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Weight loss of coffee cream in polystyrene packaging

Ľubomír Valík[1], Monika Hrušková[1], Pavel Ačai[2], Silvia Mošovská[1]

[1]Department of Nutrition and Food Quality Assessment, Institute of Food Science and Nutrition, Faculty of Chemical and Food Technology, Slovak University of Technology in Bratislava, Radlinského 9, 812 37 Bratislava, Slovakia
[2]Department of Food Technology, Institute of Food Sciences and Nutrition, Faculty of Chemical and Food Technology, Slovak University of Technology in Bratislava, Radlinského 9, 812 37 Bratislava, Slovakia
lubomir.valik@stuba.sk

Abstract: This study aimed to quantify the weight loss of coffee cream (10 % fat) packaged in 10 g and 5 g polystyrene (PS) tubes over 316 days. A total of 13,760 weight measurements were performed across four production batches. Significant linear dependence between the absolute weight of coffee cream and time was observed, with negative slopes of –0.009 g/d and –0.007 g/d, and R^2 values of 0.990 and 0.996 for 10 g and 5 g tubes, respectively. Considering the surface area of the PS tube without its aluminium lid, water vapour transmission rates were calculated as 3.34 ±0.08 g/m²·d for 10 g tubes and 2.56 ±0.07 g/m²·d for 5 g tubes. Time required to decrease the weight of the cream by 10 % was 137.0 ±3.0 days for 10 g fillings and 84.0 ±1.9 days for 5 g fillings. Conversely, a loss of 1 g occurred over 110.7 ±2.4 days and 144 ±3.3 days in 10 g and 5 g tubes, respectively. These findings provide producers with an estimate of the excess amount of coffee cream needed to maintain the declared value in PS packaging material, depending on the intended shelf life.

Keywords: coffee cream, polystyrene packaging material, water vapour transmission, weight loss prediction

Introduction

Coffee cream, a dairy product standardised to 10 % or 12 % fat, is homogenised, treated at ultra-high temperature (UHT, 140 °C for 4–6 seconds), and aseptically packed in small tubes. With a shelf life exceeding four months, maintaining quality, including the declared weight of this commercially sterile product over time, is crucial. While microbiological defects can appear quickly at ambient temperatures and are prevented through incubation tests, nutritional, chemical, and physical changes require longer periods to manifest. Although weight loss does not pose health risks, consumers can perceive it negatively.

Packaging materials play a vital role in protecting dairy products from oxygen, light, moisture, and bacterial contamination, thereby extending shelf life (Deshwal et al., 2020). Each packaging type has unique permeability characteristics. Light transmission can cause off-flavours in dairy products due to photosensitizers like riboflavin, chlorophyll, and porphyrin, leading to lipid oxidation (Deshwal et al., 2020; Böhner et al., 2016).

Currently, small volumes of coffee cream are predominantly packaged in single-use polystyrene (PS) or polypropylene (PP) tubes, which are highly permeable to light and gases (Haji-Saeid et al., 2007; Böhner et al., 2016). These materials are more permeable to molecules of low molecular weight compared to metal or glass packaging (Siracusa, 2012). Böhner et al. (2016) highlighted that PS packaging has the highest surface-to-volume ratio and oxygen admission rate, making it less effective than PP and glass containers. Aluminium foil of thickness of at least 15 microns, commonly used as a closure, provides excellent impermeability (Deshwal et al., 2020).

Various intrinsic and extrinsic factors influence water vapour permeability of packaging materials. Composition of food and ambient environment (humidity, temperature) affect the barrier properties of polymers. Water content in food can lead to polymer swelling, altering the packaging's permeability over time. Higher temperatures enhance gas transport due to increased polymer segment motion (Gajdoš et al., 2001; Siracusa, 2012).

Ensuring the declared weight of food products until the end of their shelf life is crucial for producers. This study aims to provide quantitative data on the weight changes of coffee cream packed in PP containers with aluminium foil. The findings will help determine the necessary excess initial weight to maintain the declared value throughout the product's shelf life.

Materials and methods

Design of the study

The 10 % fat-content coffee cream filled in 10 g and 5 g polystyrene tubes from four productions were kept in the laboratory at temperatures in the range of 22 °C to 24 °C and at 40–50 % RH for up to 316 days. Almost 14,000 weight measurements of whole tubes were performed with automatically calibrated analytical balances with readability from 1.0 to 0.1 mg. Primary data acquired at each measurement time were processed with Excel (Microsoft 365, Redmond, WA, USA) and @Risk vs. 8.5.1 (Lumivero, Denver, CO, USA) with periodical basic statistic evaluation and fitting of data distribution included. Net weights of the coffee cream were estimated as stochastic differences between the weights of the filled and empty containers with lids (from 160 to 820 and 200 pieces, respectively). The mean values resulting from fitting distributions were used in the regression analysis of the time dependence.

Surfaces in contact with polystyrene material

To calculate the surfaces in contact with the product or the atmosphere above it, the general formula for the area of a truncated cone was used (Fig. 1; Szczepanek, 2024). The real contact surface of polystyrene consists of the base surface (S_B, smaller circle with radius r) and the lateral surface area calculated using the following formulas:

$$S_B = \pi r^2 \quad (1)$$

$$L_S = \pi s(r + R) \quad (2)$$

S_B is the surface of the base, r is the radius of the base of an inverted truncated cone (smaller circle), R is the larger radius of the top circle, and s is the slant height calculated with the formula in which h is the height of the truncated cone:

$$s = \sqrt{((R - r)^2 + h^2)} \quad (3)$$

Thus, the surfaces in contact with the product or the atmosphere above it were calculated as the surface of the base plus the corresponding lateral surface

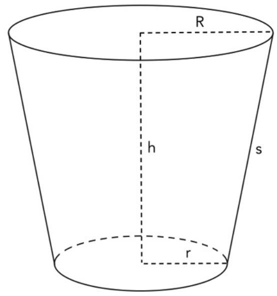

Fig. 1. Dimensional characteristics of a truncated cone.

area or the truncated cone lateral surface area corresponding to the volume of the atmosphere, respectively. The following general equation was used to calculate volumes (V) in the truncated cone:

$$V = \frac{\pi h(r^2 + rR + R^2)}{3} \quad (4).$$

The base, upper circle diameters, and height of 10 tubes were measured with a digital calliper (±0.01 mm). Uniform distributions of these dimensions were used for stochastic calculations of the slant (s), volume (V), and surface (S) of the coffee cream cones, performed using @Risk tools. The dimensions mentioned above were measured for declared weights of 10 g and 5 g tubes filled with 11 g and 6 g of cream (10 % fat), respectively. The average values and calculated surfaces of PS tubes in contact with air or cream, as well as with air and product, are summarised in Table 1.

Water vapour permeability

Water permeation through a polymer material involves four main steps: adsorption on the inner surface of the packaging material, diffusion through the polymer barrier, desorption on the outer surface, and transport of water vapour molecules into the surrounding air (Jing et al., 2021). Adsorption

Tab. 1. Average values of coffee cream tube dimensions and calculated surfaces of air and cream in contact with PS material.

	Height (mm ±SD)	Base radius (r; mm ±SD)	Upper radius (R; mm ±SD)	Slant (s; mm ±SD)	PS surface in contact with cream/air (S; mm^2 ±SD)	Volume (V; cm^3 ±SD)	Weight declared/ filled
Whole tubes	22.4 ±0.2	14.2 ±0.1	15.3 ±0.1	22.9 ±0.3	–	15,3	
Cream space	16.4 ±0.2	14.2 ±0.1	15.2 ±0.1	16.4 ±0.3	2142 ±21	11,1	10 g/11 g
Air space	6.0 ±0.1	14.3 ±0.1	15.3 ±0.1	6.1 ±0.2	566 ±6	4,2	
Whole tubes	23.3 ±0.2	13.6 ±0.2	14.5 ±0.3	23.3 ±0.3	–	15	
Cream space	12.5 ±0.3	13.6 ±0.2	13.8 ±0.1	12.5 ±0.3	1656 ±40	7	5 g/6 g
Air space	10.8 ±0.1	13.8 ±0.2	12.5 ±0.3	10.8 ±0.1	961 ±4	8	

and diffusion of water molecules are influenced by the hydrophilic nature of the polymer surface (adsorption) and the porosity and polarity of the permeable material (diffusion), which are associated with the higher solubility of water molecules. Overall moisture permeation through the packaging material can be described by Fick's law of diffusion. Polystyrene polymer (PS6), used for coffee cream containers, is an amorphous polymer generally more permeable to small molecules such as water and gases. The permeability for water vapour through polystyrene can differ between the liquid contact surface (bottom part of the cone container) and the gas-exposed surface (upper part) due to factors such as swelling, surface interactions, and contamination. Moisture loss from the coffee cream tube through the polystyrene PS6 surface under steady-state conditions was expressed for the total considered transmission permeation surface area with an overall (effective) permeation coefficient, following the Fick's law of diffusion, as:

$$\frac{\Delta m_W}{\Delta t} = \frac{\psi A\left(P_{W_1} - P_{W_2}\right)}{\delta} = \frac{\psi A\left(P_W^{'}\varphi_1 - P_W^{'}\varphi_2\right)}{\delta} \tag{5}$$

where Δm is the weight difference (moisture loss for liquid product by permeation during storage) between two weight measurements of the time coffee cream tube, Δt is the period between two weight measurements, ψ is the coefficient of moisture permeability for the packaging material PS6, A is the considered transmission permeation surface area of the coffee cream tube (truncated cone), p_{W_1} and p_{W_2} are partial water vapour pressures inside the coffee cream tube and outside (environment), respectively (driving force for moisture transmission), p'W is the saturated vapour pressure of water in air at the given temperature, φ_1 and φ_2 are relative humidities of corresponding water vapour inside the coffee cream tube and outside (environment), respectively, δ is the thickness of the wall of the truncated polystyrene PS6 truncated cone.

Water vapour transmission rate (WVTR) can be calculated using the following equation:

$$\mathrm{WVTR} = \frac{\Delta m_W}{\Delta t}\frac{1}{A} \tag{6}$$

where $\Delta m_W/\Delta t$ is the slope of the moisture loss as a function of storage time, $m_W = \mathrm{f}(t)$.

Using Equations (5) and (6), WVTR is obtained as follows:

$$\mathrm{WVTR} = \frac{\psi\left(P_{W_1} - P_{W_2}\right)}{\delta} = \frac{\psi\left(P_W^{'}\varphi_1 - P_W^{'}\varphi_2\right)}{\delta} \tag{7}$$

Finally, the water permeability coefficient through the polystyrene PS6 surface contacting the liquid and gas phase can be calculated from the rearranged equation (7):

$$\psi = \frac{\mathrm{WVTR}\cdot\delta}{\left(p_{W_1} - p_{W_2}\right)} \tag{8}$$

Results and discussion

As expected, net weight of coffee cream gradually decreased during storage. The main driving force of the release of water molecules and their transfer through the polystyrene packaging material is the difference between the relative humidity in the tubes of coffee cream and the outside atmosphere. Since coffee cream has high water activity, the equilibrium relative humidity over the product can be close to 100 %, which creates a driving force of approximately 50 % RH compared to outside storage conditions. The rate of water-vapour transmission is determined by the permeability characteristics of the material. Although water molecules can be released from the cream film, fat globules, and proteins in contact with the polystyrene material, this study only estimated the overall transfer rates of water vapour.

Weight loss trends

Figure 2 shows changes in the individual distributions of the net weights of coffee cream during long storage. The frequency of the data decreased, and the weight values expanded to broader ranges over time, leading to an increase in standard deviation with storage time.

To evaluate the overall trend of weight decrease over time, data from a linear relationship displayed in Figure 3 were analysed using regression analysis. The regression parameters and statistical indices are summarised in Table 2 for coffee creams with declared weight of 10 g and 5 g, initially filled with 11 g and 6 g, respectively. The data show low fit errors and statistically significant linear relationship, with determination coefficients higher than 0.9897.

Slope values for net weight loss express the overall weight loss in g/d. At least two partial processes are involved: saturation of relative humidity over the fluid coffee cream and transmission of water vapour through the packaging material. The volume and surface area of the packaging material over the fluid influence both processes. The study identified a lack of knowledge concerning the transfer of water molecules from the fluid in contact with polystyrene, as represented by the slope values determined. This work provides information on the general kinetics of weight loss and compares the rate in polystyrene packaging filled with different volumes of coffee cream.

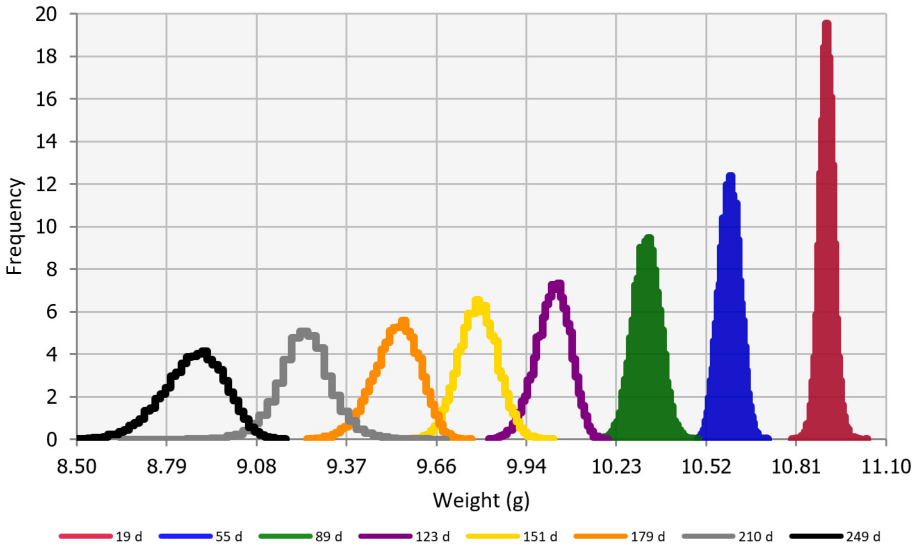

Fig. 2. Distributions of the weight of coffee cream during storage at ambient temperatures (22–24 °C).

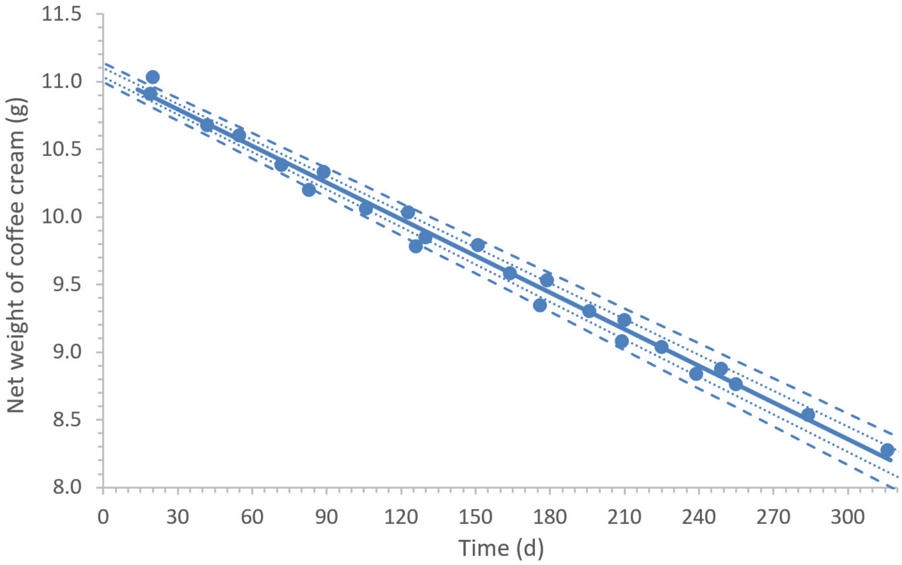

Fig. 3. Average net weights of coffee cream (declared as 10 g but filled to 11 g) in dependence on storage time under ambient laboratory conditions (T/RH: 22–24 °C/40–50 %).

From a practical perspective, the study predicts how much product should be overfilled against the declared weight to maintain it at the end of its shelf life. For example, for an initial filling of approximately 1 g above the declared weight, a 10 g coffee cream is expected to reach the declared weight after 118.1 days on average (95 % CI: 105.6 to 131.7 days). After 6 or 9 months, the net weight decreases to 9.44 g (95 % CI: 9.58 to 9.30 g) or 8.63 g (95 % CI: 8.81 to 8.45 g), respectively. However, all dry matter remains in the tubes.

Vapour transmission rates

Based on the measured dimensions of 10 coffee cream tubes and the geometry of the inverted truncated cone (Eqs. 1–4), the estimated BetaGeneral distributions of the slant height, surface, and volume were represented with the following means and standard deviations: s = 22.39 ±0.25 mm, S = 2703.04 ±29.23 mm^2, V = 15.26 ±0.23 mm^3. Considering the surface of the PS tube without an aluminium lid and the slopes from Table 1, the normally distributed vapour transmission rates were calculated as 3.34 ±0.08 g/m^2 · d for 10 g tubes and 2.57 ±0.06 g/m^2 · d for 5 g tubes (Eq. 6). These values are within the range of 0.8–3.9 g/m^2 · d mentioned by Kjeldsen (1993) and Keller and Kouzes (2017).

Comparison of net weight loss slopes

Comparison of net weight loss slopes for the 5 g and 10 g products (Table 2) revealed that the negative

Tab. 2. Regression parameters and statistical indices of linear regression.

Regression	Parameter	Estimate	SE	t-value	p-value	n	R^2	RMSE
Net weight loss (10 g)	Intercept (g)	11.0664	0.0339	326.64	4.81×10^{-42}	24	0.9900	0.0779
	Slope (g/d)	-9.03×10^{-3}	1.93×10^{-4}	−46.78	1.61×10^{-23}			
Relative weight loss (10g)	Intercept	1.0030	0.0029	346.76	1.29×10^{-42}		0.9897	0.0067
	Slope	-7.58×10^{-4}	1.65×10^{-5}	−45.99	2.32×10^{-23}			
Net weight loss (5 g)	Intercept (g)	6.0758	0.0245	247.68	4.62×10^{-15}	9	0.9982	0.0386
	Slope (g/d)	-6.94×10^{-3}	1.58×10^{-4}	−44.04	8.13×10^{-10}			
Relative weight loss (5 g)	Intercept	1.0221	0.0043	236.97	3.81×10^{-13}		0.9986	0.0054
	Slope	-1.19×10^{-3}	2.61×10^{-5}	−45.56	7.50×10^{-9}			

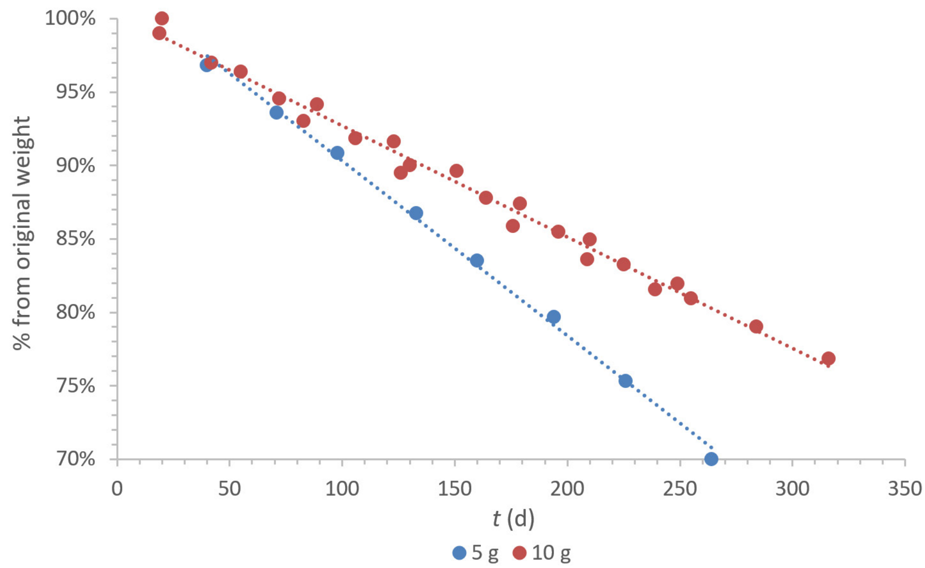

Fig. 4. Relative weight loss of coffee cream in dependence on storage time under ambient laboratory conditions (T/RH: 22–24 °C/40–50 %). Data represent the average percentages related to the initial weight of four productions, three with a declared 10 g weight and one with a declared weight of 5 g.

slope value for 10 g tubes (-9.03×10^{-3} g/d) is lower than that for 5 g tubes (-6.94×10^{-3} g/d). Parameter errors for the 5 g and 10 g products were low, about 2 % of the parameter values. The difference between the storage tests of 10 g and 5 g tubes is in the different volumes of the product and the space over it. A higher volume of fluid coffee cream in 10 g tubes is in contact with a larger surface of the polystyrene material and the outside atmosphere. Conversely, a lower volume of the atmosphere over the product can be better saturated with water vapour from the higher volume of coffee cream, suggesting higher driving force for a longer time. The opposite ratios are in 5 g tubes, with less coffee cream in contact with the packaging material and a larger volume for water vaporisation. These phenomena generally counteract each other, making it difficult to specify their effects within the presented experiment. The relevant output of this work resulted from simple total regression relations (Fig. 3).

Relative Weight Loss

The same data sets, in relative form, were used to express the relationship between the percentage of weight loss from the original weight and storage time (Fig. 4). Despite the lower net weight loss in the 5 g tubes (Table 1), the relative weight loss declined faster with time in the 5 g tubes compared to the 10 g tubes.

Water Permeability Coefficients

For validation purposes, one objective was to calculate the water permeability coefficient of the PS6 polystyrene packaging material (Eq. 8). The transmission of water through the PS tube is different in the liquid phase (coffee cream) and in the atmosphere over the product. Differences may arise from slight swelling of the polymer and surface contamination in contact with the liquid phase. The portion of the PS6 material exposed only to the atmosphere might not undergo the same swelling effect, potentially leading to lower permeability. Surface contamination in the bottom part of the tube reduces the effective permeability of water. Based on our data and the average thickness of the tube PS material (δ = 0,10 mm), the total permeability coefficients were calculated as 2.3×10^{-12} g·m/(m^2·s·Pa) for 10 g tubes and 1.8×10^{-12} g·m/(m^2·s·Pa) for 5 g tubes. These coefficients are consistent with typical polystyrene packaging material values in the range of 10^{-12} to 10^{-13} g·m/(m^2·s·Pa) (Feng, 2015) at temperatures of 25 °C and 30 °C.

Conclusions

In this study, weight loss of coffee cream packaged in 10 g and 5 g polystyrene tubes over 316 days was quantified. Results show a significant linear relationship between the weight loss and storage time, with higher weight loss rates observed in 10 g tubes compared to 5 g tubes. Primary factors influencing weight loss, include the relative humidity difference between the coffee cream and the surrounding atmosphere, the permeability characteristics of the polystyrene material. The findings provide valuable insights for producers, enabling them to estimate the necessary overfill to maintain the declared weight throughout the product's shelf life. Calculated water WVTR and permeability coefficients are consistent with existing literature, validating the study's methodology and results. On the other hand, environmental factors such as temperature and relative humidity should be carefully considered, as they significantly influence the permeability of polystyrene coffee cream tubes and the transmission of water vapour from the product. Elevated temperatures increase the free volume and molecular mobility within the polystyrene matrix, thereby enhancing its permeability to moisture. Concurrently, higher relative humidity intensifies the partial pressure gradient across the packaging barrier, accelerating moisture transfer. Together, these effects can lead to excessive water loss, potentially compromising the product's texture, flavour, and shelf life if not properly controlled.

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