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ABSTRACT

The aim of this study was to determine the suitability of using plant-based alternatives to dairy butter in a model product of a high fat content, Scottish shortbread. We study this well-known Scottish product from the viewpoint of replacing dairy-based butter with a plant-based (vegan) alternative. This widely known and loved baked good has a large content of butter, which is considered crucial for its sensorial and structural properties and thus serves as an ideal product to test butter replacements. We consider three commercially available plant-based alternatives and a generic dairy butter in terms of their fat composition, melting behavior, and corresponding dough properties. Their behavior from a rheological perspective is tested to determine how their different compositions lead to changes in their responses to oscillatory stresses. Finally, after baking the different doughs, we obtained different shortbread versions and designed a sensorial test associated with a survey to investigate their human perception. Based on these results, two of the three plant-based alternatives perform similarly to dairy-based butter. These two alternatives, vegan alternative 2 (VA2) and vegan alternative 3 (VA3), had a total fat percentage of 70% and 79% compared to dairy butter's 82%. Additionally, their rheological properties, such as storage and elastic moduli, are closer to the values of dairy butter, and the firmness of the doughs at room temperature are also similar. Thus, the final baked products using VA2 and VA3 alternatives performed indistinguishably from their dairy butter counterpart by the survey's participants and can be considered as replacements in the future without detriment to flavor or texture.

I. INTRODUCTION

Traditions and modern trends often clash, and our food culture is no exception. With rising obesity rates and the resulting strain on modern healthcare systems, there is a growing awareness of a healthy and unprocessed food culture. Especially, the consumption of saturated fatty acids (SFAs) has been shown to lead to obesity and other comorbidities, such as type II diabetes.[1,2] Dairy butter is abundant in SFAs, which provide its desired characteristics, such as firmness and palatability, while sometimes being associates with undesirable health outcomes.[3,4] The increase of plant-based products is evidenced by the growing number of plant-based and vegetarian diets.[5] However, in traditional products, the replacement of certain products with plant-based alternatives is often seen as lowering the overall quality of the product, which is especially pronounced for butter. Scottish "all-butter shortbread" is a very typical example. Versions made with vegetable fats are often considered inferior, and most people avoid them altogether. The main problem for producing plant-based alternatives seems to be the correlation between flavor, texture, and appearance of baked products along with the types and amount of fat used. In general, the main differences between plant-based alternatives to butter, such as margarine and vegetable oil spreads, arise from the type and amount of fat content (saturated vs unsaturated). Plant-based alternatives may have undergone artificial processes such as hydrogenation to achieve butter-like properties and textures, and they tend to have a higher moisture content than traditional butter, which leads to changes not only in taste but also in viscosity and other sensory properties. The initial acceptance of margarine as a healthier alternative to dairy butter after its development in the 1860s has seen a large increase in

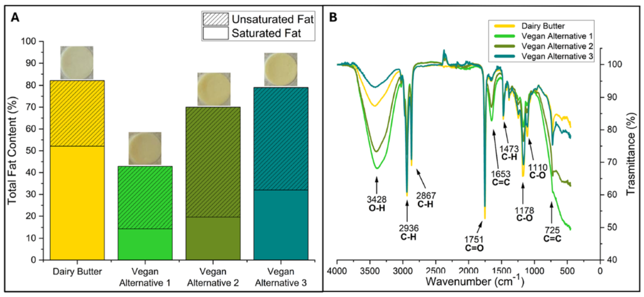

FIG. 1. (a) Comparison of the percentage of dietary fat in each type of fat used, with the stripped area denoting the fraction of unsaturated fat. The images above each bar show the color of the fat. (b) Fourier-transform infrared spectroscopy measurements were taken to determine the chemical properties of each fat type and to qualitatively measure the water content.

popularity, mostly in Europe and the United States.[4,6] In 2015, partially hydrogenated margarines were removed from the generally considered safe list of the FDA as new research had shown partial hydrogenation of oils led to a conversion of unsaturated fatty acids to trans fatty acids.[7] These have been linked to the hardening of arteries and other negative health outcomes. Therefore, it is crucial to consider the composition of dairy butter alternatives before making any health claims. The composition of butter and plant-based alternatives naturally affects the solubility of the sugar content, the hydration of the flour, and, as a result, the dough properties, including the firmness of the final dough mixture. Marconi *et al.* studied the palatability of shortbread made with fat replacements because water content and moisture do not only solely influence rheological properties but also the microbiological and sensory properties of foods.[8] The use of emulsion-filled gels to replace fat was investigated by Giarnetti *et al.*,[9] indicating that the tested population had a clear preference for the traditional version. Sanchez *et al.*[10] prepared low-fat shortbread with fat substitution to suit the demand of calorie-conscious customers. However, the term "shortbread" was interpreted rather broadly in most of these studies and several additional ingredients were added to the recipe. In Scotland, shortbread is traditionally made to perfection with only four ingredients: butter, flour, sugar, and a pinch of salt.

Here, we want to adhere to the traditional Scottish recipe and investigate the effect of replacing dairy butter with ingredients suitable for plant-based diets. Most of the sensorial perceptions of fats are linked to properties such as hardness and spreadability, which are characteristics that can be measured by rheology.[11] G' (storage modulus) and G'' (loss modulus) of fats can be measured by rheometry and can be an indicator of flavor and texture perceptions as shown by previous work by Rousseau and Marangoni.[12] We aim to investigate how different fat contents influence rheological behaviors, temperature responses, dough properties and perceived quality of baked goods, and examine how participants evaluate the final baked products. Using Scottish shortbread as a model for baked goods with high butter content, we focus on the critical role of the fat (butter and vegan alternatives) in achieving desired flavor profiles and consumer ratings.

II. RESULTS

In addition to regular dairy butter, we selected three plant-based (vegan) fat products, with different fat profiles, as shown in Fig. 1. A full list of ingredients is provided in the supplementary material and Table I. Dairy butter has a significantly higher share of saturated fats at 52.1%, while the highest share of saturated fats in the plant-based alternatives was VA3 at 32%. A part of the advertisement of the plant-based alternatives being "healthier" is the fact that they are less calorie-dense , which is achieved by a much higher water content compared to dairy butter while having a lower percentage of saturated fats that have been linked to negative health outcomes. While dairy butter has a total fat content of 82%, the plant-based alternatives reach 42.9%, 70%, and 79%, respectively. These characteristics can be detected using Fourier-transform infrared (FTIR) spectroscopy, and the water content can be compared by using the –OH functional group stretching at 3428 cm^{-1} (Fig. 1). The plant-based alternatives 1 and 2 show a lower transmittance at this wavenumber compared to the two highest total fat-containing fat types, dairy butter and plant-based alternative 3. Additionally, the unsaturated fatty acid residues with C=C bonds can be detected at 725 cm^{-1}. These are in complete agreement with the ratios of unsaturated:saturated fat compositions of the nutritional information of each type of fat investigated. In the order of the highest ratio of unsaturated fats to lowest, the tested fat types follow this succession: vegan alternative 1 (VA1), vegan alternative 2 (VA2), vegan alternative 3 (VA3), and dairy butter. A similar pattern is seen for the stretching mode of C=C at 1653 cm^{-1}, with a distinctive difference between the higher unsaturated fat ratio of VA1 and 2 and partial overlapping of dairy butter and VA3.

Whether it is caloric content (comparison in Table I), the ratio of saturated to unsaturated fats, naturally contained vitamins and micronutrients, or the content of trans fats and additives, such as emulsifiers,

TABLE I. Ingredients for dairy butter and plant-based alternatives, including their caloric content per 100 g.

Type of fat	Ingredients	kcal/100 g
Dairy butter	Cream (cows' milk) (98%) and salt (1.5%)	745
Vegan alternative 1	Vegetable oils (rapeseed, palm, and palm kernel), water, salt (1.24%), emulsifier (mono- and diglycerides of fatty acids), acidity regulator (citric acid), flavoring, color (carotenes), and vitamins A and D	351
Vegan alternative 2	Purified water, soybean oil, palm and palm kernel oil, salt, lecithin (soy), natural flavor, vinegar, vitamin A palmitate, and beta carotene (color)	644
Vegan alternative 3	Plant oils (rapeseed, coconut, and sunflower, in varying proportions), water, sea salt (1.1%), faba bean preparation, emulsifier (sunflower lecithin), natural flavorings, and color (carotene)	713

the evaluation of which option is "healthier" is complex and might differ strongly depending on individual health conditions.

The rheological properties of the fat, joint with solubilities and hydration, determine the texture of the dough.

The storage (G') and loss (G'') moduli indicative of the elastic (solid-like) and viscous (liquid-like) responses within the linear viscoelastic region were determined using small-amplitude oscillatory tests. We compare this behavior for dairy butter and the three plant-based alternatives at 20 °C [cf. Fig. 2(a)]. Butter is known to exhibit an elastic modulus (G') higher than the viscous modulus (G'') at low frequencies[13,14] with phase angles lower than 45° indicating a structured, solid-like behavior. The fact that all samples are predominantly elastic is also clear in the plot of tan δ in Fig. 2(b), where the corresponding phase angle is always below 30°. Comparing dairy butter with the plant-based alternatives, dairy butter exhibits the largest G', which is related to the sample hold its shape. VA1, which exhibits the lowest G', is associated with its softer, more liquid-like structure, with VA2 and VA3 exhibiting intermediate behavior matching the results of saturated and total fat content shown in Fig. 1(a), which are known to affect its viscoelastic behavior. For low frequencies, the viscosity as a function of shear rate has a slope of −1 on a log plot, indicative of yield stress (Fig. S6).

Figure 2(c) shows the plot of elastic stress (stress associated with the storage modulus G') as a function of strain for a fixed frequency at 20 °C. A peak in the elastic stress indicates the yield point, with dairy butter exhibiting the largest yield stress, associated with its structural strength.

The temperature-dependent behavior of butter is well known. A fixed-frequency temperature ramp test was performed between 5 and 45 °C for a strain (0.1%) within the linear viscoelastic region. Additionally, we evaluated the melting behavior of all individual fats on a heated stage microscope (see Fig. 3). At low temperatures, dairy butter exhibits a storage modulus approximately one order of magnitude greater than VA1, indicative of its stiff, elastic structure at low (fridge) temperatures. As the temperature is increased, the moduli for dairy butter decrease significantly, indicating softening of the structure associated primarily with the melting of the crystalline milk fat matrix.[15] Milk fat is known to have a sharp melting point in the 37–42 °C temperature range.[16] Our melting profile measurements indicate that the dairy butter softens at low temperatures just below 30 °C and liquifies in a rather narrow range below 40 °C (see yellow line of Fig. 3), which is reflected in the clear dip in G' and G'' curves between 30 and 40 °C.

It can be seen that the plant-based alternative VA3, despite the most similar composition and FTIR signals, shows a melting behavior that differs strongly from butter, this is also reflected in its rheology, including a broad melting range >15 °C and quite an inhomogeneous phase separation during its melting process.

Additionally, we analyzed the dough response to an applied force using a texture analyzer. The doughs showed that the dairy butter version was the firmest, while the plant-based alternatives followed a trend from firm to soft in the following order: VA3, VA2, and VA1. This trend is mirrored at both tested temperatures [room temperature (RT) and 4 °C]. Interestingly, none of the rheological parameters of the pure fats described above correlate directly with the analyzed textures of the corresponding doughs. This trend in terms of firmness is mirrored also at a lower temperature of 4°C[Figs. 2(a) and 2(b)]. However the firmness of dairy butter at 4°C is approximately six times larger than at RT, while the plant-based doughs donot show significant changes with temperature (see dough textures in Fig. 4). This is contrasted by the pure fat rheology showing temperature dependences in both G' and G'' for all fat types, with most significant changes for dairy butter, as shown in Fig. 2, which is also reflected in the dough behaviors from which the doughs were made. Finally, to transform the doughs into shortbread, a heating or baking step is required. This is traditionally executed at low temperatures to avoid excessive caramelization of the final baked dough, which is traditionally fairly pale in its final form.

After baking the shortbreads, they were cut and "labeled" for identification by using a method called dimpling, see supplementary material Fig. S1. While the shortbreads are hot after baking, dimples are poked into each shortbread . This allows for easy identification while preserving a traditional technique used for decorating.

Individual packages containing all four types of shortbread with dimples ranging from 1 to 4 were prepared and labelled. The label showed the compiled ingredient list and a QR code lead the participant

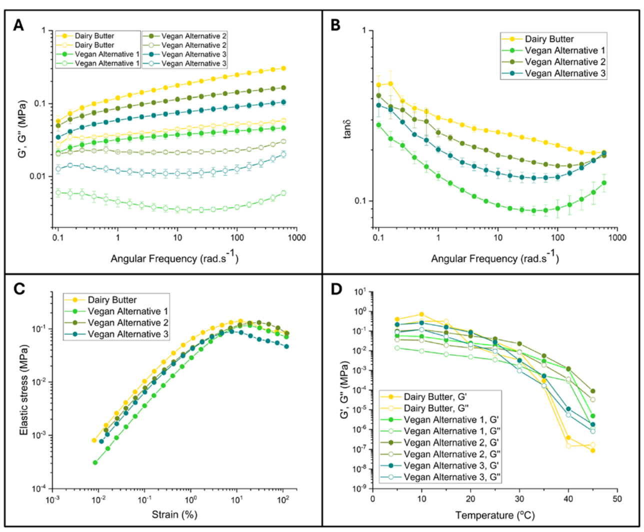

FIG. 2. (a) G' (storage modulus) and G'' (elastic modulus) as a function of the angular frequency of all four types of fat, (b) tan δ dependency on angular frequency, (c) elastic stress as a function of strain (%), and (d) temperature sweep of all four types of fat ranging from 5 to 45 °C.

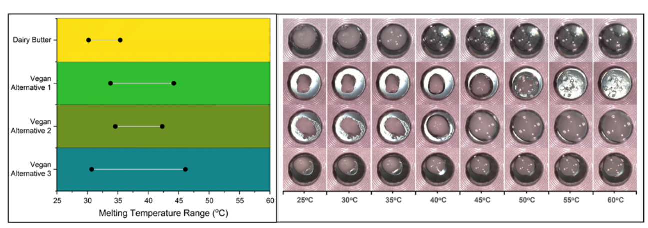

FIG. 3. Melting temperature range for dairy butter and three plant-based alternatives when heated at 6 °C/min. The graph shows the beginning of phase separation as the initial melting point and ends when the fat globules start to be transparent.

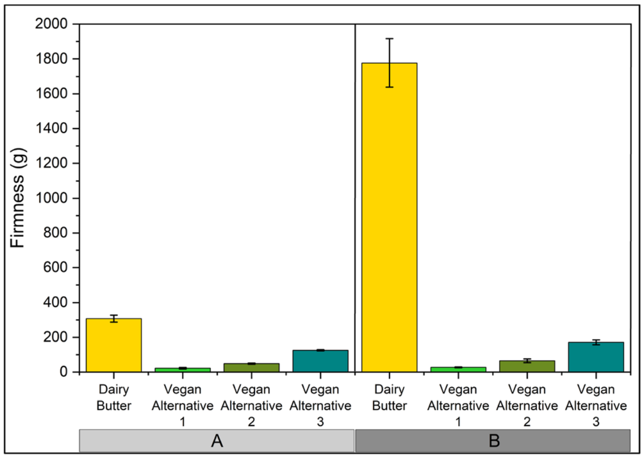

FIG. 4. The firmness of the dough was measured using a 20-mm-diameter cylindrical probe, which upon contact with the dough reduced the dough's height by 20% and measured the peak resistance. Values are shown as mean ± SD. Section A shows peak resistance at RT and section B at 4 °C.

to the survey questionnaire (Fig. S2). Dimpling was an important identification measure that allowed participants to rate the shortbread and fill in the corresponding section in the survey while being blind to the type of fat used. This minimized personal preferences to skew their ratings.

VA1 has the highest water content, which increases sugar solubility and flour hydration compared to the higher fat alternatives. This clearly resulted in a less crumbly structure and a chewy texture in the center (Fig. 5) of the baked product. Figure 5(a) indicates that the dairy butter-based dough achieved the highest score, closely followed by VA3 and VA2, despite the fact that >55% indicated buttery flavor as a preferred aspect of shortbread [Fig. 5(c)]. VA1 scored lower for flavor, with several participants strongly disliking the taste. However, there were also comments indicating that some participants had a preference for VA1. The ratings for texture [Fig. 5(d)] are very similar, with the traditional dairy butter version receiving the highest rating, closely followed by VA3 and VA2. The visibly different structure of VA1 [Fig. 5(b)] did not appeal to most of the participants in our survey.

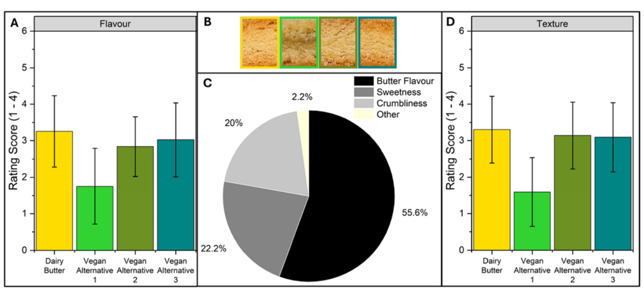

FIG. 5. Results from the sensory perceptions survey of 45 participants. (a) Mean values (±SD) flavor ratings (1–4) (b) Visual appearance of the shortbread. (c) The pie chart indicates the participants' preferred aspect of the shortbread. (d) Mean values (±SD) of texture ratings (1–4) of the baked shortbread types made using different fats.

III. CONCLUSION

We obtained traditional and plant-based versions of shortbread, maintaining the same mass proportions of flour, overall added fat product, and sugar in dough preparation. Even though the fat properties, such as macronutrient composition, melting range (Fig. 4), G' and G'' from rheological measurements (Fig. 2), and raw dough firmness (Fig. 3), differed quite significantly, we were able to produce dough and bake it into shortbread from all of them.

We could not observe a direct translation of the rheological properties of the added fats into structural elements of the dough, although a pattern has formed in the order of dairy butter, VA2/3, and VA1 in terms of firmness of the pure fat and their respective doughs. The properties of this complex mixture depend on a variety of interactions, including chemical transitions, which are able to modify the purely rheological influences. Additionally, we observed that the specific scientific properties of individual components of the doughs do not always hint at sensorial properties of flavor and texture. While we could not directly measure the structural properties of the baked shortbread, the survey results indicated that most participants did not enjoy the higher water content of the VA1 variant, leading to a more sticky or ductile structure. The higher fat content of dairy butter and the vegan VA2 and VA3 alternatives showed comparable ratings of both tested featured when compared to dairy-based butter. Therefore, investigating both texture and taste preferences, we could clearly see that plant-based alternatives can yield high-quality baked goods with a direct swap of dairy butter-based recipes for plant-based alternatives of similar fat content to that of dairy butter. This is a very promising result for increasing the availability of vegan food options while reducing the climate impact of food production.[17] The food chain is responsible for a significant proportion of all greenhouse gas emissions,[18,19] and by replacing the average diet with one without animal products, without requiring significant perceptual sacrifices, we will be able to achieve greater acceptance of plant-based products for a global impact.[19,20] It is, therefore, important to innovate and provide plant-based options not only for traditional recipes, such as Scottish shortbread, but also for tackling a broader range of baked goods. This will not only have a positive influence on the climate but also make more inclusive choices easy for caterers and public institutions.

IV. MATERIALS AND METHODS

This study examined three commercially available plant-based alternatives of butter and regular dairy-based butter.

- Dairy butter
- Vegan alternative 1 (VA1)
- Vegan alternative 2 (VA2)
- Vegan alternative 3 (VA3)

Pictures and ingredient lists are available in the supplementary material.

A. Characterization of ingredients

Fat color analysis was determined using red-green-blue (RGB) analysis of the four types of fats used. Illuminated sample pucks of consistent thickness (0.65 mm) and diameter (8 mm) were used for this analysis. The pixel RGB values were extracted for the whole area of the sample puck in the image using ImageJ and a median value was calculated for each.

Fourier-transform infrared spectroscopy was used to determine the functional groups in the samples of fats. A scanning regime from 500 to 4000 cm^{-1}

Rheology measurements were performed using a DHR-2 Rheometer (TA Instruments) with a parallel plate geometry ($d = 40$ mm) with a roughened surface using matching diameter sandpaper of grit size 240, with a measurement gap width of 1.8 mm. Oscillatory measurement is more sensitive to capture differences in applied yield stress and viscosity.[14] After performing an amplitude sweep at a frequency of 1 rad s^{-1} and 20 °C, on all types of fat, the chosen oscillatory strain for all rheological analyses was 0.1% due to falling within the linear viscoelastic region for all types of fat tested. Each measurement was repeated three times on a separate sample of fat to ensure statistical robustness of the measured values. For the temperature sweeps from 5 to 45 °C, the temperature was increased in increments of 5 °C using the Peltier plate temperature control and a soak time of 5 min to propagate the changed temperature throughout the measured fat product disk.

B. Shortbread preparation and characterization

The formula for the traditional (butter-based) shortbread was inspired by the famous Walkers shortbread recipe. Per 100 g of dough, the ingredients were as follows: plain flour, 49 g; butter, 34 g; caster sugar, 16 g; and salt, 0.4 g. Initially, the fat was weighed with sugar and mixed into a paste, then the flour and salt were added and mixed again until a smooth homogeneous dough was formed. The dough was flattened to a thickness of 1 cm and baked at 160 °C for 45 min. While still hot and malleable, a sharp knife was used to cut the area into portion sizes (1 × 3 cm^2) and dimples were made into each piece to signify the type of fat used.

Those ingredients are commonly used in traditional recipes, as well as in commercial shortbreads. To enable sensorial testing with 45 participants, four shortbread types were prepared for each test with a total of 190 individual portions of shortbread prepared.

1. Firmness vs spreadability

Dough firmness: A texture analyzer, TA.XTplus100C (Stable Micro Systems), was used to measure the firmness of the dough before baking. A 1-cm high cylindrical piece of dough of 13 mm diameter was made of each of the four types of dough. A method was chosen to detect the initial contact of the cylindrical probe ($d = 20$ m) with the dough and then measure the applied force to reduce its height by 20%. The displayed value is a mean of ($n = 5$) individual pieces of dough.

Color evaluation: Color differences among the shortbread varieties were determined by performing an RGB analysis of an area of an image capturing the fats' (>16 720 px) and shortbread' cross sections (40 428 px) in Tables S2 and S3, respectively.

Sensorial testing: A blind survey of 45 participants was conducted to determine the flavor and texture of the four final baked shortbread types. Dimpling was used to distinguish between the different types, but which number of dimples corresponding to which fat used was kept hidden from the participant to minimize personal preferences skewing their ratings. The standard recipe in Sec. IV B was used for each type of shortbread with the same mass of fat substituted. At the beginning of the survey questionnaire, each participant chose what their preferred aspect of shortbread is. Then a score from 1 (lowest rating) to 4 (highest rating) was given by each participant to each of the four types of shortbread provided, each scoring their texture and flavor separately. Participants were left to choose in which order they tasted the samples provided in the sample bag (Fig. S2). These data were averaged per sample and characteristic and displayed with error bars showing the standard deviation. In Fig. S3, the raw data are displayed as collected by the survey.

SUPPLEMENTARY MATERIAL

See the supplementary material for the ingredient list for dairy butter and plant-based alternatives; color analysis of fats and shortbread; ethical information; and figures, including visual documentation, ratings from the survey, and additional rheology data.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Khalifa Mohamed: Data curation (equal); Investigation (equal); Writing – original draft (equal). **Peter Jenkins:** Investigation (equal). **Mónica S. N. Oliveira:** Data curation (equal); Formal analysis (equal); Writing – original draft (equal). **Juliane Simmchen:** Conceptualization (lead); Data curation (equal); Funding acquisition (lead); Methodology (lead); Project administration (lead); Writing – original draft (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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