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ABSTRACT

The BaGaTel database, guided by an ontology of dairy gels, has been developed to organise and integrate data on dairy products (process, composition, structure, nutritional, sensory and environmental quality), using a common vocabulary and metadata organisation. BaGaTel was queried to explore relationships between composition, rheological properties and sensory perception in 68 model cheeses from six different projects. Principal component analyses were performed on the total set of 68 samples and on sample subsets. Sensory hardness was well explained by the low moisture-in-non-fat-substances ratio. As expected, salty taste was correlated with salt content but, interestingly, in cheese with a low amount of salt, salty taste was less intense at low water content and was perceived better with increased chewing activity. In cheeses with a high amount of salt, salty test was less intense at high protein content. Salty taste was also influenced by lipid content and correlated with fat perception.

1. Introduction

The food processing sector is facing sustainability challenges of growing complexity, such as global warming, increase of overweight, obesity or population aging. These problems make it necessary for the food industry to develop new strategies to formulate well-balanced products in terms of nutritional/environmental requirements and acceptability by consumers. However, changes in food composition highly influence the structure of food and, as a consequence, the sensory properties. A lot of literature has been devoted to the effect of food reformulation (salt/sugar/fat reduction, substitution of animal by plant proteins, use of more sustainable raw materials), on nutritional and sensory properties together with consumer acceptability. However, the results available in the literature are difficult to compare due to the large variety of formulations, the lack of harmonisation of methodologies used for the analyses and parameters considered.

Lawrence et al. (2012a) and Lawrence, Septier, Achilleos, Courcoux, and Salles (2012b) studied eighteen lipoprotein matrices (lipid-protein matrices) varying in dry matter and lipid contents and observed that sensory texture descriptors were correlated with rheological parameters and that saltiness perception was correlated with salt content, but that other factors were involved such as lipid composition or chewing behaviour. It is noteworthy that these effects were dependent on salt content. In the case of products with a low salt content, saltiness perception was higher at a high dry matter content and low lipid/dry matter ratio, but the effect was opposite at high salt content. In another project on eight model cheeses varying in lipid/dry matter, salt level and pH at renneting, Syarifuddin, Septier, Salles, and Thomas-Danguin (2016) observed that the three composition factors (salt, fat content and pH at renneting) influenced the sensory texture of model cheeses and that there were some interactions between these factors. Lipid content influenced the texture of the cheese, mainly the melting properties, but high fat cheeses were also perceived as less salty, which was explained by a barrier effect of fat towards the release of salt in the mouth, this effect being modulated by salt level and pH.

Boisard et al. (2014b) studied six model cheeses varying in lipid/protein ratio, at similar dry matter contents, and observed that saltiness perception was explained by sodium ion release in saliva and sodium ion mobility in the food matrix. This relationship between saltiness and sodium ion mobility was also observed in meat products (Foucat, Donnat, & Renou, 2003; Foucat, Donnat, Joffraud, Cardinal, & Renou, 2004). Moreover, for a given salt content, model cheeses with a higher lipid/protein ratio were perceived as saltier. The authors suggested that this result could be due to sensory fatty-salty interactions (Boisard et al., 2014b). Lauverjat, Déléris, Tréléa, Salles, and Souchon et al. (2009) studied model cheeses varying in lipid and dry matter contents and found that the diffusion of sodium ions was higher in cheeses with low dry matter and protein contents, which could be explained by a modification of cheese microstructure (Floury et al., 2009a; Floury, Rouaud, Le Poullennec, & Famelart, 2009b). However, these authors did not carry out sensory tests to assess the effect on saltiness perception. Phan et al. (2008), working on four model cheeses varying in lipid content and cheese texture, found that a low fat content and consequently a high water content contributed to a higher NaCl release at the beginning of chewing and thus to a higher perception of saltiness. Working on solid lipoproteic colloid foods, Kuo and Lee (2017) found that saltiness perception was dependent on texture perception and mainly on the perception of syneresis and explained this by a large amount of serum released during gel compression in the mouth, which could contribute to a large amount of sodium ions being available for the taste receptors and thus to an increased perception of saltiness.

All the information available on these individual projects is difficult to generalise to dairy foods with a wider range of composition, due to the limited number of samples studied and to the small variability in composition in one specific project. Nevertheless, it seems highly relevant to be able to gather all the information available in the literature relative to the impact of food formulation on physicochemical and sensory properties, to identify or explore principles for food formulation following nutritional/environmental requirements.

To tackle this challenge, a database, called BaGaTel, has been built, guided by a process and observation ontology in food science, PO² ontology (Ibanescu, Dibie, Dervaux, Guichard, & Raad, 2016) and hosted by the PLASTIC platform INRAE (https://www6.inrae.fr/pfl-cepia/). This database gathers data in the field of reformulation of dairy products taking into account their nutritional, sensory and environmental properties, using a consensual model and a shared structured vocabulary (available online at http://agroportal.lirmm.fr/ontologies/PO2_DG/?p=summary). Data from a total of 65 different projects have been imported in BaGaTel (list available at http://plasticnet.grignon.inra.fr/portailbagatel/); 693 samples, 450 methods, 297 materials and 1045 measured characteristics are included, up to November 2020. The data are either non-published but used with the permission of the authors or are extracted from the literature. The database is continuously enriched with data from new articles in the field. This database has already been successively used to (i) find correlations between one rheological parameter, the Young's modulus and one sensory descriptor, i.e., firmness in hard cheeses, (ii) estimate missing experimental data due to this correlation and (iii) estimate the environmental impact for specific foods, for which a process was described in BaGaTel (Pénicaud et al., 2019).

In the present paper, we aim to demonstrate that the BaGaTel database can be successfully used (i) to gather data obtained in different projects that used similar methodologies and (ii) to reach a critical number of samples from similar food products differing in composition, to better understand the relationships between physico-chemical data and sensory perception. The final objective would be to find general rules to reformulate dairy products with a low salt/fat content and acceptable for the consumers.

2. Material and methods

2.1. Data preparation

Specific queries were done to export data from the BaGaTel database. We searched for samples, which had data on composition, rheological properties and sensory profile analyses. In BaGaTel, 271 samples are characterised by rheological data, 365 samples by sensory data, while 228 samples by both sets of data. However, the composition and structure of the dairy products and the measured variables were often very different. We thus restricted our query to hard cheeses and related model cheeses. For such types of cheeses, the materials and methods used for rheological analyses were comparable (data available in BaGaTel) and the bulk of sensory description can be considered as quite similar.

We finally selected 68 cheese samples (hard-type model cheeses) from six different projects. These samples had been characterised for their composition (lipid, protein, water, sodium ions), sensory properties (salty, fatty, springy, hard/firm, crumbly, sticky, melting, granular, dry), rheological properties (Young modulus, fracture stress, fracture strain, work at fracture) and chewing activity parameters (total muscular work, number of chewing cycles, chewing duration). The whole data set (2021-01-22_cheese-compo-rheo-senso_Guichard-V3.tab, sheet whole-dataset) is available on-line (Guichard et al., 2020). The description of the samples, data, associated metadata, experimental, material and analysis methods, together with the scatter-plots of the values in the different projects (Figs. S1–S5), are available in a co-submitted data paper (Guichard et al., 2021). The information concerning the different projects (title, abstract, coordinator, scientists involved, DOI of publications) are available on line in the database website (http://plasticnet.grignon.inra.fr/portailbagatel/). For each project, the number of samples, the lipid, protein, water, salt contents and the pH are listed in Table 1, along with the literature references.

To standardise the data on composition, we first aligned all content to the same unit (g kg^{-1} product) and calculated for each sample the amount of sodium ions (Na^+), considering both the amount of NaCl added and the sodium ions from the melting salts. However, even if it is well known that saltiness perception is due to the activation of taste ion channels by sodium ions (Lewandowski, Sukumaran, Margolskee, & Bachmanov, 2016), it is modulated by the associated anion (Vanderklaauw & Smith, 1995), with sodium salts containing small anions being perceived as saltier than those with large anions. Even if the sodium ions present in the melting salts (emulsifying agents) have less impact on saltiness perception than those from added NaCl, we decided to take it into account.

The final list of composition variables is the following: water, protein, lipid, Na^+. We also added three variables. Lipid/DM is the ratio of lipids per dry matter and represents the impact of lipids in the lipid/protein network and food texture. Na^+/water is the amount of sodium ions in the water phase and should better represent the concentration in sodium ions available for the taste receptors. The ratio moisture-in-non-fat-substances (MNFS) is a useful variable in cheese manufacturing and is used in the classification of cheeses (Codex Standard 283-1978, FAO). It gives an estimation of the water/ protein ratio and influences a wide range of textural characteristics (Lucey, Johnson, & Horne, 2003). The values for these variables in the different samples were calculated and uploaded in the database. To include a greater number of samples and variables, we performed multiple linear regressions to estimate missing data (See 2.2.1).

2.2. *Multivariate statistical analysis*

2.2.1. *Multiple linear regression*

The data extracted from BaGaTel had missing values for several parameters. MLR (XLStat, Addinsoft, Paris, France) was applied to estimate missing values. In addition to Young's modulus (YM) and fracture stress (FS), other rheological parameters such as fracture strain (CS) and work to fracture (WF) were available for several samples. Thus, we estimated the missing values for CS and WF, separately, using multiple linear regression (MLR) with the following variables: Na^+, lipid, protein, water, lipid/DM, YM, FS. Considering sensory profiles, the descriptor hard/firm was estimated with MLR based on the following variables: Na^+, lipid, protein, water, lipid/DM, YM, FS, but crumbliness and stickiness were estimated separately with the same variables, excluding lipid because of strong multicolinearity. The dataset with the estimated data (2021-01-22_cheese-compo-rheo-senso_Guichard-V3.tab, sheet: dataset+estimated-data) and the parameters of the MLR used for the estimation (2021-01-22_cheese-compo-rheo-senso_Guichard-V3.tab, sheet: missing-data-estimation) are available on-line (Guichard et al., 2021). Another alternative would be to use the missMDA (R package), which performs PCA on incomplete data sets (Josse & Husson, 2016). We performed PCA with the two methods and calculated the RV coefficient, which is of 0.992, confirming that, in our case, with only few missing data, the mode of estimation has very little impact on the PCA results. We thus used the data estimated using MLR.

2.2.2. *Principal component analysis*

Principal component analyses (PCAs) were performed on different subsets of data to highlight the relationships between food composition, food rheology and sensory perception. PCAs were performed with XLStat (Addinsoft, Paris, France).

On the total dataset of 68 samples, a PCA was done on the 7 variables of composition, two sensory descriptors (salty and hard/firm) and two rheological parameters (YM and FS). We also performed PCA on two subsets, one subset of 32 samples (Adi, Lawrence, PraSel and Tarrega projects) with a sodium ion content below 5 g kg^{-1}, and a second subset of 36 samples (Adi, Boisard, Lawrence, Phan and Tarrega projects) with a sodium ion content higher than 5 g kg^{-1}. As for some projects, measurements on chewing behaviour were obtained (Total muscular work, Number of chewing cycles, Chewing duration), we also performed two additional PCAs, using only the samples with data on chewing behaviour, to assess (i) the impact of chewing behaviour on sensory perception and assess (ii) the hypothesis formulated by Lawrence et al. (2012b) that the relationship between chewing behaviour and saltiness was dependent on salt content. For the low sodium content, the PCA was done on thirteen samples from two projects (Lawrence and Tarrega projects) and, for the high sodium ion content, the PCA was done on fifteen samples from three projects (Boisard, Lawrence and Phan projects).

Finally, a PCA was performed on the 22 samples with all the sensory descriptors (salty, hard/firm, fatty, springy, crumbly and sticky), in the aim to better understand the relationships between fat perception and saltiness of model hard cheeses.

For each PCA, values of Pearson correlations between variables were calculated with a significance level of 95%. The matrices of correlation are available as supplementary tables in the co-submitted data-paper (Guichard et al., 2021).

3. Results

3.1. Explaining cheese hardness and salty taste by composition and rheological data

3.1.1. Data set of 68 samples and 11 variables

A PCA was done on the set of 68 samples containing data for the two sensory descriptors hard/firm and salty (estimated data for hard/firm in Phan project), available on-line (2021-01-22_cheese-compo-rheo-senso_Guichard-V3.tab, sheet: dataset_PCA-68samples). The map of the samples (Fig. 1A,B) shows that there is a good overlap of the samples from the different projects. Figure 1C,D represents the map of the variables on the three main dimensions, which account for 81.26 % of total information. On axis 1, water content (negative part of axis 1) is opposed to sodium ion and lipid contents (positive part of axis 1). On axis 2, protein content (positive part of axis 2) is opposed to lipid/DM content (negative part of axis 2). The sensory descriptor hard/firm is located on the positive part of axis 2 close to the protein content and opposed to moisture-in-non-fat-substances (Fig. 1C). Looking at the correlation matrix (Table S1), hard/firm was negatively correlated with level of moisture-in-non-fat-substances (–0.723) and positively correlated with protein (0.542) and with the Young's modulus (0.629). The salty taste is located on the positive part of axis 3 (Fig. 1B) but also on the positive part of axis 1 and positively correlated with the sodium ion content (0.672) and Na^+/water (0.626). A high correlation (0.972) was observed between Na+ and Na^+/water; this suggests that, in such food matrices, most of the sodium ions are free and solubilised in the water phase. However, a lower correlation (0.861) was observed between lipid and lipid/DM. In fact, lipid/DM was negatively correlated with the protein content (-0.804) while MNFS was highly negatively correlated (–0.723) with sensory hardness (graphic representation in Guichard et al., 2021: Fig. S6).

Because of the large differences in sodium ion content in our dataset and since several authors found different conclusions as a function of salt content, the initial set of samples was divided into two subsets according to the sodium ion content (below or above 5 g kg^{-1} sodium ion). Two other PCA analyses were performed on these subsets of samples.

3.1.1.1. Subset of samples with a low sodium ions content

The PCA on samples with a low sodium ion content is plotted on Fig. 2A (32 samples from projects Adi, Lawrence, PraSel and Tarrega, matrix of Pearson correlations in Guichard et al., 2021: Table S2); the two main components accounted for 70.06% of the information. Cheese sensory hardness (hard/firm) is located on the positive part of axis 2 (31.16% of the information), together with protein content, justified by a positive correlation between hard/firm and protein (0.717) and a negative correlation with MNFS (-0.641). Salty taste is located on the positive part of axis 1 (38.90% of the information), together with sodium ion content and was positively correlated with Na^+ (0.692) and Na^+/water (0.693). Water content is located on the negative part of axis 1 and was negatively correlated with salty taste (–0.398). A positive correlation was also observed between salty taste and fracture stress (0.493).

3.1.1.2. Subset of samples with a high sodium ions content

The PCA on samples with a high sodium ions content is plotted on Fig. 2B (36 samples from projects Adi, Boisard, Lawrence, Phan and PraSel, matrix of Pearson correlations in Guichard et al., 2021: Table S3); the two main components account for 65.53% of the information. On axis 1, which accounts for 41.74% of the information, the water content is located opposite to the sodium and lipid content. Protein content is located on the positive part of axis 2 (23.79% of the information), opposed to the lipid/DM ratio. Salty taste is located on the positive part of axis 2 and positively correlated with protein content (0.316); however, it is not well represented on this PCA plot. It has to be noticed that salty taste has a lower positive correlation with the amount of sodium ions compared with the analysis including samples with a low sodium content (0.417 versus 0.692). The sensory descriptor hard/firm is located opposite to MNFS on this plane, due to a high negative correlation (-0.774).

3.1.2. Data set of 28 samples with data on chewing behaviour

Data on chewing behaviour are available in four projects (Boisard, Lawrence, Phan and Tarrega projects). A subset of these samples with the data on chewing activity was selected (2021-01-22_cheese-compo-rheo-senso_Guichard-V3.tab, sheet: dataset_chewing-activity). Because it was previously observed that the relationships between saltiness and chewing behaviour were highly dependent on salt content (Lawrence et al., 2012b), PCAs were performed on two subsets of samples according to their sodium ion contents. The aim of this analysis was to increase the number of samples compared with the Lawrence project (Lawrence et al., 2012b). The added samples had a different composition and especially a lower amount of water and a harder texture, so that they required a more intense chewing activity.

A first PCA was performed on a subset of 13 samples with a low sodium ion content (projects Lawrence and Tarrega). The results (Fig. 3A; Guichard et al., 2021: Table S4) showed that salty taste is located on the positive part of axis 1, together with the sodium ion content and, to a lesser extent, the lipid content and the total muscular work (TMW). This result confirms that, at a low sodium content, increasing chewing activity increased the amount of sodium released in saliva and enhanced salty taste.

On the PCA on the 15 samples with a high sodium ion content (Boisard, Lawrence and Phan projects, Fig. 3B; Guichard et al., 2021: Table S5), salty taste is located on the positive part of axis 2, together with hard/firm sensory perception, and opposite to total muscular work (TMW) and fracture stress (FS). This observation suggests that the amount of sodium ions was high enough in the cheese, to easily access the taste cells and induce a salty taste without a strong chewing activity.

In both PCA analyses, the number of chewing cycles (NCC) is located on the negative part of axis 1, opposite to the lipid content and was negatively correlated with lipid content (–0.785 at low sodium content and –0.790 at high sodium ions content) and lipid/DM (–0.662 at low sodium ion content and –0.704 at high sodium ion content).

3.2. Explaining perception of saltiness and fat

The individual studies showed different relationships between lipid composition and salty taste. To better understand the influence of lipid content and fat perception on salty taste, a complementary analysis was carried out on a limited number of projects and samples, for which the intensity of fat perception (fatty descriptor) was available.

A subset of 22 samples from three projects (Adi, Boisard, Tarrega projects), in which fatty and springy descriptors were assessed, was extracted. We included in this subset other sensory descriptors (crumbly and sticky) and estimations of these descriptors in the case of the Adi project. Thus, this subset contains a total of six sensory descriptors (2021-01-22_cheese-compo-rheo-senso_Guichard-V3.tab, sheet: dataset_22samples-fatty).

Fig. 4A,B shows the position of the variables on the three main dimensions of the PCA, which account for 79.05% of total information (31.91% for dimension 1, 29.76% for dimension 2 and 17.38% for dimension 3). On axis 1, samples are separated according to their lipid and sodium ion content on its positive part and protein and water content on its negative part. On axis 2, samples are separated according to their Young's modulus and fracture stress on its positive part and MNFS on its negative part. On axis 3, samples are separated according to their water content on its positive part. The sensory descriptor hard/firm, located on the negative part of axis 1 and positive part of axis 2, was positively correlated (Guichard et al., 2021: Table S6) with the protein content (0.620), the Young's modulus (0.503) and fracture stress (0.402) and negatively with MNFS (–0.606).

The descriptor fatty is located on the positive part of axis 1, and was positively correlated with the lipid content (0.578). The descriptor crumbly is located on the positive part of axis 2, and was positively correlated with the rheological parameter Young's modulus (0.698). The descriptor springy is located on the positive part of axis 2 and was positively correlated with the Young's modulus (0.465) and the fracture stress (0.464). The descriptor sticky is located on the positive part of axis 1 and was positively correlated with lipid/DM (0.479) and negatively correlated with protein (–0.740). The descriptor salty is not well represented on the first plane but is located on the positive part of axis 3. The correlations between salty and the variables of composition are lower than 0.4, even with Na^+ (0.358). Concerning the relationships between sensory descriptors, negative correlations were found between hard/firm and both sticky (–0.702) and fatty (–0.651). Interestingly, the descriptor salty was positively correlated with the sensory descriptor fatty (0.613).

4. Discussion

The principal component analyses, conducted on different sets of samples extracted from BaGaTel database, confirmed previous hypotheses on the effect of the composition and structure of model cheeses on their sensory perception. In this sense, the present paper was able to generalise observations made on a small number of samples, but also highlighted new relationships.

4.1. Impact of cheese composition on texture

The sensory descriptor most explained by cheese matrix composition and structure was hardness (hard/firm). As expected, cheese hardness was explained by a high protein content and low water content. Hence the highest correlation was observed with the moisture-in-non-fat-substances (MNFS), representative of the ratio water/ protein network, meaning that the lipid content has only a low impact on sensory hardness of these products. The strong correlation observed between cheese sensory hardness and/or firmness and rheological parameters (Young's modulus and fracture stress) was previously observed (Brown, Foegeding, Daubert, Drake, & Gumpertz, 2003, Foegeding, Brown, Drake, & Daubert, 2003). The added value of our analyses is to confirm that this relationship is also observed when merging data from different projects and obtained in different experimental conditions, thus highlighting the strength of this relationship. Another important result is that MNFS is a very relevant parameter to predict sensory hardness.

In the analyses of the different datasets, the sodium ion content was positively correlated with the Young's modulus and the fracture stress. This supports the knowledge that sodium ions strongly participate in the protein network. In cheese, salt addition improves casein hydration due to a strong binding of sodium ions (Floury et al., 2009a,b), which can influence cheese texture differently according to the type of cheese and its composition in other cations, such as calcium ions. The effect of salt content on cheese texture varies according to the manufacturing process. In rennet-induced lipoprotein gelled matrices, an increase in salt content and pH induced a decrease in hardness and firmness, which was explained by an effect of the substitution of divalent calcium ions by monovalent sodium ions in the casein network (Lawrence et al., 2012a).

In other model cheeses differing in lipid/protein ratio, samples with added salt were perceived as being less fragmented, hard, elastic and compact (Boisard et al., 2014a), which could be explained by a reduction of coagulation efficiency at high salt content (Saint-Eve, Lauverjat, Magnan, Deleris, & Souchon, 2009). However, in real cheeses such as Cheddar, Camembert, feta, gaziantep, mozzarella and Munster cheeses, an increase in salt-to-moisture ratio induced an increase in hardness for S/M values in the range of 0.4 to 12% (w/w) (Guinee, 2004). The cheeses with a high salt-to-moisture content had also a low moisture content (Chevanan, Muthukumarappan, Upreti, & Metzger, 2006). Similar observations were reported for Cheddar cheeses produced with different salt contents, where a reduction in salt levels resulted in increased proteolysis, together with moisture, fat-in-DM and moisture-in-non-fat substances, and as a consequence decreased hardness (Murtaza et al., 2014). Different effects were observed in different types of mozzarella pasta filata cheeses. In high moisture mozzarella cheeses, an increase in sodium content increased the protein water-holding capacity so that the dry matter content is reduced, leading to decreased hardness (Bahler, Kunz, & Hinrichs, 2016). In contrast, in another type of mozzarella cheese, a lower addition of salt in the curd decreased hardness, of both full-fat and reduced-fat cheeses (Henneberry, Wilkinson, Kilcawley, Kelly, & Guinee, 2015), this effect being modulated by the calcium content. There is a lack of information on the exact mineral composition of these cheese samples, which makes it difficult to elucidate the combined effect of minerals such as calcium and sodium on cheese structure and hardness.

The different effects observed in the literature on the sodium ion content and the cheese sensory support our conclusion that sodium ion content is not directly correlated with sensory hardness and that MNFS is the main parameter responsible for sensory hardness, with a high negative correlation (–0.723). The descriptor hard/firm was neither correlated with the lipid content 0.028) nor with the lipid/dry matter content (–0.231). In real cheeses, it was observed that Cheddar cheeses with a high-fat content were perceived as less springy and firm than low-fat cheeses, which was explained by a modification of the protein network and of the fat-protein interface; full-fat cheeses presented weak points in the protein network, thus inducing more breaking down at fracture and during chewing and consequently a decrease in the sensory firmness (Rogers et al., 2009). In our analysis on three projects, in which other sensory descriptors than hardness were measured, lipid/DM was negatively correlated with the descriptors hard/firm (–0.607) and crumbly (–0.448) and positively with sticky (0.479). Our hypothesis was that a high lipid content may increase the perception of other sensory descriptors such as stickiness and thus decrease the perception of hardness. The negative effect of lipid/DM ratio on crumbliness means that cheeses with a reduced fat content tend to break more easily. It has to be noted that not only the lipid content but also the geometry of the fat globules and the nature of the interface may modify the cheese structure (Yang, Rogers, Berry, & Foegeding, 2011) and thus the texture, but such data were not available in the projects considered.

4.2. Impact of cheese composition and rheological properties on salty taste

The PCA performed on two subsets of samples selected according to the sodium ion content showed that the impact of lipid, protein and water on salty taste depended on salt level. At a low sodium content, salty taste perception was lower in cheeses with a high water content, which confirms previous observations (Lawrence et al., 2012a). This can be explained by a dilution effect of sodium ions in water and saliva. In cheeses with a low water content, at a low level of sodium ions, the ions are more concentrated in the water phase allowing a higher transfer into saliva to reach the ionic channels, and thus to give a more intense signal for perception. Salty taste was also positively correlated with fracture stress, which means that a more resistant cheese will favour the release of sodium ions in saliva and thus salty taste perception.

A preliminary study on nine cheddar cheeses varying in composition and texture (Jack, Piggott, & Paterson, 1995) previously suggested that hard cheeses required more chewing which induced a higher rate of sodium release and thus a higher salty taste. This matrix effect was also noticed with camembert cheeses (Engel, Nicklaus, Septier, Salles, & Le Quere, 2001), in which saltiness was perceived with a higher intensity in cheeses with a brittle texture and a greater ability to release water and thus water-soluble molecules such as sodium ions. This effect of the chewing process on salty taste was validated by the present study. Indeed, the PCA on 13 samples for which data on chewing behaviour were available showed that, at a low sodium content, an intense chewing activity increased salty taste. This finding suggests that this intense chewing activity increases the amount of sodium released in saliva and eases their access to the taste cells to produce an intense salty taste. This mechanism was already suggested in a previous publication on the data obtained with five lipoprotein matrices (Lawrence et al., 2012b). The present analysis included samples from other projects, which needed a higher chewing activity (Guichard et al., 2021: Fig. S4) and thus strongly reinforces the hypothesis.

At high sodium content, the intensity of salty taste was less correlated with the amount of sodium in cheese, which can be explained by the fact that the level of available sodium ions is sufficient to induce a salty taste and that the texture/structure of the food matrix thus plays a minor role. In contrast to what was observed in low-salt samples, salty taste was less perceived in the hardest products, as already shown by Lawrence et al. (2012b). In the present study, the positive effect of lipid content on salty taste previously observed by Lawrence et al. (2012b) at high salt content, was not confirmed, which suggests that this specific effect cannot be generalised to a wider range of cheese matrices.

4.3. Relationships between composition, rheological properties and sensory perception

The PCA carried out on the set of data that included all the sensory descriptors allowed general trends to be identified that could explain cheese sensory perception as a function of cheese composition and rheological properties, and to clarify the relationships between salty and fatty perception. The cheeses with a high protein and low lipid content were perceived as harder and less fatty and sticky (Rogers et al., 2009).

In terms of the correlations between variables (Guichard et al., 2021: Table S6), the descriptor fatty does not show a high correlation with the lipid content (0.578). This could be partly explained by the fact that fatty perception is a multimodal perception involving olfactory, gustatory and tactile perception (Guichard, Galindo-Cuspinera, & Feron, 2018). Many volatile compounds are described with fatty odour descriptors, such as butter, creamy, and thus contribute to fat perception. Indeed, the addition of butter aroma in model cheeses was found to increase global fat perception (Syarifuddin et al., 2016). The gustatory dimension of fat perception is due to the presence of free fatty acids (Chale-Rush, Burgess, & Mattes, 2007). Concerning the tactile modality, it has been clearly demonstrated that the presence of lipids in foods is associated with textural descriptors such as meltability, spreadability and greasy film (Di Monaco, Giancone, Cavella, & Masi, 2008). Thus, not only the lipid content but also its composition in odorant compounds and its impact on the texture are likely to drive global fat perception. In our study, the sensory descriptor fatty is less correlated with the ratio lipid/dry matter (0.367) than with the lipid content (0.578), whereas the descriptor sticky is more correlated with the ratio lipid/dry matter (0.479) than with the lipid content (0.279). This observation suggests that fatty perception is much more related to the lipid content per se than to the lipid-protein network. However, stickiness, which is a texture attribute, is more influenced by the lipid-protein network, as suggested before in the literature.

Several factors have been found to contribute to stickiness. In different hard cheeses produced with two levels of fat, a lower fat content contributed to a lower stickiness (Ritvanen et al., 2005). In model processed cheese analogues, cheeses with high moisture content were found stickier than cheeses with lower moisture levels (Pereira, Bennett, McMath, & Luckman, 2002), which was explained by the weakening of the protein structure induced by water, acting as lubricant for the movement of casein in relation to fat. Such a negative correlation was also observed, using texture profile analysis, between hardness and stickiness in nonfat processed cheeses (Brickley et al., 2008). The addition of an emulsifying salt which solubilises the colloidal calcium phosphate and hydrates caseins induced a decrease in rheological hardness and an increase in stickiness; however, no sensory analyses were done on these cheeses (Brickley et al., 2008).

4.4. Relationships between salty and fatty perception

It was observed that salty and fatty sensory descriptors are positively correlated (0.613; Guichard et al., 2021: Table S6, Fig. S7) and that fatty perception was correlated with the lipid content (0.578) but not salty (0.232). Salty taste was also not well explained by salt content (0358). Conversely, even if fatty perception was clearly explained by lipid content, it was only poorly related to sodium ions content (0.14). In the literature, contradictory results were reported with regard to the impact of lipid content on salty taste. A very small positive correlation was observed between lipid content and salty taste (0.232). Our results cannot confirm a previous hypothesis that an increase in lipid content in dairy products increased the salt content in the water phase and thus the perception of salty taste (Metcalf & Vickers, 2002). The opposite effect has also been reported (Lynch, Liu, Mela, & Macfie, 1993; Rietberg, Rousseau, & Duizer, 2012; Suzuki, Zhong, Lee, & Martini, 2014) and explained by a lipid layer coating the tongue and limiting the access of sodium ions to the taste cells. However, this coating effect of lipids limiting saltiness perception was never clearly demonstrated.

An alternative hypothesis suggested direct interactions at the peripheral level between fatty acids and channel taste buds (Gilbertson, Liu, Kim, Burks, & Hansen, 2005), but again without clear demonstration. A more plausible explanation would be to consider perceptual interactions between salty and fatty perceptions at the central level. The correlation between salty taste and fatty perception was higher (0.613) than that between salty taste and lipid content (0.232), thus advocating for perceptual interactions between these two perceptions. This hypothesis is supported by previous reports showing that a fat-associated butter aroma can enhance not only fat perception but also salty taste perception in model dairy products (Syarifuddin et al., 2016). Moreover, as plotted on Guichard et al. (2021) Fig. S7, the impact of fat perception on salty taste is more pronounced for the highest values of fatty descriptor. As fat is a multimodal perception, dedicated experiments should be performed to specifically test the impact of the different sensory modalities of fat perception on salty taste.

5. Conclusions

The multivariate simultaneous analyses of the results of six different projects covering a wider range of compositions and structures of cheeses led us to confirm several hypotheses raised in individual projects. The sensory hardness was negatively correlated with the moisture-in-non-fat-substances, whatever the lipid content. The protein and lipid content highly influenced sensory texture of cheese such as firmness, crumbliness and stickiness, salt content impacted firmness, and a high chewing activity was required to increase salty taste in low-salt cheeses. Moreover, this integrative approach allowed clarifying the perception of salty and fatty taste in cheese, highlighting the contrasted influence of cheese composition on salty taste depending on the salt level. The results also reinforced the hypotheses concerning fatty/salty sensory interactions in the context of cheese, based on results obtained from different projects and with different sensory panels. Therefore, the BaGaTel database appears of tremendous support not only to confirm previous hypotheses, but to propose new formulations for well-balanced products in terms of nutritional requirements and sensory acceptability by consumers. However, even though it was possible to estimate some missing data, our study highlights the need to gather data on a great number of relevant parameters, measured in similar conditions, in different projects.

Our database allows to gather data from different projects, using a common vocabulary and structuration with their associated metadata (e.g., materials, methods, experimental conditions). A follow-up of this analysis could be to propose some harmonisation of the methods used and suggest useful parameters to be measured in foods, to efficiently exploit data from different projects, in the objective of a FAIR data management. Another objective is to exploit the data obtained on different types of dairy products, varying in their technological process, including data on the environmental impact, to assess the combined effects of technological processes on nutritional/sensory quality and environmental impact of dairy foods.

Acknowledgements

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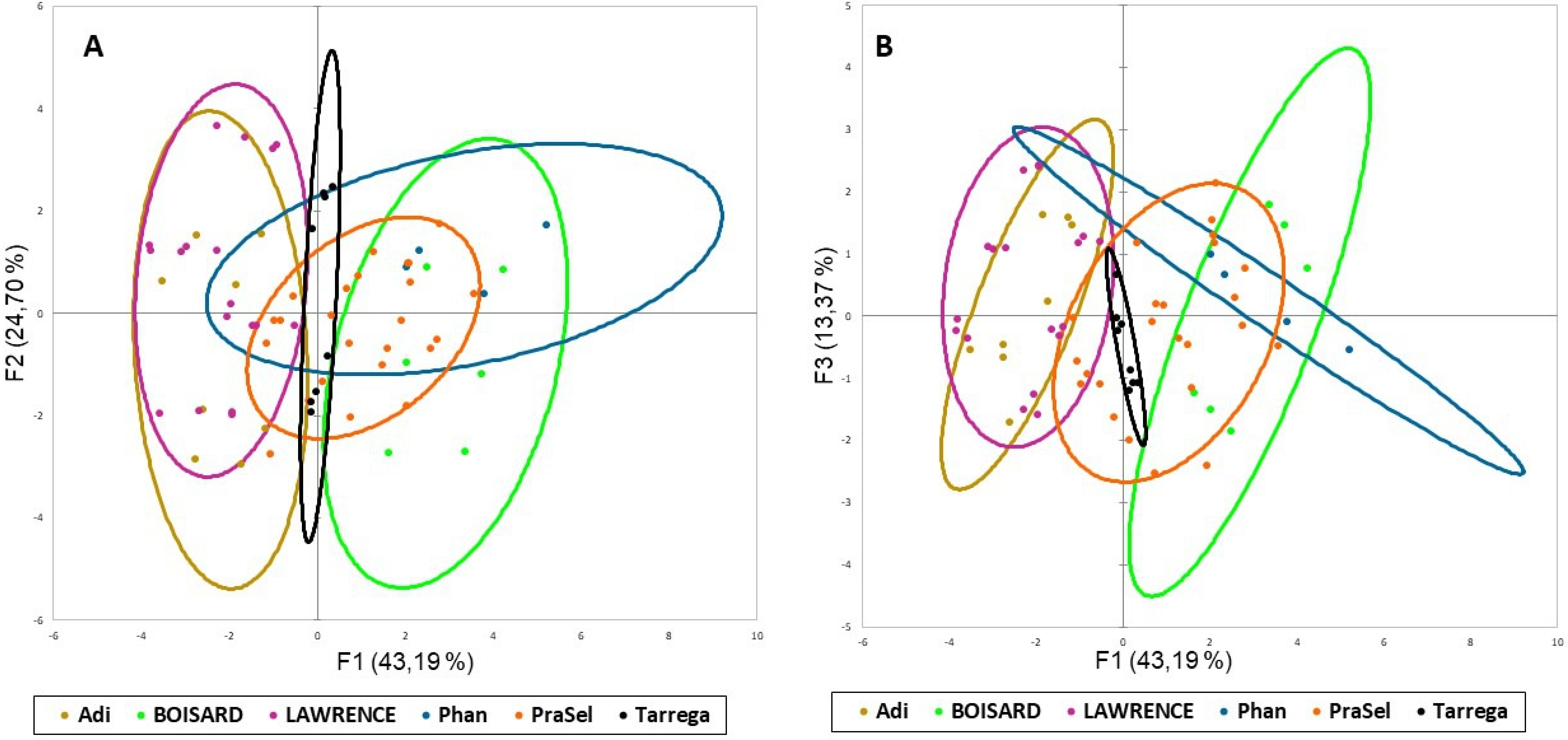
Figure legends

Fig. 1. PCA on 68 samples (projects Adi, Boisard, Lawrence, Phan, PraSel, Tarrega) and 11 variables (composition: water, protein, Na^+, Na^+/water, Lipid, Lipid/DM, MNFS), rheology (YM: Young modulus, FS: fracture stress), sensory descriptors (salty, hard/firm). Representation of the samples (A) in the plane corresponding to axes 1–2 and (B) in the plan corresponding to axes 1–3, with the 80% confidence ellipse for each project. Representation of the variables (C) in the plane corresponding to axes 1–2 and (D) in the plan corresponding to axes 1–3. Correlation matrix in Guichard et al. (2021): Table S1.

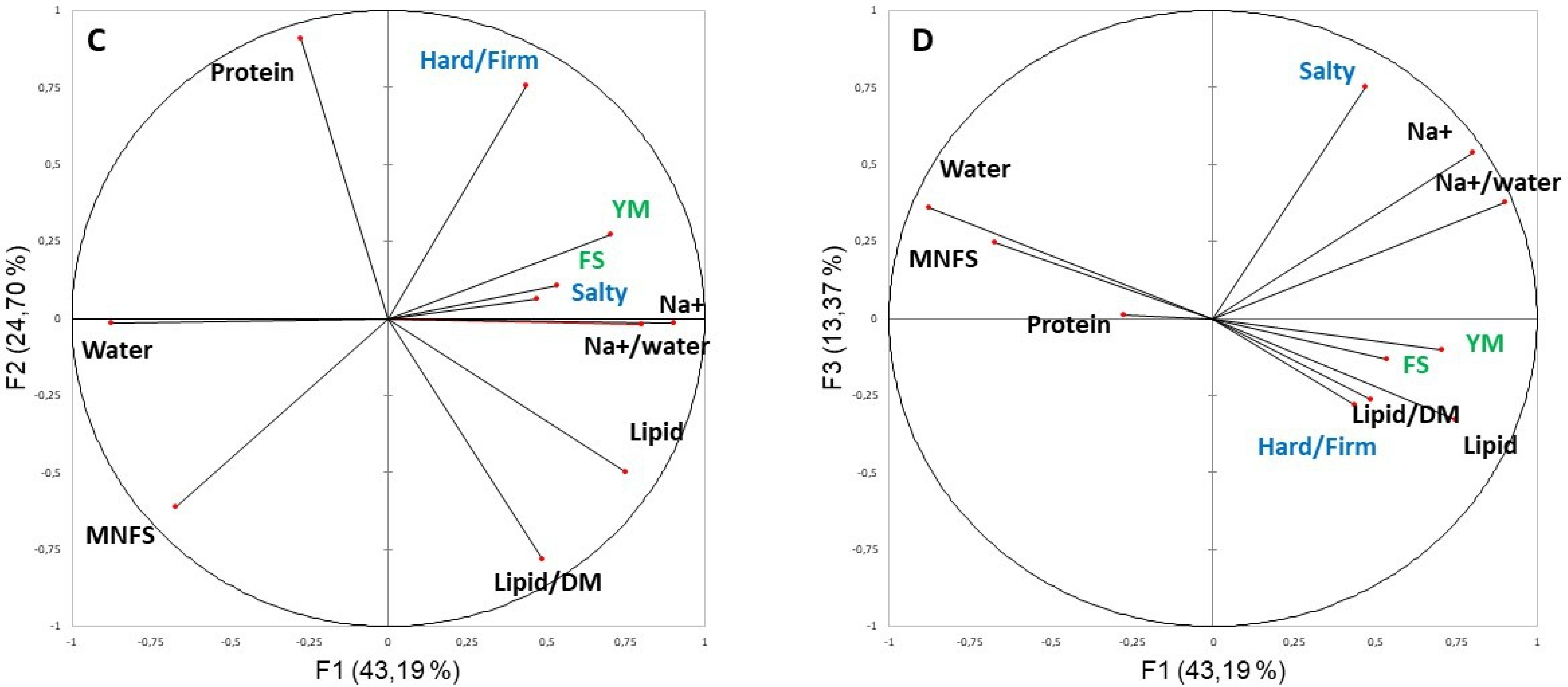
Fig. 2. Panel A: PCA on 32 samples with a low sodium ions content (projects Adi, Lawrence, PraSel, Tarrega) and 11 variables, 7 for the composition in black (Water, Protein, Na^+, Na^+/water, Lipid, Lipid/DM, MNFS), 2 rheological parameters in green (YM: Young modulus, FS: fracture stress), 2 sensory descriptors in blue (salty, hard/firm). Representation of the variables in the plane corresponding to axes 1–2 Correlation matrix in Guichard et al. (2021): Table S2. Panel B: PCA on 36 samples with a high sodium ions content (projects Adi, Boisard, Lawrence, Phan, PraSel) and 11 variables, 7 for the composition in black (Water, Protein, Na^+, Na^+/water, Lipid, Lipid/DM, MNFS), 2 rheological parameters in green (YM: Young modulus, FS: fracture stress), 2 sensory descriptors in blue (salty, hard/firm). Representation of the variables in the plane corresponding to axes 1–2 Correlation matrix in Guichard et al. (2021): Table S3.

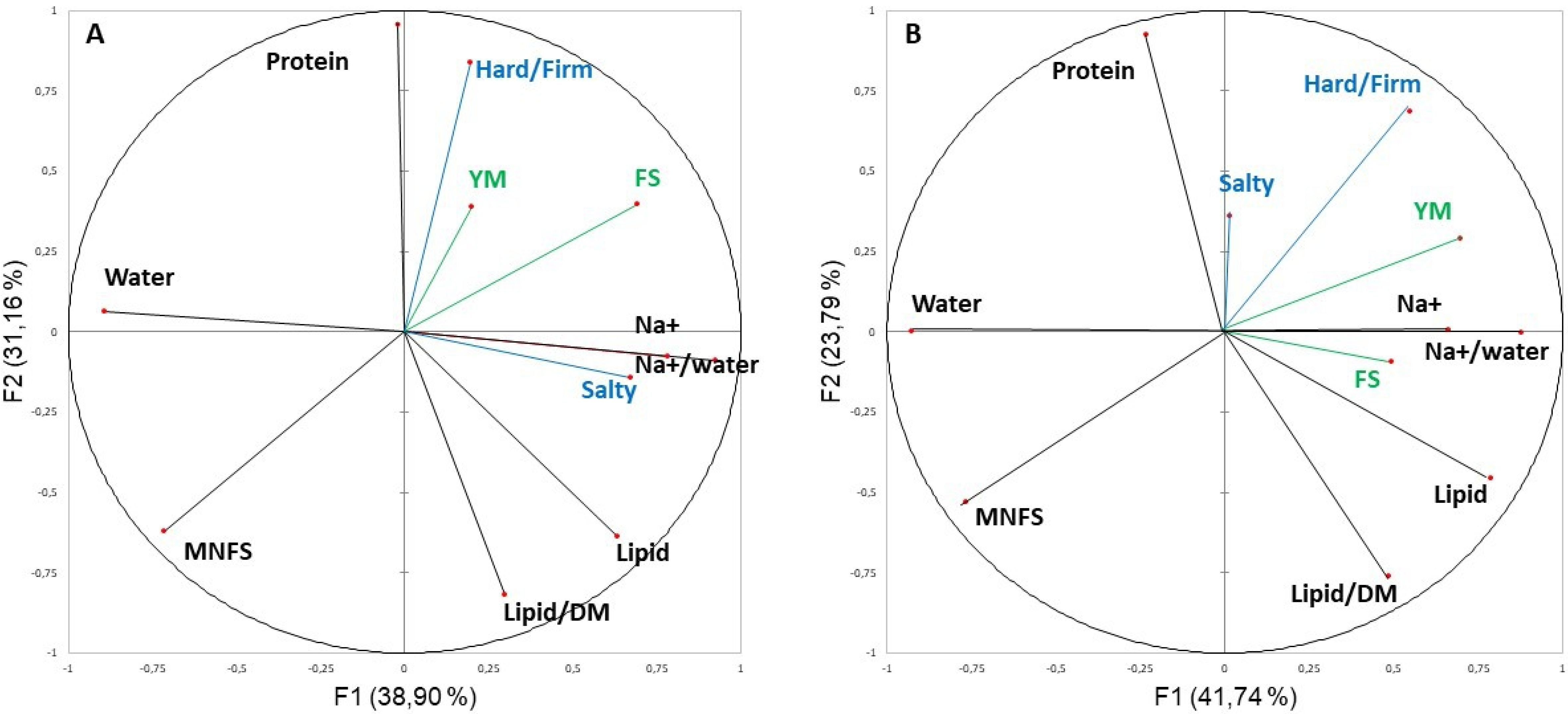
Fig. 3. Panel A: PCA on 13 samples with a low sodium ions content (projects Lawrence, Tarrega) and 14 variables, 7 for the composition in black (Water, Protein, Na^+, Na^+/water, Lipid, Lipid/DM, MNFS), 2 rheological parameters in green (YM: Young modulus, FS: fracture stress), 2 sensory descriptors in blue (salty, hard/firm) and 3 for the chewing activity (TMW: total muscular work, CD: chewing duration, NCC: number of chewing cycles). Representation of the variables in the plane corresponding to axes 1–2 Correlation matrix in Guichard et al. (2021): Table S4. Panel B: PCA on 15 samples with a high sodium ions content (projects Boisard, Lawrence, Phan) and 14 variables, 7 for the composition in black (Water, Protein, Na^+, Na^+/water, Lipid, Lipid/DM, MNFS), 2 rheological parameters in green (YM: Young modulus, FS: fracture stress), 2 sensory descriptors in blue (salty, hard/firm) and 3 for the chewing activity (TMW: total muscular work, CD: chewing duration, NCC: number of chewing cycles). Representation of the variables in the plane corresponding to axes 1–2. Correlation matrix in Guichard et al. (2021): Table S5.

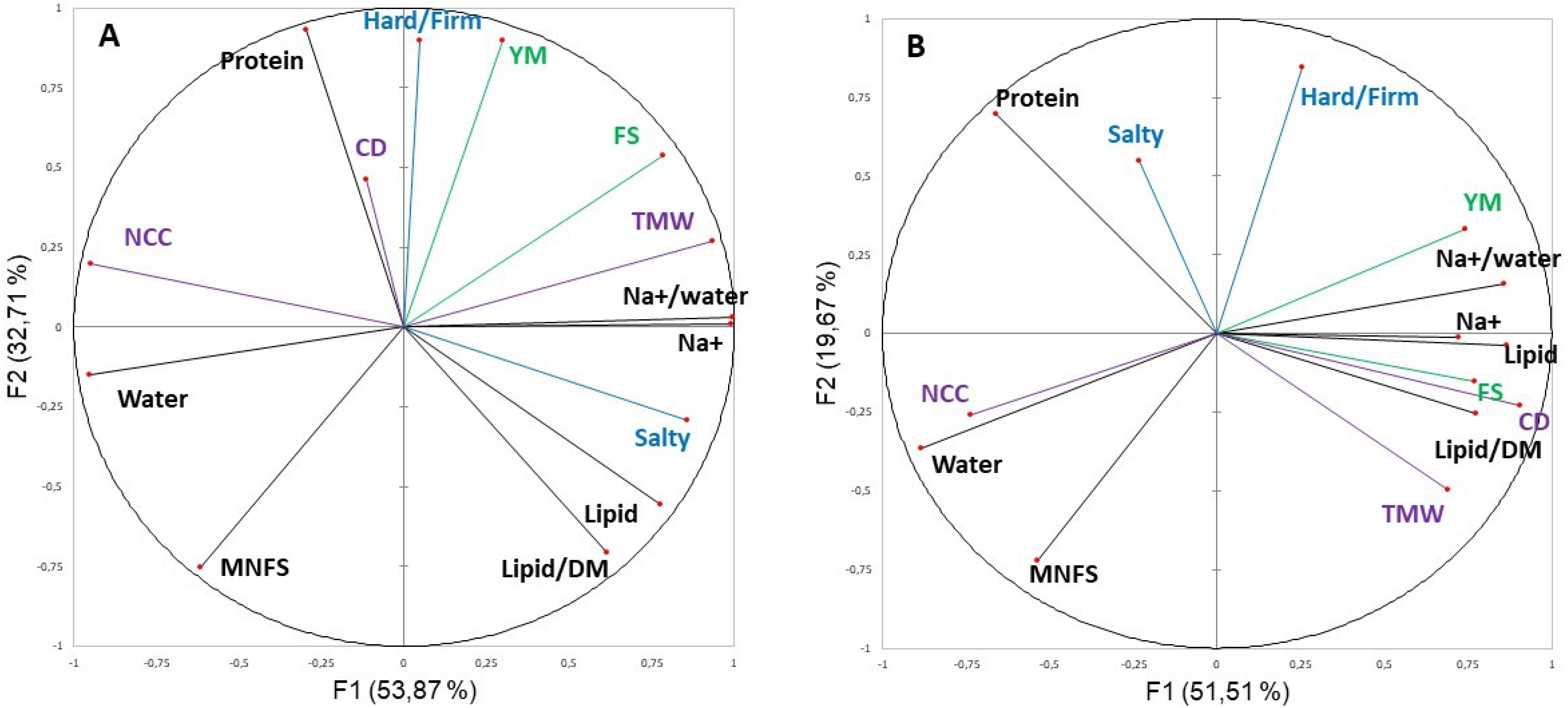
Fig. 4. PCA on 22 samples (projects Adi, Boisard, Tarrega) and 15 variables, 7 for the composition in black (Water, Protein, Na^+, Na^+/water, Lipid, Lipid/DM, MNFS), 2 rheological parameters in green (YM: Young modulus, FS: fracture stress), 6 sensory descriptors in blue (salty, hard/firm, crumbly, sticky, fatty, springy). Representation of the variables (A) in the plane corresponding to axes 1–2 and (B) in the plane corresponding to axes 1–3. Correlation matrix in Guichard et al. (2021): Table S6.

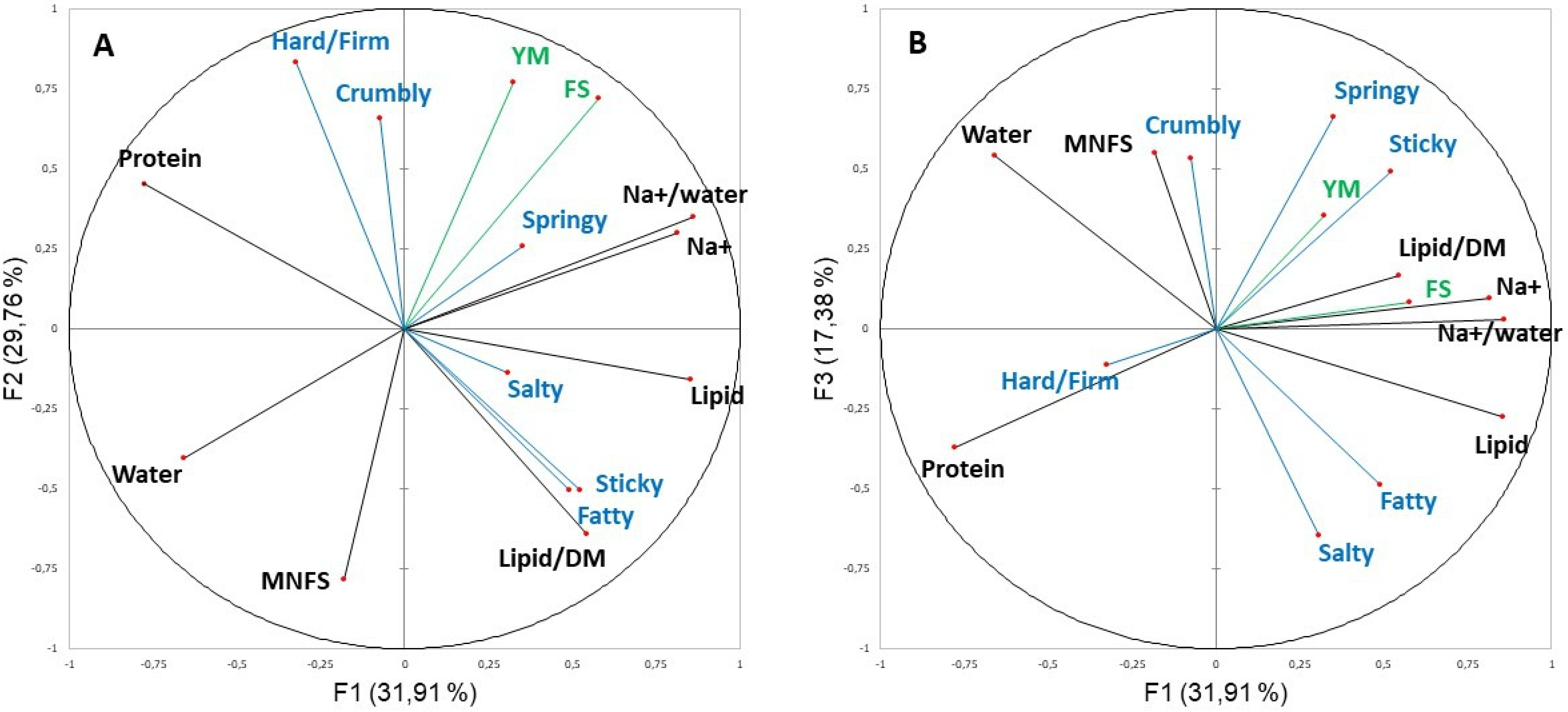


A
B
F1 (43,19 %)
F2 (24,70 %)
F3 (13,37 %)
Adi
BOISARD
LAWRENCE
Phan
PraSel
Tarrega


C
Protein
Hard/Firm
YM
FS
Salty
Na+
Water
Na+/water
Lipid
MNFS
Lipid/DM
F2 (24,70 %)
F1 (43,19 %)
D
Salty
Na+
Water
Na+/water
MNFS
Protein
YM
FS
Lipid/DM
Hard/Firm
Lipid
F3 (13,37 %)
F1 (43,19 %)


A
Protein
Hard/Firm
YM
FS
Water
Na+
Na+/water
Salty
MNFS
Lipid
Lipid/DM
F1 (38,90 %)
F2 (31,16 %)
B
Protein
Hard/Firm
Salty
YM
Water
Na+
Na+/water
FS
Lipid
MNFS
Lipid/DM
F1 (41,74 %)
F2 (23,79 %)


A
Hard/Firm
YM
Protein
CD
FS
TMW
NCC
Na+/water
Na+
Water
Salty
Lipid
MNFS
Lipid/DM
F2 (32,71 %)
F1 (53,87 %)
B
Protein
Hard/Firm
Salty
YM
Na+/water
Na+
Lipid
NCC
FS
CD
Lipid/DM
Water
TMW
MNFS
F2 (19,67 %)
F1 (51,51 %)



A
Hard/Firm
Crumbly
YM
FS
Protein
Springy
Na+/water
Na+
Salty
Lipid
Water
Sticky
Fatty
Lipid/DM
MNFS
F1 (31,91 %)
F2 (29,76 %)
B
Springy
Water
MNFS
Crumbly
Sticky
YM
Lipid/DM
FS
Na+
Na+/water
Hard/Firm
Protein
Lipid
Fatty
Salty
F1 (31,91 %)
F3 (17,38 %)

Table 1

Short description of the samples from the six different projects. [a]

Project	Number of samples	Lipid content (g kg^{-1})	Protein content (g kg^{-1})	Added NaCl (g kg^{-1})	Water (g kg^{-1})	Melting salts (g kg^{-1})	pH	Ref.
Adi	8	80/160	204–310	4.94/14.94	600	0	5/6.2	a
Boisard	6	200–280	170–240	0/10	454–467	6,2	6.67/6.85	b, c, d
Lawrence	18	74–176	236–375	5–15	537–616	0	6.2	e, f, g
Tarrega	8	160–240	240–320	10	479	0	5.4	h, i, j
PraSel	24	173–290	228–297	7–25	419–542	0	4.96/5.35	k
Phan	4	197/297	283	0	383/483	31,2	5.4	l

[a] References are: a, Syarifuddin et al. (2016); b, Boisard et al. (2013); c, Boisard et al. (2014); d, Boisard et al. (2014b); e, Lawrence et al. (2011); f, Lawrence et al. (2012a); g, Lawrence et al. (2012b); h, Tarrega, Yven, Semon, and Salles (2008); i, Tarrega, Yven, Semon, and Salles (2011); j, Tarrega, Yven, Semon, Mielle, and Salles (2019); k, unpublished results (personal communication); l, Phan et al. (2008).