds Eye Steamfresh Family Favourites mix of carrots, broccoli and sweetcorn.

Product Category	Product name	Source	Attributes measured	Produced	Start of experiment	Best before date
Poultry	Crispy Chicken	Lowestoft Store	Microbiology, Sensory, Rancidity	03-2022	11-2022	06-2023
Fish Fingers	Omega3 FiFi	Bremerhaven Store	Microbiology, Sensory, Rancidity	09-2022	11-2022	03-2024
Fish Fingers	Chunky FiFi	Lowestoft Store	Microbiology, Sensory, Rancidity	02-2023	03-2023	05-2023
Natural Fish	Salmon Fillets	Campden	Microbiology, Sensory,	10-2022	11-2022	05-2023

			Rancidity, Drip loss			
Vegetables	Garden Peas	Lowestoft Store	Microbiology, Sensory, Nutrition	08-2022	11-2022	02-2024
Vegetables	Leaf Spinach	Reken	Microbiology, Sensory, Nutrition	08-2022	11-2022	08-2024
Vegetables	Family Mixture	Lowestoft Store	Microbiology, Sensory, Nutrition, Texture	09-2022	11-2022	03-2024
Plant Based	Meat Balls	Vallodolid Store	Microbiology, Sensory, Texture	04-2022	11-2022	06-2023
Pizza	Margherita	Naas Store	Microbiology, Sensory	09-2022	11-2022	09-2023

2.1 Experimental methods

2.1.1 Microbiology

Food safety was assessed by measuring three microbiological tests, using standard protocols accredited to Campden BRI Limited by the United Kingdom Accreditation Service (UKAS). Bacterial populations were counted using Aerobic Plate Count (APC) at 30°C per gram of product according to the protocol TES-MB-002, which is based on BS EN ISO 48333, using Plate Count Agar.

Presumptive *Enterobacteriaceae* were counted per gram of product using the protocol TES-MB-006, which is based on BS ISO 21528-2:2004.

Presumptive *Escherichia coli* was counted per gram of product using the protocol TES-MB-176, using a membrane method on tryptone bile x-glucuronide agar based on BS ISO 16649-1:2001.

For the vegetable products (peas, spinach, and vegetable mix), also *listeria monocytogenes* and listeria species was counted in 25 gram of product, using the TES-MB-174 enrichment technique at 37°C based on BS EN ISO 11290-1:1996 + A1:2004.

For every storage temperature and time point, experiments were performed in triplicate. Microbial counts were expressed as the logarithm of colony-forming-units per gram of product (log cfu/g).

2.1.2 Sensory

The products were analysed on the sensory attributes *Appearance*, *Aroma*, *Flavour*, and *Texture/Mouthfeel* using a panel of 4 panellists, trained by Campden using standard protocol TES-S-023. Products were prepared using relevant domestic grade appliances, following instructions provided by the supplier. Attributes were scored on a scale ranging from 1 (bad) till 9 (excellent), see Table 2. The overall quality of a product (*Overall Quality*) was determined as the minimum value of the scored attributes.

Table 2 Sensory quality grading scale used by the panellists.

Score	**Quality**
9	Excellent
8	Very Good

7	Good
6	Fairly Good
5	Satisfactory
4	Just Acceptable
3	Poor
2	Very Poor
1	Bad

2.1.3 Fat and oil composition and rancidity

Degradation of fats and oils was quantified in triplicate using the TBA Rancidity (TBAR) method by measuring the concentration of thiobarbituric acid reactive substances, which are byproducts of lipid (per)oxidation based on the method published by Zeb and Ullah [24]. The free fatty acid (FFA) concentration was measured according to protocol TES-AC-211, based on BS EN ISO 660:2009

Omega 3 and total fat content was determined for the products containing fish according to protocols TES-AC-090, based on BS EN ISO 12966-2 : 2017 and TES-AC-536, based on BS 4401: Part 5: 1996, respectively.

2.1.4 Nutrition

For the vegetable samples, nutritional value was assessed in triplicate by measuring the concentration of carotene and vitamin C according to protocols TES-AC-021, based on [25] and TES-AC-745, based on [26], respectively.

2.1.5 Drip loss

Drip loss W of the salmon fillets was measured using a protocol based on EZ Driploss method [27], which corresponds to the release of water during thawing, and was quantified in triplicate as the relative difference in weights of the salmon product before, m_0, and after 16 hours, m_1, stored at 4°C; $W = \frac{m_1 - m_0}{m_0} 100\%$.

2.1.6 Texture

Physical textural properties of a selection of products were assessed from compression curves using a Texture-Analyser (MODEL TA-XT2i,Stable Micro Systems, Godalming, Surrey, United Kingdom) and a variety of attachments.

Textural properties of plant-based meatballs were measured for 15 replicates. A 45mm flat disk probe was used, with a double compression test, with a test speed of 5mm/s, test strain of 50%, a trigger force of 50g and a 0.1s gap between compressions. *Hardness* (g) was defined as the maximum of the compression curve, *Adhesiveness* was defined as the area of negative force after the first compression, *Resilience* to the ratio of the area under the curve from the first probe reversal point to the crossing of the x axis, and the area from the first compression cycle. It is measured in both speed and height, *Cohesiveness* was defined as the area between the first and second compression, and has no units. *Springiness* was calculated as the ratio between the time differences of the first and second compressions, *Gumminess* as peak force x ratio of the positive area for the first and second compression and *Chewiness* to hardness x cohesiveness x springiness.

The *upper skin strength* (g) of the garden peas was assessed using a pea rig (Model Multiple Pea Test Rig, Stable Micro Systems, Godalming, Surrey, UK). Test conditions were speed of 2mm/s, 15mm distance and a trigger force of 5g. Five replicate tests were performed. The *upper skin strength* is defined as the maximum in the compression curve, showing the average peak force required to penetrate through the top surface of the peas.

The *peak force* (g) and *area* (g.mm) of carrots that are part of the vegetable family mixture were assessed using a P6 cylinder probe (Stable Micro Systems, Godalming, Surrey, UK). Test conditions were speed of 1mm/s. target mode of 50% strain and a trigger force of 5g. Thickness and diameter of carrot slices were selected within the range of 0.3-0.5mm thick, and 2-2.5cm in diameter. 15 replicate tests were performed and the results were defined as the maximum in the compression curve to penetrate the sample to 50% stain, and as the area under the compression curve indicating the amount of work, or energy, to deform the sample, respectively.

2.1.7 Freezer temperatures and energy use

The temperatures and energy use in the 8 freezers were monitored using temperature data-loggers (Model Temp101A, Madgetech, New Hamshire, USA), and energy monitoring devices (Model KP115, TP-Link, Irvine, California, USA).

2.2 Data analysis and model development

Data plotting and data analysis was performed using Python; the packages *scikit-learn* and *SciPy* were used for statistical and linear regression analysis and the package *lmfit* for non-linear data fitting. Different models were compared, which are often used to quantify the experimental product quality $q(t,T)$ as function of time t and storage temperature T, (see e.g. [23] [28]), including:

Arrhenius model

$$\mathrm{q}(t,T) = q_0\, exp[-k_0 t\, exp(-E_a/RT)] \quad (1)$$

with fit parameters q_0 the initial quality, k_0 the reference rate, and E_a being assessed from experimental data and R the universal gas constant.

Weibull model

$$\mathrm{q}(t,T) = q_0 + (\mathrm{q}_\infty - \mathrm{q}_0) exp\left[-b(T)t^{n(t)}\right] \quad (2)$$

with $b(T) = ln\,[1 + exp(m(T - T_c)]$ where the parameters q_0 the initial quality, q_∞ the asymptotic final quality at long term storage, m, T_c and $n(t)$ are assessed from experimental data.

Logistic model

$$\mathrm{q}(t,T) = q_0 + \frac{\mathrm{q}_\infty - \mathrm{q}_0}{1 + exp[-k(t - t_c)]} \quad (3)$$

with $t_c = \mathrm{a}_T \mathrm{T} + \mathrm{b}_t$ and where the fit parameters q_0, the initial quality, q_∞, the asymptotic final quality at long term storage, and a_T and b_t are assessed from experimental data. For simplicity we assumed that k is not dependent on storage temperature.

Linear regression model

$$\mathrm{q}(t,T) = \beta_T \mathrm{T} + \beta_t \mathrm{t} + \beta_0 \quad (4)$$

with β_0, β_T, and β_t as assessed from experimental data.

Models were fitted or trained on the whole data set. Goodness of fits were expressed as the coefficient of determination, R^2, for the linear regression models and as the reduced chi-squared, χ^2_ν, for the non-linear models. Prediction intervals were assessed using Monte-Carlo simulations of the trained models, where for each simulation a set of fitted input parameters were taken, chosen from a Gaussian distribution according to the fitted mean and standard deviation of the input parameter. The linear regression model was used for data that did not show a clear sigmoidal shape with time.

2.3 Data availability

Part of all data generated or analysed during this study is included in the figures included in this published article. The results from the data analysis and model development is available in the supplementary data.

2.4 Code availability

The underlying code for this study is not publicly available but may be made available to qualified researchers on reasonable request from the corresponding authors.

3 RESULTS AND DISCUSSION

3.1 Freezer temperatures and energy use

3.1.1 Freezer temperatures

Figure 1 shows measured temperatures of the 8 freezers used in the experiments. Freezer temperatures are measured at specific dates and averaged over a day, starting at t=0 that corresponds to November 7, 2022. For all freezers, the measured actual temperature is lower than the set temperatures, as summarized in Table 3. The focus of the study is on the effect of storage temperate on food quality and the potential to increase storage temperature in the food supply chain. Therefore, we did not focus on specific temperature profiles with time of a specific product, but only focused on the averaged values. The actual averaged storage temperatures shown in Table 3 are used in the statistical analysis and model development.

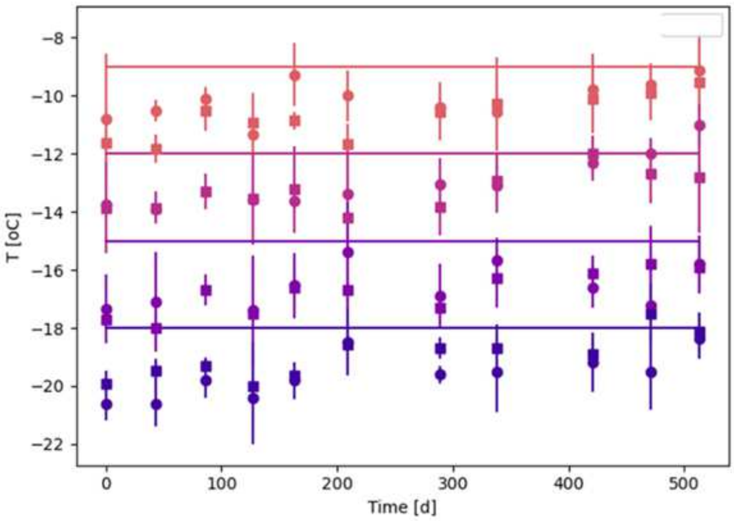

Figure 1. Measured temperatures of the 8 freezers averaged over the measurement day, as a function of storage time. Time t=0 corresponds to November 7, 2022. The horizontal lines correspond to the set

temperature (-9,-12,-15 and -18°C) and the symbols (circles and squares) to the two freezers for the set temperature. Vertical lines correspond to the standard deviation.

Table 3 Set freezer temperatures and averaged actual temperatures, with standard deviations, of the freezers. The average is taken over the entire measurement period.

Set T (°C)	Actual T (°C)
-18	-19.5 ± 1.5
-15	-16.7 ± 1.7
-12	-13.3 ± 1.3
-9	-10.6 ± 1.6

3.1.2 Energy use

Figure 2 shows the averaged energy use of the freezers during the project as function of time (left panel) and as a function of set temperature (right panel). The energy use shows a clear linear trend with storage temperature. It also shows large variation with time for each set storage temperature. Although it seems plausible that this is related to the seasons and resulting varying outside climate properties, we did not investigate this in more detail. From a linear regression analysis it follows that $E_{use} \propto \alpha_E T_{storage}$ with the slope equal to $\alpha_E = -0.024 \pm 0.004$ kWh/T. This indicates that an increase of 3°C, e.g. from -18°C to -15°C, would correspond to an energy gain of about 7%.

This is in line with what can be roughly estimated from the coefficient of performance (COP) of a refrigerator (see e.g. [23]). The COP corresponds to the ratio of useful cooling energy provided, Q, and the work required, W. It is defined as $COP_r = \frac{|Q|}{W} = \frac{Q_C}{Q_C - Q_H} = \frac{T_C}{T_C - T_H}$, where the subscript C and H refer to the cold and hot reservoir of the Carnot cycle. Assuming an outdoor temperature of 20°C, the difference in COP between storage at -18°C and -15°C is then about $COP_{-18}/COP_{-15} = 0.9$. This implies that storage at -15°C would require about 0.9 times the energy compared to storage at -18°C. This corresponds to a 10% energy gain, close to what is found experimentally.

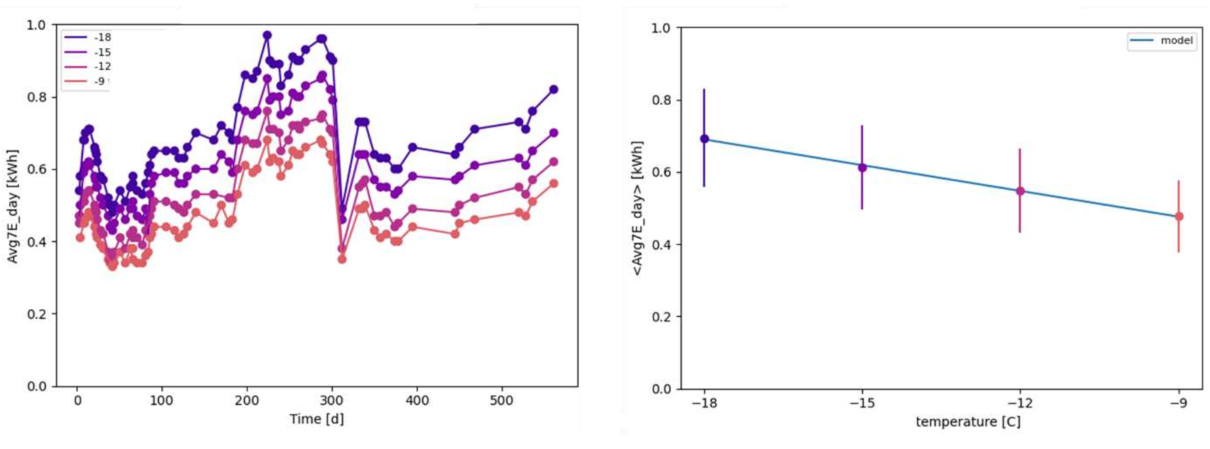

Figure 2. Left panel: Freezer energy use [kW/h] as a function of time for the different set storage temperatures (as indicated in the legend). The energy use is averaged over one week and over both freezers having the same set storage temperature. Right panel: Averaged energy use per day as function of set storage temperature. Vertical lines indicate standard deviations. The blue continuous line corresponds to the fitted linear regression model.

3.2 Microbiology

Figure 3 shows the microbial counts of *Omega Fish Fingers* as a typical example of data of the microbiological tests performed on the investigated products. For this product, for all times and storage temperatures, the count values are clearly below the lowest limit of acceptance. This is the case for most products and microbiological tests, except for *ChunkyFiFi* for which the log APC was slightly above the limit 5 for all times and storage temperatures (about 5.3) and the *Margarhita* pizza of which the APS started at about 6 ± 1 and reduced to about 5 ± 1 after 18 months of storage.

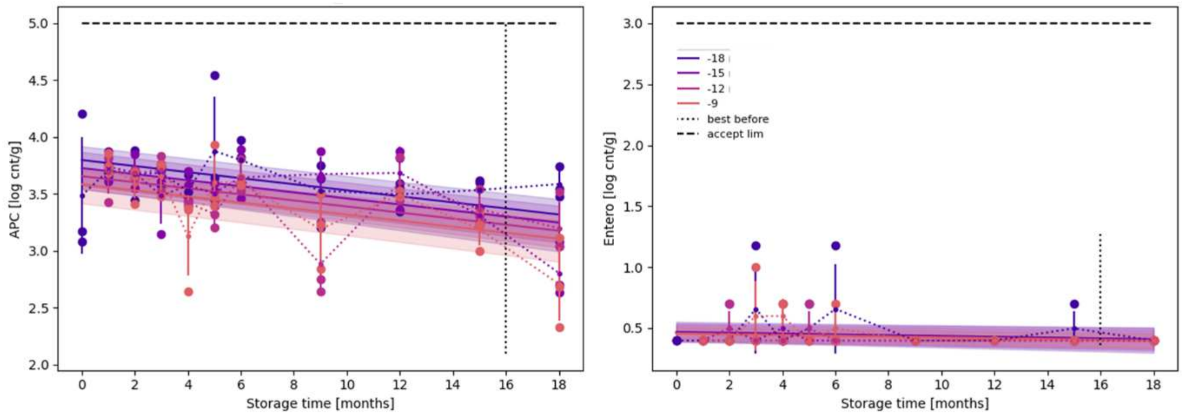

Figure 3 Example of Aerobic Place Count (left panel) and presumptive Enterobacteriaceae count (right panel) measurements of Omega Fish Fingers as a function of storage time for different set storage temperatures. Counts are expressed as log cfu/g. The symbols correspond to the measured values of the triplicates, the vertical continuous lines correspond to the standard deviations. Different colours correspond to different set storage temperatures as shown in the legend. Shaded regions correspond to prediction intervals. The vertical dotted line correspond to the best before date of the product while the horizontal dashed line correspond to the limit of acceptance. The continuous coloured lines correspond to the fitted linear regression models.

Figure 4 shows linear regression results (equation 4) of all products for the logarithm of the APC-counts. It is seen that the coefficients of determination, R^2, are low, but that regression coefficients are significant ($p<0.05$) except for *MeatBalls* and *ChunkyFiFi*. Furthermore, it is also seen in Figure 3 and Figure 4 that the microbial counts decrease with storage time for all products except for *ChuckyFiFi*, that shows a slight increase with storage time. Similarly, the microbial counts are also inversely correlated with the storage temperature for almost all products. The reason for this in not yet clear. It is noted that there is a large variation in the measured data and that the linear multivariate regression model only explains a small part, reflected in the small R^2, but that the regression parameters in most cases are significant ($p<0.05$), indicating a clear trend of the microbial counts with time and storage temperature.

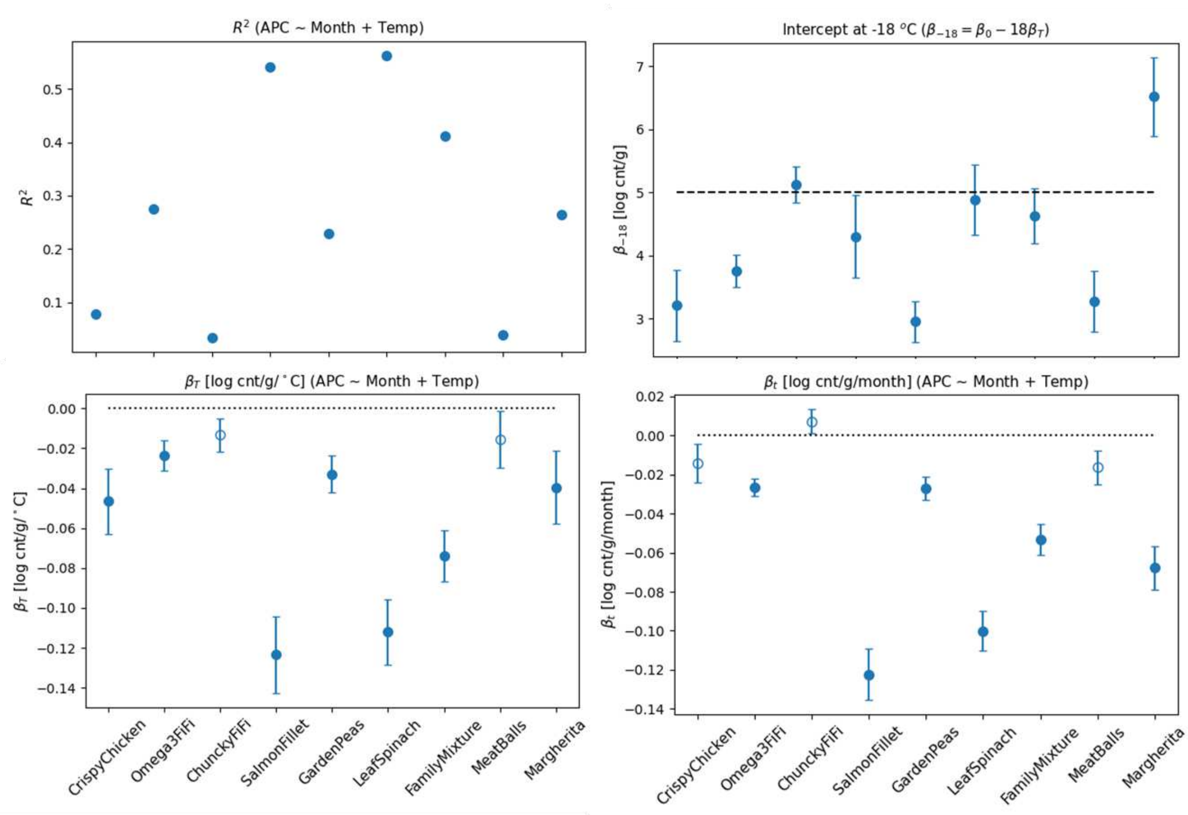

Figure 4 Results of the linear regression models (equation(4)) for $q(t,T)$ = log APC-counts of all products, showing the coefficients of determination R^2 (top left) and regression coefficients $\beta_{-18} = \beta_0 - 18\beta_T$ corresponding to the intercepts at -18°C (top right), β_T (bottom left) and β_t (bottom right). For the regression coefficients also the standard deviations are shown (if not visible, than smaller than the symbol). Closed symbols correspond to a significant regression parameter with p-value smaller than 0.05 while an open symbol corresponds to a regression parameter with p-value larger than 0.05. The dashed line corresponds to the acceptance limit and the dotted lines to zero.

These results indicate that increasing storage temperatures from -18°C to -15°C, -12°C or -9°C does not have a negative impact on food safety for storage times up to the set expiring dates of the products.

3.3 Sensory

Figure 5 shows the *Overall Quality* of the vegetable *Family Mixture* as a typical example of a measured sensory attribute as a function of storage times for different storage temperatures. Furthermore, the figure shows the fitted logistic model (equation (3)) including the standard deviation based prediction interval. It is seen that the *Overall Quality* of *Family Mixture* depends on both storage time and temperature and can be very well described by the logistical model. This is also the case for the other sensory attributes of the vegetable *Family Mixture*, *Appearance*, *Aroma*, *Flavour*, and *Texture*, that define *Overall Quality*. For most products, the sensory attributes could be well described by the logistic and Weibull model. This is also reflected in the reduced chi-squared, which is in all cases below one. For the *ChunkyFiFi*, the data was very scattered and no good model description could be obtained.

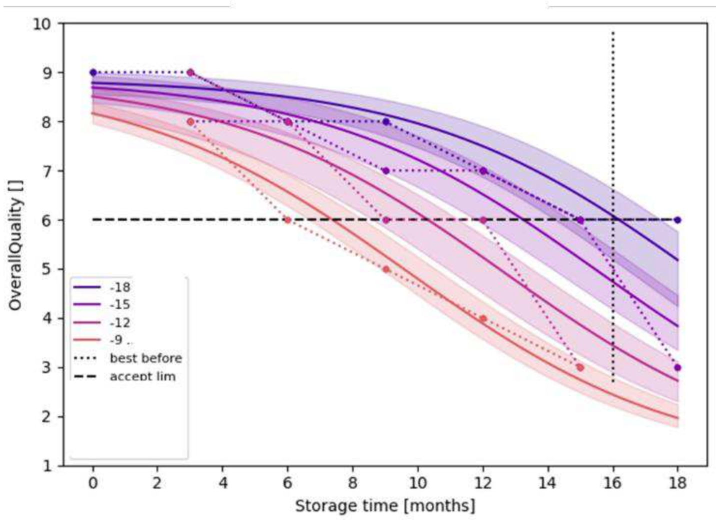

Figure 5 Sensory attribute Overall Quality *of the product* Vegetable Mix *as a function of storage time and for different set storage temperatures. The symbols correspond to the sensory evaluation and the dotted lines between the data points are added as guide for the eye. Different colours correspond to different set storage temperatures as shown in the legend. The vertical dotted line correspond to the best before date of the product while the horizontal dashed line correspond to the lower limit of acceptance. The continuous coloured lines correspond to the fitted logistic model and the shaded regions to the prediction interval based on the standard deviation.*

The Arrhenius model (equation (1)) performed worse with respect to the Weibull (equation (2)) and logistic model (equation (3)). For all sensory attributes and products, the reduced chi-squared of the logistic and Weibull models were lower than that of the Arrhenius model (not shown). The logistic and Weibull models gave very similar results (see Supplementary Data). For clarity, we therefore only present the logistic model in this paper.

Figure 6 shows the time $t_{L=6}$ that the sensory *Overall Quality* of the products reached the acceptance limit 6 according to the logistic models, for the different storage temperatures. It is seen that for all products $t_{L=6}$ is inversely correlated with the storage temperature, as expected: a higher storage temperature caused a faster decrease of the food sensory quality and reduces the time until which the product attributes are above the acceptation limit. In addition, it can also be observed that for the products *CrispyChicken*, *Omega3FiFi*, *LeafSpinach*, and *MeatBalls*, the storage temperature could be increased with at least 3°C, while it still has acceptable quality after 18 months of storage.

In Table 4 the predicted durations until the *Overall Acceptability* value of 6 is reached for storage at -18°C and -15°C are given for all products. For the *CrispyChicken*, *MeatBalls* and *ChunkyFiFi* storage at -18°C and -15°C results in the same duration with acceptable quality for this attribute. However, the *Flavour* of *ChunkyFiFi* stored at -18°C and -15°C reached the acceptance limit of 6 already after a few months, while for the other storage temperatures corresponding sensory scores where higher. This resulted in a bad fit with the logistic and Weibull model. For *LeafSpinach* the storage duration at -15°C is half of the duration at -18°C. For the other products a smaller reduction is storage duration is predicted, with reductions in the range of 22.2-33.3%.

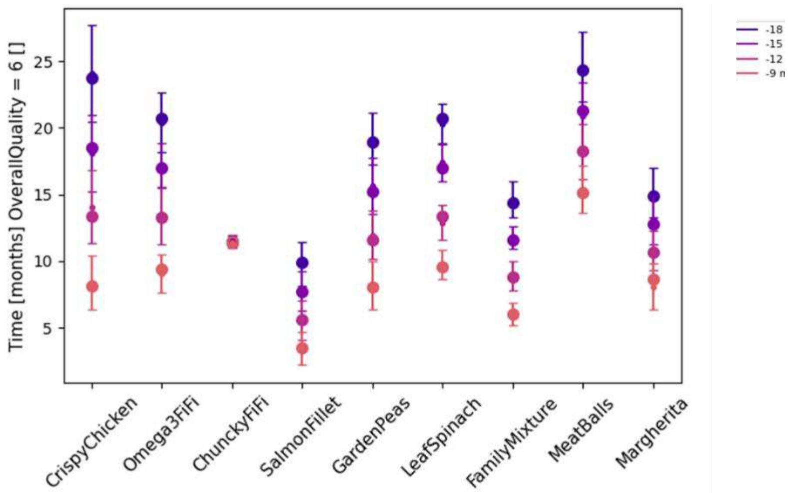

Figure 6 The time in months that the Overall Quality of the products reach the acceptance limit of 6 according to the product specific logistic model, for different storage temperatures (indicated by different colours as shown in the legend). Vertical bars indicate standard deviations.

Table 4 Overall Quality *sensory score, q, for the investigated products at the expiration time t_{bb} (time best before) at set storage temperatures T_s=-18°C and -15°C, with an acceptance limit of 6. Also differences between time of production, t_p, time of start of the experiments, t_0, and expiration time, t_{bb}, are shown.*

Product name	$t_0 - t_p$ [months]	t_{bb}-t_0 [months]	$q(T_s$=-18C, $t_{bb})$	$q (T_s$=-15C, $t_{bb})$
CrispyChicken	8	7	9	9
Omega3FiFii	2	16	9	6
ChunkyFiFi	1	14	5	5
SalmonFillet	1	7	8	7
GardenPeas	3	15	8	6
LeafSpinach	3	21	6	3
FamilyMixture	2	17	5	4
MeatBalls	7	7	9	9
Margherita	2	10	9	7

3.4 Fat and oil composition and rancidity

Figure 7 shows typical examples of the measured indicators for fat composition in relation to degradation and rancidity. The examples shown are from the product *SalmonFillet*. In general, the variation in experimental data is large, which is also reflected in the low coefficient of determination R^2, as also can be seen in Figure 8. Regression results for *Total Fat Content* are not shown because for all product the R^2 was below 0.1 and regression parameters were not significant, except for the intercept. In addition, Figure 8 shows that the initial FFA concentration of *SalmonFillet* is much larger than that of the other products, as expected for the type of fish, and that it decreases with time with about 0.4 g/100 g/month, while for the other products it is constant or increases with time with about 0.6 g/100 g/month. For all products FFA concentration increases with about 0.2 g/100 g/°C about (except *TriBasaFiFi*, of which β_T is not significant indicating that FFA is about constant with storage temperature). Furthermore, *Omega3* concentration is about constant with storage temperature and only significantly increases (decreases) with less than 10% per month for *SalmonFillet* (*ComBasaFiFi*). For *TBAR* significant relations with storage temperature and time are found for *Chicken*, *OmegaFiFi*, and *ComBasaFiFi* (β_T ~ +0.1μM/g/°C, β_t ~ -0.3 μM/g/month).

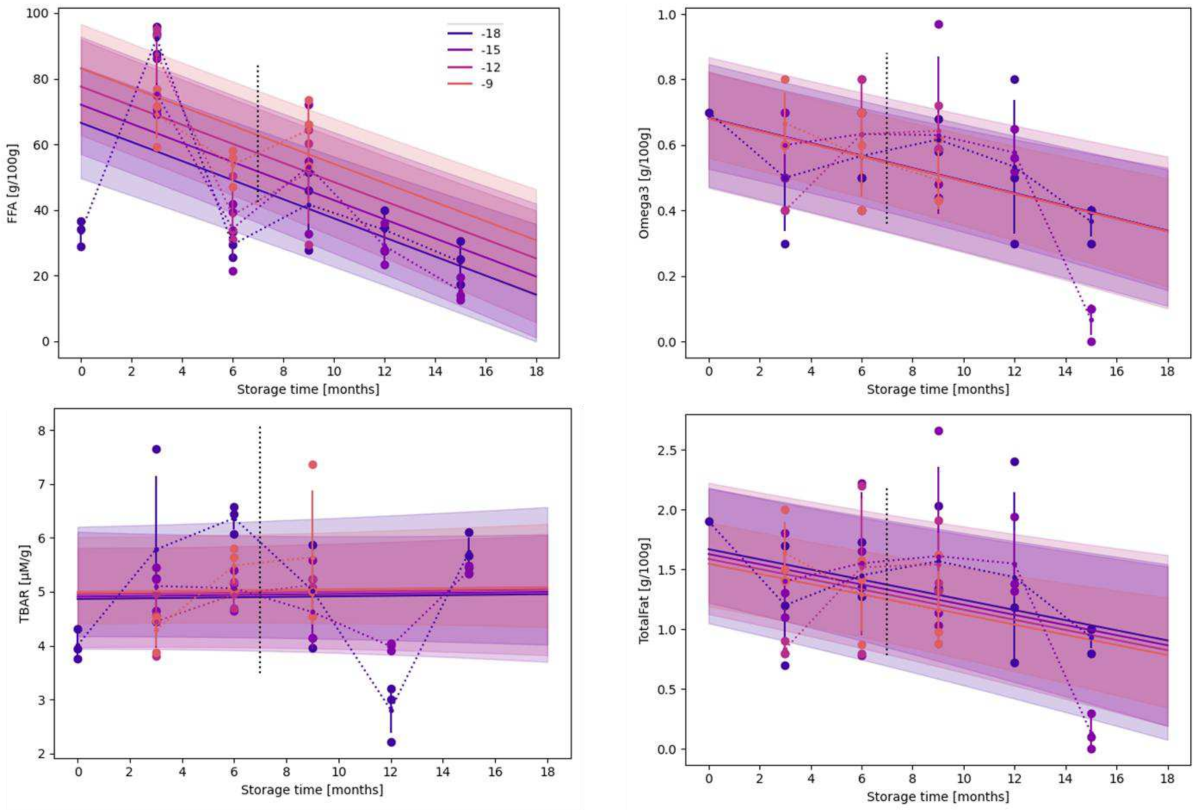

Figure 7 Indicators for degradation of fats in SalmonFillet as a function of storage time (x-axis) for different set storage temperatures (colours as in legend): Free Fatty Acid (FFA) concentration (top left), Omega 3 concentration (top right), thiobarbituric acid reactive (TBAR) substances concentration (bottom left) and total fat content (bottom right). Symbols correspond to the measured values, the vertical continuous lines correspond to the standard deviations and the dotted lines between the data points are added as guide for the eye. Different colours correspond to set storage temperatures as shown in the legend. The continuous coloured lines correspond to the fitted linear regression models and the shaded regions to the prediction interval based on the standard deviation.

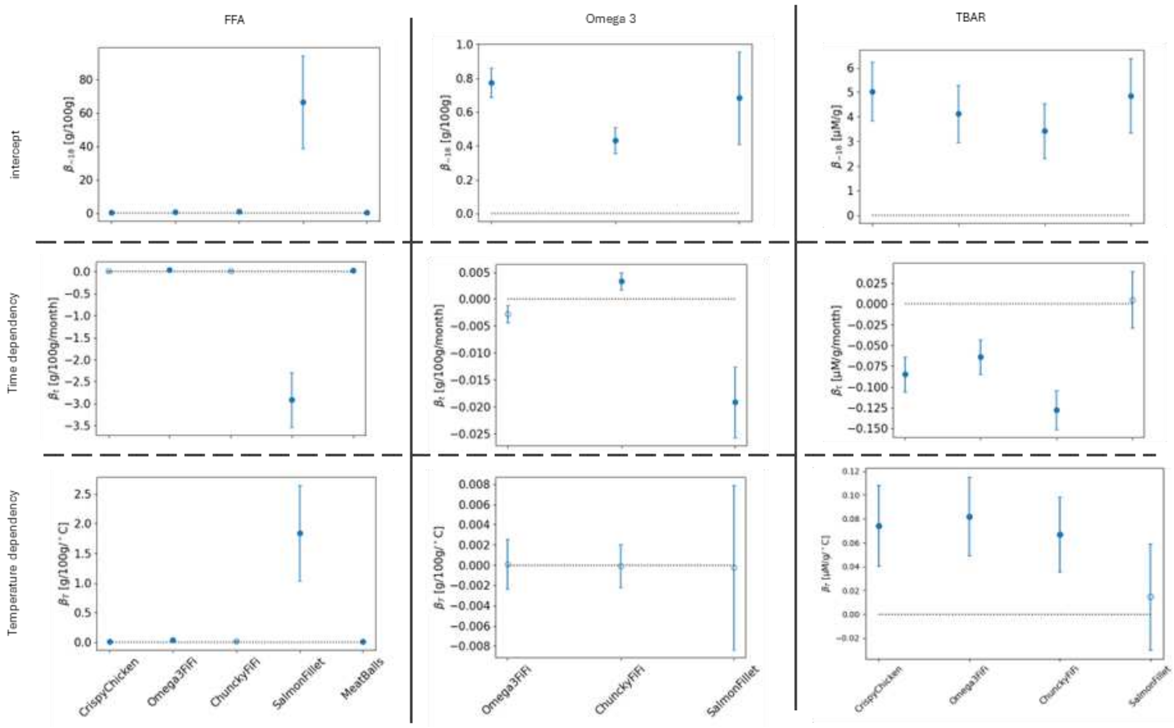

Figure 8 Results of the linear regression models (equation 4) for q(t,T) = FFA concentration (panels in left column), q(t,T) = Omega3 concentration (panels in middle column) and q(t,T) = TBAR concentration (panels in right column) as measured for the products showing on the x-axis. The top row shows the intersect at time zero and storage temperature -18°C, and the middle and bottom rows show the regression coefficients related to the storage time β_t and temperature β_T, respectively. Standard deviations are also shown (if not visible, than smaller than the symbol). Closed (open) symbols correspond to a significant (not significant) regression parameter with p-value smaller (larger) than 0.05.

3.5 Nutrition

Figure 9 shows examples of measured nutritional values in *Peas*, being vitamin-C and carotene concentration as a function of storage time and for different storage temperatures. Vitamin C concentration showed sigmoidal change and could be well described by the logistic model (equation (3)). Carotene concentration showed large variation and were modelled using linear regression (equation (4)). Similar results are obtained for the other data on vegetables, being the *Spinach* product and carrots as part of the vegetable mixture (*Family Mixtue*).

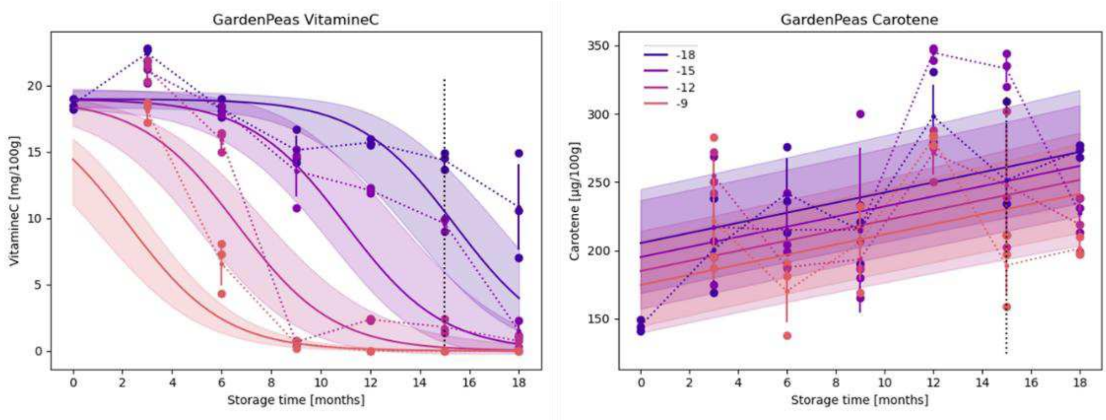

Figure 9 Examples of vitamin C (left panel) and carotene (right panel) in GardenPeas during storage as function of storage time (x-axis) and for different set storage temperatures (indicated by the different colours as shown in the legend). Symbols correspond to the measured values, the vertical continuous lines

correspond to the standard deviations and the dotted lines between the data points are added as guide for the eye. The vertical dotted line correspond to the best before date of the product. The continuous coloured lines correspond to the fitted logistic model (left panel) and linear regression models (middle and right panel) and the shaded regions to the prediction interval based on the standard deviation.

Results for the nutritional values and vegetables are summarized in Figure 10. It can be seen that for all investigated vegetables the vitamin C concentration decays with time and decays faster when the storage temperature is higher, because the half-time decreases with increasing storage temperature. The half-time is the time that the concentration equals half its initial value. They show large variation and coefficients of determination smaller than 0.33. Carotene concentrations are slightly increasing with storage time for peas (β_t~0.5 µg/100 g/month) and spinach (β_t~5 µg/100 g/month) and decreasing for the carrots in the vegetable mix (β_t~-7 µg/100 g/month), while it decreases with increasing storage temperature (only for spinach a significant relation is observed (β_T~-6 µg/100 g/°C, with p,0.05).

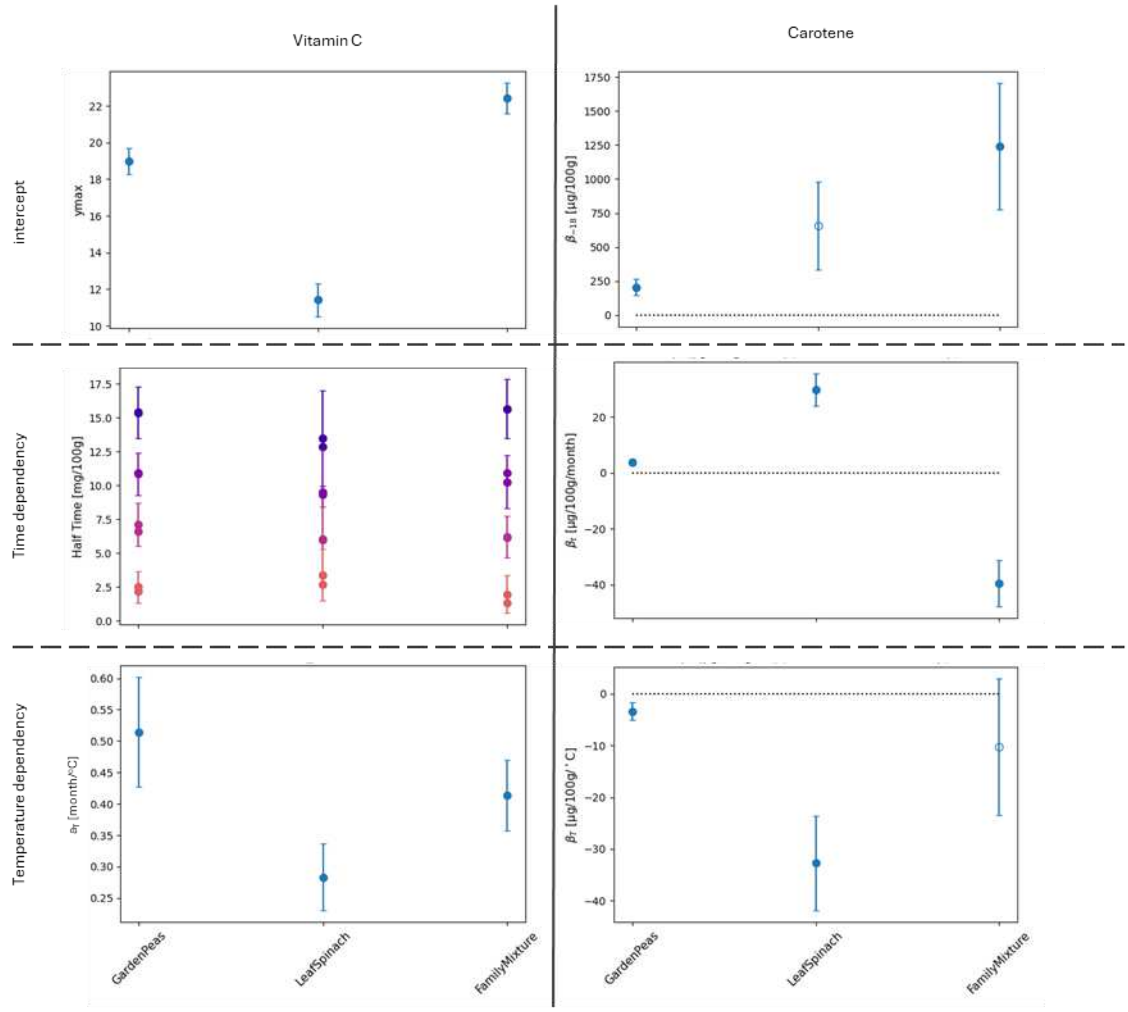

Figure 10 Results of the logistic model (equation (3)) for q(t,T) = vitamin C concentration (panels in left column) and linear regression models (equation (4)) and for q(t,T) = carotene concentration (panels in right column) as measured for the products showing on the x-axis. The top row shows the value at time zero and storage temperature -18°C, the middle row show the time that half of the amount of vitamin C is reached for different storage temperatures (left) and regression coefficients related to the storage time β_t (right) while the bottom row shows the temperature dependence of the halftime (left) and regression coefficients related to the storage temperature β_T (right). Standard deviations are also shown. Closed (open) symbols correspond to significant (not significant) regression parameter with p-value smaller (larger) than 0.05.

3.6 Drip loss

Drip loss of salmon fillet with storage time and storage temperature is displayed in Figure 11. Variation in measured drip loss is large, which is also reflected in the low R^2. Drip loss decreases with storage time, for all storage temperatures. No significant relation with storage temperature is observed.

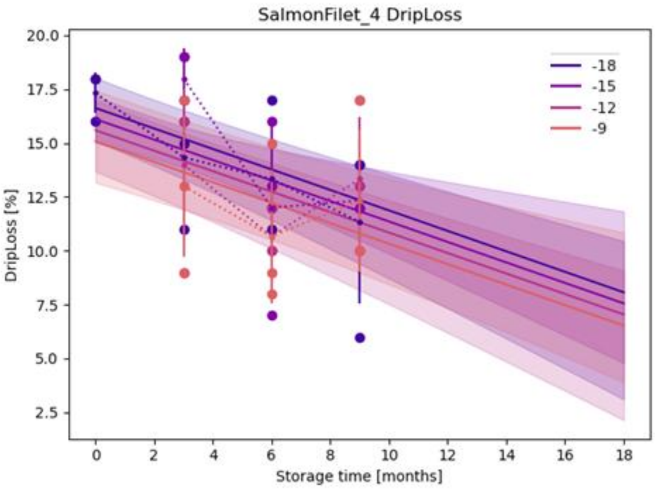

Figure 11 Drip loss [%] of SalmonFillet as function of storage time [months] for different set temperatures (indicated by the different colours as shown in the legend). Symbols correspond to the measured values, the vertical continuous lines correspond to the standard deviations and the dotted lines between the data points are added as guide for the eye. The continuous coloured lines correspond to the fitted linear regression model (equation (4) with R^2=0.2, β_{-18} = 16.5 ± 1.0 [%], β_t = -0.5 ± 0.2 [%/month]; β_T not significant). Regression parameters have p-values below 0.05, except for β_T. The shaded regions correspond to the prediction interval based on standard deviation.

3.7 Texture

Figure 12 shows examples of texture characteristics of different vegetables as function of storage time and temperatures, including linear regression results. Variation is large and coefficients of determination R^2 are low. This is also seen in Table 5, where we summarized the linear regression results of the texture parameters for the three products.

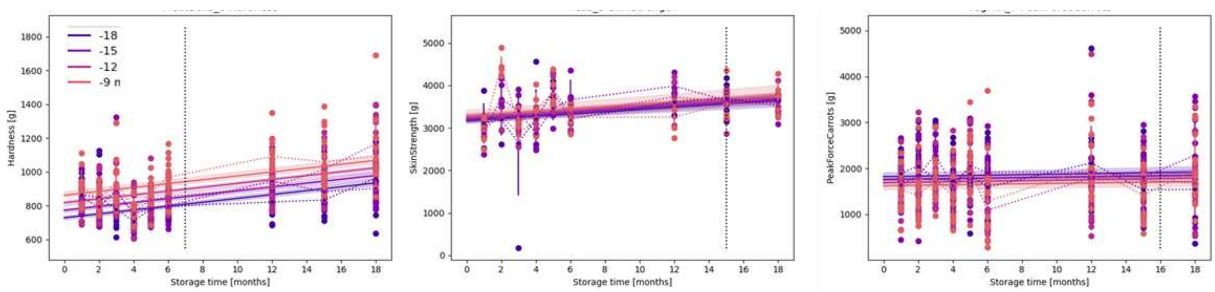

Figure 12 Examples of texture characteristics as function of storage time and for different set storage temperatures: Hardness [g] of MeatBalls (left panel), skin strength [g] of GardenPeas (middle panel) and peak force [g] of carrots in the vegetable Family Mixture (right panel). Symbols correspond to the measured values, the vertical continuous lines correspond to the standard deviations and the dotted lines between the averaged data points are added as guide for the eye. The vertical dotted line corresponds to the expiration date.

Table 5 Coefficient of determination, R^2, and linear model parameters (equation (4)) of texture characteristics as function of storage time and temperature. Only significant model parameters with p-values below 0.05 are shown.

Characteristic	Product name	R^2	β_{-18}	β_t	β_T
Hardness	Meat Balls	0.3	730 ± 10 g	11 ±12 /month	15 ± 2 g/°C
Adhesiveness	Meat Balls	0.02	40 ± 20		-1.7 ± 0.4 /°C
Cohesion	Meat Balls	0.02	0.21 ± 0.02	-0.004 ± 0.001 /month	
Springiness	Meat Balls	0.2	19.0 ± 0.1	0.19 ± 0.02 /month	0.14 ± 0.03 /°C
Gumminess	Meat Balls	0.2	155 ± 15	2.4 ± 0.2 /month	2.8 ± 0.4 /°C
Chewiness	Meat Balls	0.3	28 ± 1	0.15 ± 0.02 /month	0.8 ± 0.1 /°C
Skin strength	Garden Peas	0.09	3200 ± 400 g	26 ± 6 g/month	
Peak force	Family Mixture	0.01	1800 ± 300 g		-22 ± 8 g/°C
Area	Family Mixture	0.02	1100 ± 300 g.mm	15 ± 5 g.mm/month	

4 DISCUSSION

An extensive study has been performed to the effect of storage temperature and time on the quality of frozen foods. This to investigate whether freezing temperature could be increased to increase sustainability in the frozen food supply chain by reducing energy use. Different categories of foods are investigated, including poultry, coated fish, fish, vegetables, plant-based meat alternatives, and pizza. Various quality attributes are investigated, including microbiological indicators, sensory attributes, rancidity related aspects, nutritional values for vegetables, drip loss for salmon fillet, and textural attributes for vegetables and meat-analogue balls. Products stored at different storage temperatures (-18°C, -15°C, -12°C , and -9°C) were followed for 18 months from November 2022 till April 2024. This resulted in more than 20,000 data points of product quality attributes. In addition, storage temperature and energy use of the freezers are also monitored during the experiments. It was measured that an increase with 3°C in storage temperature would save about 7% of energy. This is somewhat below the theoretically estimated value of 10%, which was deduced from the efficiencies of Carnot cycles operating between -18°C and 20°C, and -15°C and 20°C.

The majority of quality attributes are within the acceptability limits before the best before dates if the products are stored at -15°C. Minor discrepancies could be attributed to batch to batch variability and further studies could be carried out to quantify and understand this further.

For the microbial indicators, results show no clear trend with storage temperature and storage time. From these results it could be concluded that for all products an increase in the storage temperature did not result in microbial spoilage above acceptance limits after 18 months of storage, so that from a food safety point of view, storage temperature could be increased even up to -9°C for 18 months.

For the sensory attributes, a clear trend with storage temperature and storage time were observed; higher storage temperature lead in general to a faster decrease in sensory attributes and a shorter shelf-life. These could be well modelled using the Weibull and logistic models, nonlinear in storage time and temperature, which allows defining combinations of storage temperature and best before date for each product. This is product specific. For example, almost no change in sensory attributes were observed for the meat-analogue balls for all storage temperatures during 18 months, while the salmon fillet already reach the acceptance limit after a few months when stored at -9°C.

Of interest from a sustainability point of view is an increase in storage temperature from -18°C to -15°C. This study indicated that for the majority of products the sensory quality attributes are within the acceptability limits before the used by dates when the products are stored at -15°C. A minor deviation in the multicomponent product could be attributed to batch to batch variability.

Increased testing within the last 3 months of shelf life could be carried out to understand this further.

Increasing storage temperature seems related to more rancidity for some products related to more fattier fish such as salmon and known to the trade [29] [30].

For the nutritional aspects of frozen vegetables it is observed that increasing storage temperature results in faster decrease of vitamin C, a vitamin that acts as a proxy for worse-case nutrient losses in vegetables.

Drip loss of salmon fillet is observed to decrease with storage time, but no relation with storage temperature is observed. For the textural related properties, no significant changes with storage time and storage temperature are observed.

5 CONCLUSION

An extensive study has been performed to the effect of storage temperature and time on the quality of frozen foods of which the results are presented in this paper. Based on the data analysis it is concluded that for a majority of quality attributes, including microbial, storage temperature could be increased from -18°C to -15°C, without the attribute exceeding the acceptance limit.

On the other hand, sensory properties are sensitive for storage temperature and storage time, depending on the product. However, for the majority of products the sensory quality attributes are within the acceptability limits before the used by dates when the products are stored at -15°C.

Therefore, in order to increase sustainability in the frozen food supply chain by increasing storage temperature, without a loss in food quality, and knowing that already different products have different use by dates, the supply chain should be able to store different products at new higher temperature that is proven to be safe and retains product quality. Further studies in this area would provide additional reassurance regarding sensory attributes at higher storage temperature.

6 AUTHOR CONTRIBUTIONS

SB and GT-M commissioned the research, developed the experimental study and managed its progress. LS and GT-M contributed in writing and reviewed the manuscript. EH and MA supervised the experimental research, provided the methodology descriptions and reviewed the manuscript. MM executed the data analyses, and MM and MV wrote the manuscript. All authors read and approved the final manuscript.

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