Developing a reformulation strategy to improve the nutritional and sensory quality of the food offer : A case study on chocolate chip cookies

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THÈSE DE DOCTORAT

NNT : 2022UPASB043

université PARIS-SACLAY

Développement d'une stratégie de reformulation pour améliorer les qualités nutritionnelle et sensorielle de produit alimentaire. Cas des cookies aux pépites de chocolat

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Thèse de doctorat de l'université Paris-Saclay

École doctorale n°581 agriculture, alimentation, biologie, environnement, santé (ABIES)
Spécialité de doctorat : Génie des procédés
Graduate School : Biosphera. Référent : AgroParisTech

Thèse préparée dans l'UMR **SayFood** (Université Paris-Saclay, INRAE, AgroParisTech), sous la direction de **Anne SAINT-EVE,** Maîtresse de Conférences (HDR), la co-direction de **Julien DELARUE,** Professeur, le co-encadrement de **Isabelle SOUCHON,** Directrice de Recherche, et de **Véronique BOSC,** Maîtresse de Conférences

Thèse soutenue à Paris-Saclay, le 16 juin 2022, par

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ÉCOLE DOCTORALE
Agriculture, alimentation, biologie, environnement, santé (ABIES)

Titre: Développement d'une stratégie de reformulation pour améliorer les qualités nutritionnelle et sensorielle de produit alimentaire. Cas des cookies aux pépites de chocolat

Mots clés: Propriétés nutritionnelles, Formulation, Analyse sensorielle, Comportement alimentaire, Enfants, Biscuits

Résumé: La reformulation des aliments est un des leviers possibles pour tendre vers une alimentation plus saine. Dans ce contexte, l'objectif de ce travail de thèse était de proposer une approche multicritère pour développer un produit (cookies aux pépites de chocolat) plus sains pour les enfants, tout en maintenant ou optimisant leur perception sensorielle et leur appréciation. Dans un premier temps, un inventaire du marché français a été réalisé, suivi d'une sélection d'un sous-ensemble de produits représentatifs.

Ensuite, nous avons proposé une stratégie de formulation des cookies, basée sur un plan de mélange avec cinq facteurs. Trente cookies reformulés ont ainsi été développés et caractérisés sur de multiples critères.

En plus des approches méthodologiques développées, cette étude a ainsi permis de montrer qu'il était possible de diminuer les kcal (-5,9%), le sucre (-15,9%), les matières grasses (-24,7%), et les pépites de chocolat (-20%) par biscuit, d'augmenter la teneur en fibre (+49,3%), et d'améliorer l'indice glycémique calculé (-8,2%) ; sans ajouter ni d'additif, ni augmenter le degré de transformation des biscuits. Un niveau d'appréciation élevé a été confirmé par les enfants.

Cette approche multicritère de reformulation des aliments est ainsi un outil prometteur pour améliorer l'offre alimentaire, à travers la reformulation de produits gras et sucrés, largement consommés par les enfants.

Title: Developing a reformulation strategy to improve the nutritional and sensory quality of the food offer. A case study on chocolate chip cookies

Keywords: Nutritional properties, Formulation, Sensory analysis, Eating behavior, Children, Biscuits

Abstract: Food reformulation is one leverage to move toward a healthier food offer and diet. In this context, the aim of this PhD work was to propose a multicriteria approach to develop a healthier product (chocolate chip cookies) for children, while maintaining or optimizing sensory perception, liking an behavior. As a first step, a French market inventory was carried out, followed by a representative subset selection. In a second step, sensory-led formulation of cookies was proposed, based on a mixture design with five factors.

On these cookies, multi criteria characterizations were carried out. As main result, this approach led to propose possible reduction of the kcal (-5.9%), sugar (-15.9%), fat (-24.7%), and chocolate-chip (-20%) per cookie and increase in oat bran (+49.3%), with also improvement of the calculated glycemic index (-8.2%) and the Rayner score (-8.7%), while maintaining the liking among children. This work led thus to sensory modeling and recipe optimization for healthier products.

This multicriteria food reformulation approach might reinforce food reformulation as a promising tool to improve the food quality for children.

A. Communications & Valorizations

Oral presentations at conferences

1. Liechti C., Delarue J., Bosc V., Souchon I., Saint-Eve A. *"Free sorting: an interesting task to study the similarities and differences between cookies by 6-13 years old children."* Eurosense Conference, Online, 13-16 December 2020.

2. Liechti C., Saint-Eve A., Aubry L., Riesi V., Souchon I., Bosc V., Delarue J. *"Food reformulation: a multi-criteria approach for a healthier cookie for children."* Food Reformulation – Regulation and Marketing Conference, Online, 17-18 June 2021.

Poster presentations at conferences

1. Liechti C., Delarue J., Bosc V., Souchon I., Saint-Eve A. *"Qualités nutritionnelles et potentiel de reformulation des marques de biscuits françaises et internationales : Une analyse du marché des cookies."* Les Journées Francophones de Nutrition, Rennes, France, 27-29 November 2019.

2. Liechti C., Saint-Eve A., Aubry L., Riesi V., Bosc V., Souchon I., Delarue J. *"A leverage against childhood obesity: a multi-criteria approach for a healthy and appreciated cookie by reformulation."* Eurosense Conference, Online, 13-16 December 2020.

Foreseen conference:

1. Liechti C., Delarue J., Bosc V., Souchon I., Saint-Eve A. "*An approach to multicriteria reformulation to provide healthier food for children aged 7-12 years old while maintaining sensory perception and liking – A case study on cookies*". Edulia Conference, Florence, Italy, 21-22 June 2022.

Oral presentations within the STOP project:

1. Liechti C., Delarue J., Bosc V., Souchon I., Saint-Eve A. *"Impact of food reformulation strategies on eating behavior among children aged 7-12 years in France and Europe."* STOP General Assembly Meeting, Paris, France, 19-21 June 2019.

2. Liechti C., Delarue J., Bosc V., Souchon I., Saint-Eve A. *"Impact of food reformulation strategies on eating behaviour among children aged 7-12 years in France and Europe."* STOP General Assembly Meeting, Online, 18-20 October 2021.

Publications

1. **<u>Liechti, C.,</u>** Delarue, J., Souchon, I., Bosc, V., & Saint-Eve, A. (2022). How to Select a Representative Product Set From Market Inventory? *"A Multicriteria Approach as a Base for Future Reformulation of Cookies."* Frontiers in Nutrition, 8. *doi.org/10.3389/fnut.2021.749596*

2. **Research Paper (Manuscript submitted to Food Quality and Preferences):**
<u>Liechti C.,</u> Saint-Eve A., Souchon I., Bosc V., & Delarue J. *"Multicriteria analysis of a product category to identify reformulation possibilities: a case study using commercial chocolate chip cookies."*

3. **Research Paper (Manuscript submitted to Journal of Sensory Studies):**
<u>Liechti C.,</u> Saint-Eve A., Souchon I., Bosc V., & Delarue J. *" Sensory preference patterns of French children aged 7-12 and their implications for the reformulation of commercial chocolate-chip cookies."*

4. **Research Paper (Manuscript submitted to Food Research International):**
<u>Liechti, C.,</u> Delarue, J., Cosson, A., Souchon, I., William B., Bosc, V., & Saint-Eve, A. *"Sensory-led reformulation of chocolate chip cookies using multifactor optimization."*

5. **Research Paper (Manuscript in Preparation):**
<u>Liechti, C.,</u> Delarue, J., Souchon, I., Bosc, V., & Saint-Eve, A. *"Validation and perspectives of a multicriteria food reformulation approach targeting on children 10-13 years old. A case study on chocolate-chips cookies."*

6. **Research Paper (Manuscript in Preparation):**
<u>Liechti, C.,</u> William B., Delarue J., & Saint-Eve, A. Bosc, V., *"Development of an in vitro starch hydrolysis protocol for biscuits "*

B. Acknowledgement

Anne Saint-Eve. Anne I would like to thank you for amazing way to supervise me during these three years. Besides your expert knowledge in sensory sciences, your motivated, kind and enthusiastic character inspired me a lot. You were able to motivate me even in harder periods, thank you so much for this!

Julien Delarue. Julien thank you so much for your clear, direct and always supportive way of supervision. Your immense knowledge inspired me a lot and you made it possible to collaborate even in different time zones. Thank you so much for your patient, energy and constructive way!

Véronique Bosc. Thank you so much for teaching me about physicochemical sciences and helping me take important decisions for the project. It was a pleasure to be hosted in your lab with many interesting encounters.

Isabelle Souchon. It was a pleasure to work with you closely especially at the beginning of my PhD. I really appreciated your kind and warm way of supervising and teaching. Thank you so much for your very valuable contributions during these three years.

STOP team. Thank you so much to all the members of the STOP team for letting me participate in all your interesting discussions, which allowed me to obtain a better understanding of the childhood obesity epidemic. A special thank you to **Olivier Allais** who was responsible of our work package during these three years.

Thank you to all the members of the thesis committee **Sophie Nicklaus, Camille Michon, Jean-François Huneau** for taking the time to bring up valuable critic for the project during these three years.

GéPro & IHAC Equipe (Massy & Grignon) with special mention: **Sophie Berland, Brigitte Deau, Audrey Cosson, David Forest, Lucia Espinosa.** Thank you so much for supporting me in very different ways during my PhD with your friendly and kind way. I appreciated a lot working with you.

Master student **William Baidoo.** Thank you so much for your amazing work related to the glycemic index. You contributed a lot to this project and you put so much time and effort in this work. It was a pleasure to meet you and working with you.

Engineer students from AgroParisTech. **Lyna Haddadi, Amelie Germond, Ophélie Auroux, Victoire Riezi, Lucie Aubry, Lorna Bassis,** thank you so much for your very valuable work and your contribution to this project.

A huge thank you to my family, friends and especially my parents **Annerös & Ernst Liechti** who supported me in any difficult time.

Niccolò Buetti, thank you so much for helping and supporting me all the way with patient and a lot of love. Without you, it wouldn’t have been possible!

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F. List of Abbreviations

EFSA	European Food Safety Authority
STOP	Science and Technology in Childhood Obesity Policy
FAO	Food and Agriculture Organization
WHO	World Health Organization
PCA	Principle Component Analysis
MFA	Multiple Factor Analysis
NCD-RisC	Non communicable Disease-Risk Factor Collaboration
NNS	None Nutritive Sweeteners
TSO	Trends, scatters, outlier approach
pGI	Predicted glycemic index

1.Chapter 1

Overall Introduction

1 Overall Introduction

The global rise in childhood obesity is a serious public health concern (NCD-RisC, 2017). An important causing factor is the unhealthy diet composed of high caloric, ultra-processed and highly palatable foods (Costa et al., 2018; Forde et al., 2013; Hall et al., 2019). Further it is well known that products targeting children do have a higher sugar content than compared to those of adults' (Moore et al., 2020; Rito et al., 2019). In order to prevent overweight and obesity in childhood, improving the food offer is crucial.

In this context, the project "STOP" (Science and Policy in Childhood Obesity Policy, EU Horizon 2020) was launched, in order to manage and prevent childhood obesity (school aged children aged 7-12 years old) among European regions (STOP, 2017). Funded in the frame of project STOP, this PhD aims to contribute to improve the nutrition quality of the food offer.

Obviously, past interventions to reduce and manage obesity failed as the obesity pandemic is still increasing. Obesity interventions which are based on behavior change are delicate, as a behavior change was shown to be most difficult for concerned people (Burgess et al., 2017; Hill et al., 2008). Important reasons why a behavior change failed were for example poor motivation; environmental, societal and social pressure; lack of time; health and physical limitations; negative thoughts/moods; socioeconomic constraints; gaps in knowledge/awareness; and lack of enjoyment of exercise (Burgess et al., 2017).

New innovative approaches are therefore urgently needed. Possible powerful leverages are for example labelling, taxation, policies and re/formulation of healthier foods (Gressier et al., 2020; Vandevijvere & Vanderlee, 2019). Indeed, food reformulation (reducing overconsumed nutrients such as sugar, fat and salt) is an interesting way to first focus on products' quality and properties. An improved product quality might automatically positively impact consumers' intake, without largely changing consumers eating habits (Gressier et al., 2021; Raikos & Ranawana, 2019; Spiteri & Soler, 2018).

Recent multi-nutrient models showed that food reformulation may lead to a reduction in daily energy, fat, sugar and salt intake and to a significant increase in fiber intake among children and adolescents (Combris et al., 2011; Leroy et al., 2016; Masset et al., 2016; Muth et al., 2019). Several studies demonstrated that food reformulation could improve children's' diet while they keep consuming the same foods (Hashem et al., 2019; Muth et al., 2019; Yeung et al., 2017). Maintaining high levels of liking for reformulated food is possible. For example, for dairy products and grape nectar, some research highlighted the possibility to reduce the sugar content up to 27%, respectively 21.6% while maintaining children's' appreciation (Lima et al., 2019; Velázquez et al., 2021a).

However, despite the high potential for food reformulation among many product categories and the voluntary food reformulation agreements among industries (Belc et al., 2019; Breda et al., 2020; Van Gunst et al., 2018), the scope for reformulation remains limited, due to technological and sensory barriers, and often addition of economic constraints. In particular, decreasing sugar and fat is challenging because of their multiple functional properties in the food matrix, in particular in bakery products (Ghotra et al., 2002; Miller et al., 2017; Pareyt et al., 2009). Indeed, any sugar and fat reduction may lead to reduced processability of the dough and modified food product structure and decreased shelf-life. Moreover, classical food reformulation approaches in the past often excluded consumer-oriented methodologies such as sensory and hedonic evaluation, although consumer preference is a key determinant of food reformulation (Federici et al., 2019; van Kleef et al., 2006). In particular, decreasing sugar and fat amount in food will likely alter the sensory perception and decrease the potential liking (Marty et al., 2018; Nguyen et al., 2015, Cooper, 2017). Another problem is the fact that food reformulation is often done on a voluntary basis and only applies to single products. This allows consumers to switch to brands with higher energy density induced by a higher sugar and fat content (Van Gunst et al., 2018).

These hindrances also reflect in the poor reformulation successes in the food industry. A recent study across 20 European countries showed that many packaged foods and drinks still have a too high fat, sugar and salt- and a too low fiber content (Bonsmann et al., 2019). For example, in the UK, most of the companies between 2015 and 2018 did not reach an overall sugar reduction of 5% among the top 5 product categories which contribute the most to sugar intake (biscuits, cereal bars, breakfast cereal, chocolate and sugar confectionery, yoghurts) in the UK population (Bandy et al., 2021). Further, this might be as well a reason why – according to a recent review – only limited studies were available for reducing sugar in bakery products without any substitution and additives (Luo et al., 2019). However, because substitutions and use of additives have a poor image and possibly a negative influence on sensory perception, consumers demand safer, healthier and more natural foods.

All these reasons constitute a real challenge for food scientists and food manufacturers and may contribute to the hesitant willingness for voluntary food reformulation on the part of the food industry as cost and time effectiveness are not immediately granted (Cooper, 2017; Harastani et al., 2020; Lacey et al., 2016; Vagnoni & Prpa, 2022; Van Gunst et al., 2018).

By consequences, it is clearly necessary to improve the quality of the food offer and to develop new approaches to overcome the barriers of food reformulation. Encouraging industries to reformulate healthier versions of their products is urgently needed.

Therefore, it is important to better exploit the potential for reformulation by showing further pathways to the industry and government in order to reinforce food reformulation as an impactful lever against childhood obesity. This line of thinking would help promoting the improvement of processed foods' nutritional quality while maintaining liking. Food reformulation must therefore be strengthened, in line with public health policies. This can be achieved by studying the composition and properties of products on the market and possible levers. On this basis, it would be possible to set realistic reformulation targets and identify levers for each food category or family.

To answer to this challenge, a study of literature was first conducted to identify reformulation levers with potential impact on health and obesity. Based on this, a large focus on the reduction in energy density from sugar and fat was done (Bogl et al., 2018; Combris et al., 2011; Masset et al., 2016; Muth et al., 2019). However, sugar and fat are key determinants of consumers' perceptions and liking which makes their reduction very challenging. The stake to maintain similar sensory perception while reducing sugar and fat is thus very high. In this objective, different pathways were described. For example, a sugar reduction while maintaining foods' sweetness might be achieved by using vanilla aroma (Velázquez et al., 2021; Wang et al., 2019). A fat reduction while maintaining foods' texture and mouthfeel might be achieved by using, for example, fibers (Conforti et al., 1997; Lee & Inglett, 2006; Milićević et al., 2020; Zoulias et al., 2000a,b).

Besides modifying nutrient content, it is further possible to reduce the total energy intake by enhancing the satiation and satiety, induced by modifying foods' texture and the oral process, as shown in FIGURE 1 (Fogel et al., 2017; Forde et al., 2013; Krop et al., 2018; Quah et al., 2019). In particular, it was shown that texture modification might be successful to decrease children's 'obesogenic' eating style, which is associated with faster eating rates, achieved through larger bites, reduced chewing and shorter oral exposure time (Fogel et al., 2017). An interesting lever to modify foods' texture and oral processing in order to influence the satiation and satiety, could be the addition of fibers (Pentikäinen et al., 2014; Priyanka et al., 2019).

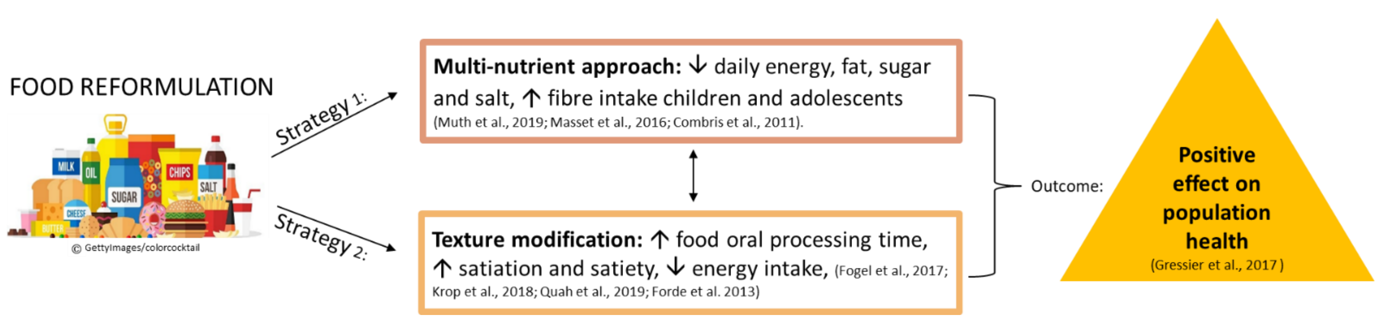


FIGURE 1: Two possible reformulation approaches, with either nutrient (strategy 1) or texture modification (strategy 2), while both strategies do impact each other.

As highlighted previously, food reformulation within a complex food matrix with high sugar and fat is challenging due to several reasons. To address this challenge, we propose a new strategy of food reformulation, developed in a comprehensive way because of the multifactorial determinants of the interactions between food components, food preferences and healthier diet. To set realistic reformulation targets, this reformulation approach was first based on commercial products. Sweet biscuits, in particular chocolate-chip cookies were chosen as a case study as this category has a high impact on the diet due to its consumption frequency and poor nutritional properties (Alessandrini et al., 2019; European Food Safety Authority, 2011).

The objective of this PhD was thus to identify reformulation leverages on commercial products to create a healthier food offer, while improving key sensory properties and the liking. In a second time, the goal was then to validate and to evaluate the impact of the reformulated product on health relevant indicators such as the predicted glycemic index, the food oral processing and the satiety.

For that, a multi criteria approach, integrating nutrition, sensory, physicochemical and hedonic characteristics was proposed, followed by an experimental approach focused on the study of the impact of reformulation on health relevant indicators and children’s perception.

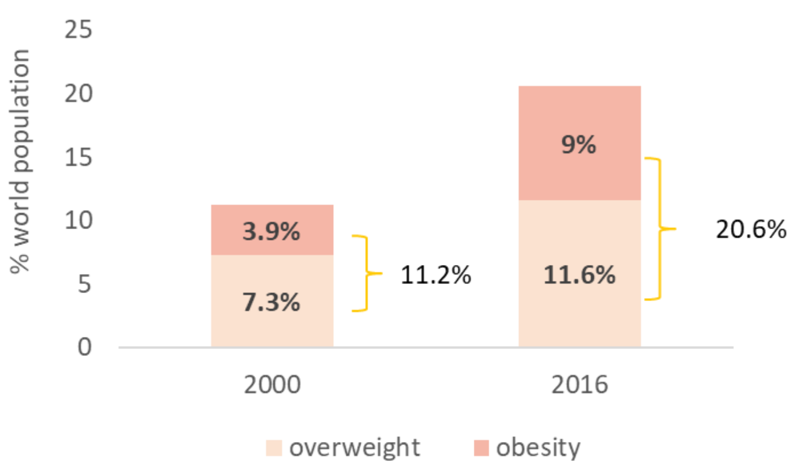
2. Chapter 2

State of the art

2 Chapter: State of the art

2.1 Childhood obesity: prevalence, determinants and possible leverages

Since 1975, the global childhood obesity rate increased tenfold and affects low-, middle-, as well as high-income countries, although it would be preventable (NCD-RisC 2017). As shown in FIGURE 2, between 2000 and 2016, the global rates for overweight (BMI≥25) and obesity (BMI≥30) among children aged 5-9 years old increased constantly (FAO, 2019; WHO, 2021). It is alarming that the obesity prevalence increased even more compared to the overweight prevalence. As well among 35 European countries or regions, around 27.3% of school aged children are suffering from overweight, while 10.5% are affected from obesity (WHO, 2018). Similar overweight and obesity trends were observed for France with 24%, respectively with 7.5% (FAO, 2019).



(Source: adapted from FAO et al., 2019)

FIGURE 2 : Worldwide prevalence of childhood overweight and obesity among school-aged children 5-9 years old between 2000 and 2016.

2.1.1 Determinants and consequences of childhood obesity

Childhood obesity is a very complex public health concern, explained by many determinants as shown in FIGURE 3. Environmental factors, lifestyle preferences, and cultural environment play key roles in the rising prevalence of overweight and obesity worldwide (Meldrum et al., 2017).

Child behaviors (eating, physical activity and sedentary behaviors) are considered therefore as the most important determinants for developing childhood obesity. Among them, an unhealthy diet is assumed to be the results of the increased portion size, the frequent consumption of refined grains, or the excessive sugar and fat intake in foods and beverages (Grosso & Di Cesare, 2020; Moreno & Rodríguez, 2007).

In addition, possible explanation for this ongoing epidemic is the shift in social and environmental contexts (Lee, 2012). Environmental factors such as school policies, demographics, and parents' work-related demands further influence eating and activity behaviors. It is well known that especially school aged children from low income and ethnic minority groups with a low educational level are affected from obesity (Beaulac et al., 2009; Brophy et al., 2009; FAO, 2019; Larson et al., 2009; Williams et al., 2018). Further, these children often live in poor food environments with high concentrations of fast-food and convenience stores.

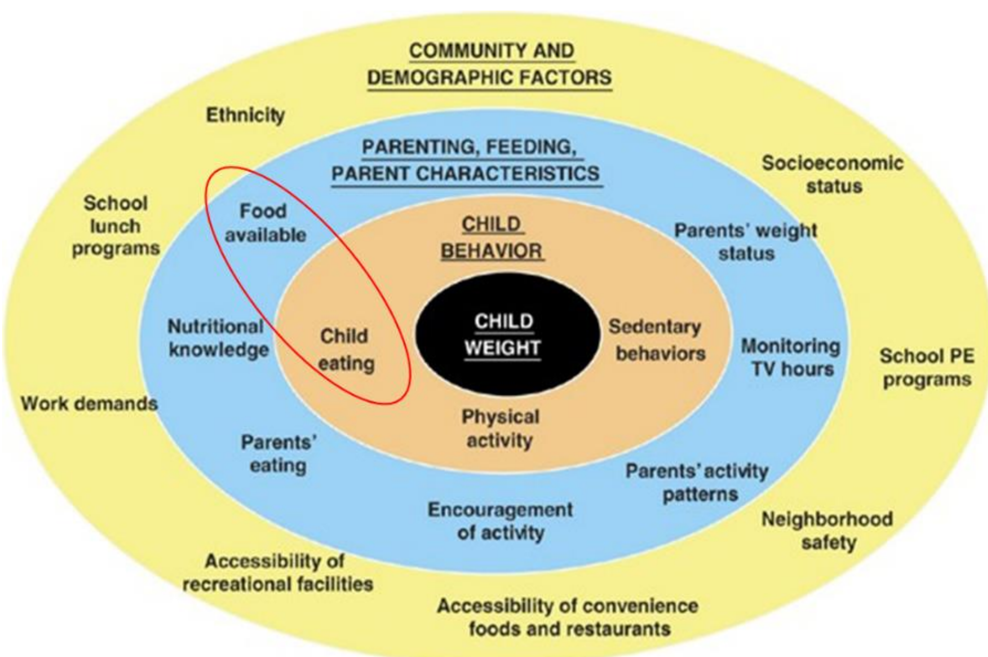


FIGURE 3 : Multiple determinants of childhood obesity. (Source: Modified from Davison & Birch, 2001; Birch & Ventura, 2009)

Childhood obesity has various negative health consequences, such as for example cardiovascular diseases, type 2 diabetes and adult metabolic syndrome (Bacha & Gidding, 2016; Cote et al., 2013; Lloyd et al., 2012). Furthermore, psychological problems, low self-esteem and social problems can further occur (Beck, 2016; Halfon et al., 2013; Morrison et al., 2015).

Moreover, obese children are exposed to a higher risk for diseases in adulthood, including the risk to become adults with obesity (Bass & Eneli, 2015; Gordon-Larsen et al., 2010).

2.1.2 High sugar and fat intake as an underlying dietary risk factor for childhood obesity

One underlying reasons of overweight and obesity increase is the consumer shift towards an unhealthy diet composed of highly palatable, caloric and ultra-processed foods during the last decades (Costa et al., 2018; Forde, Mars, & de Graaf, 2020; Hall et al., 2019; Khandpur et al., 2020). Some recommended daily values for fat, saturated fat, sugar, carbohydrate and salt for a healthy diet were proposed based on WHO and British Nutrition Foundation guidelines for children and confronted to eating habits of French children aged 0-10 years (FIGURE 4). The highest value to exceed the daily recommended values was clearly found for free sugar, with an overconsumption of +15% or even of +20%. The total fat consumption is still within the range, knowing that the fat is providing one of the most important energy sources for younger children, whereas the recommended value will decline when children are getting older. However, it must also be noted that saturated fat intake was too high.

Daily recommended values for fat, saturated fat, sugar carbohydrates, salt and fibre	Eating habits French children aged 0-10 years	
▪ **Fat:** ~max. 35% / Increased fat intake in early life (British Nutrition Foundation, 2016; WHO, 2018)	~33%	
▪ **Saturated fat:** 10%↓ of total energy intake (WHO, 2018)	~17%	+ 7%
▪ **Carbohydrates:** ~50% (British Nutrition Foundation, 2016)	~50%	
▪ **Free sugar:** 10%↓ of total energy intake (WHO, 2018) → 5%↓ (WHO, 2018; British Nutrition Foundation, 2016)	At least 25%	+ 15% or + 20%!
▪ **Salt:** max. 5g/day (WHO, 2018), 2-15 years ↓	4.4g	

(Source: Adapted according to Agence nationale de sécurité sanitaire de l'alimentation, de l'environnement et du travail, 2017)

FIGURE 4 : Diet recommendations for children vs. eating habits among French children aged 0 – 10 years between 2014 and 2015. On the right side of the table, numbers in black color with consumption habits, numbers in red (in rectangle) with comparison to diet recommendations (on the left side). (Source: Agence nationale de sécurité sanitaire de l'alimentation, de l'environnement et du travail, 2017).

Several authors identified the excessive sugar intake as a key dietary determinant of obesity among children and adolescents (Ambrosini et al., 2015; Te Morenga et al., 2012). Added sugar in industrial process food is the main source of sugar consumption (Afeiche et al., 2018; Powell et al., 2016; Rauber et al., 2019). Further it was shown that a diet rich in refined carbohydrates with a high glycemic index (GI) and sugars was associated with obesity (Chiavaroli et al., 2018; Harris Jackson et al., 2014; Pawlak et al., 2002).

In addition to this, increased insulin spikes and fat metabolism changes caused by the high sugar intake impact appetite and energy intake, and can cause food cravings (Dimitriadis et al., 2011; Lennerz & Lennerz, 2018; Stanhope, 2016). But sugar is not the only key determinant. An energy dense diet from total fat and sugars was also responsible for increased adiposity in childhood and adolescents (Ambrosini et al., 2015). Fat in processed foods can induce overeating due to the low satiety effect, while having high palatability but also high energy density (Blundell et al., 2010; Bray & Popkin, 1998; Drewnowski, 2007, 2018; Golay & Bobbioni, 1997) Further, energy overconsumption was associated with the increasing obesity rate (van Buul et al., 2014).

Besides sugar and fat, fiber intake may play an important role in children's weight status. According to a recent study with 330 children from six European countries, fiber (naturally present in foods) was associated to food intake and children's BMI (Hörmann-Wallner et al., 2021). Children with a high consumption of wholegrain alternatives of common foods showed significantly a lower BMI. Furthermore it is well known, that the fruit and vegetable consumption among European children is weak (Yngve et al., 2005).

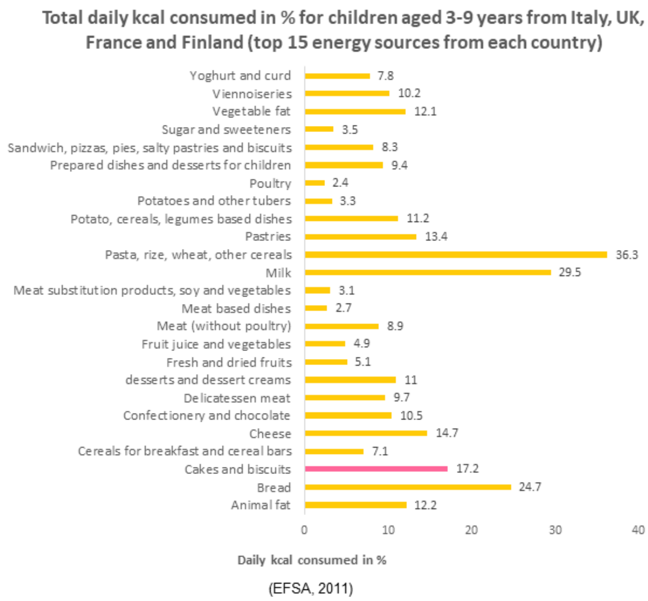
Trying to provide an answer for the above mentioned eating behavior, a recent study investigated 2691 pre-packed products, where around 68% were considered to be ineligible for children according to WHO Europe guidelines (Bonsmann et al., 2019) due to their high free sugar content and too low fiber content. Similar results were found in another study (Elliott & Truman, 2020).

Thus, as highlighted in the latest report of the World Health Organization (WHO, 2021), it is urgent to carry out an immediate reduction in the extreme consumption of added sugars and easily assimilated carbohydrates. This, combined with an increase in daily physical activity would curb the tendency towards increasing obesity and type 2 diabetes.

2.1.3 Which product categories are responsible for a high energy intake from sugar and fat among children from European regions?

To better study the source of the high sugar and fat intake and to identify product categories with high impact on children's diet, consumption data from the EFSA (2011) from countries among European regions were analyzed (without beverages). The FIGURE 5 presents, for children aged 3-9 and 10-17 years old, the top four product categories contributing to a higher extent to the daily kcal intake: "pasta, rize, wheat, other cereals", "milk", "bread" and "cakes and biscuits".

For both children categories, cakes and biscuits are among the core product categories (fourth position) which contribute to a high extent to the daily kcal intake in percent. Cakes and biscuits are also among the core product categories that contribute to the fat and the carbohydrate content (FIGURE 6) (EFSA, 2011).



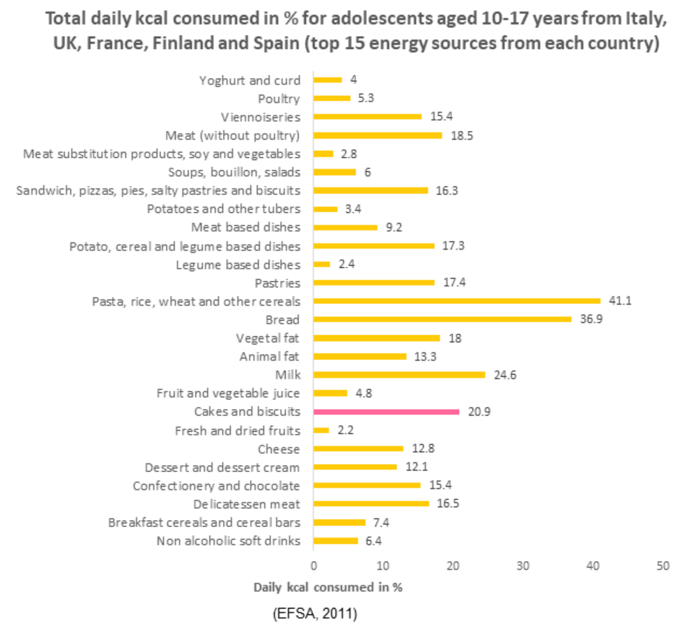


FIGURE 5 : Total daily kcal consumed in % for children from European countries, on the left side aged 3-9 years old and on the right side adolescents 10-17 years old. (EFSA, 2011)

Those finding were in line with the literature. It was found that cakes and biscuits contribute to a high amounts of added sugar intake worldwide (Alessandrini et al., 2019; Azaïs-Braesco et al., 2017; Herrick et al., 2020; Lei et al., 2016; Luo et al., 2019; Popkin & Reardon, 2018; Zoulias et al., 2000a,c). Another European study demonstrated that added sugars were mostly found in sweet products, even before beverages (Azaïs-Braesco et al., 2017). In addition to added sugar and fat intake, biscuits are part of a "processed diet pattern" (Fernández-Alvira et al., 2014). This may relate to the debate over the health effects of food processing, for which some studies showed that a highly processed food increases energy intake and weight gain (Fernández-Alvira et al., 2014; Hall et al., 2019; Morenga et al., 2013).

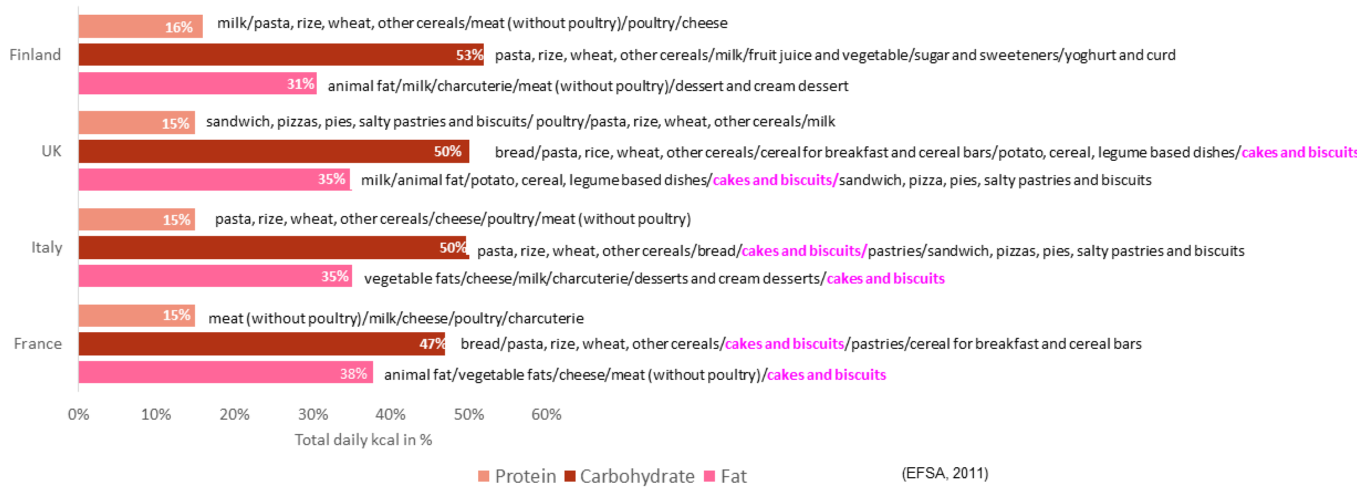


FIGURE 6 : Food sources from total daily kcal consumed for protein, carbohydrates and fat for children aged 3-9 years for Finland, UK, Italy and France.

To conclude, as sweet bakery products, such as biscuits and cakes, are consumed around the world in large quantities and frequencies and contribute to the high sugar and fat intake among children, this product category is of interest for reformulation perspectives.

2.1.4 Overview of possible leverages to tackle childhood obesity

As already mentioned, childhood obesity is a complex public health concern that is multifaceted. Therefore, it is important to highlight that no single intervention would be powerful enough to prevent and tackle the childhood obesity epidemic. In order to be impactful, the obesogenic environment must be changed with multi-sectorial action such as national plans, policies and programs (WHO, 2017). As shown in FIGURE 7 B, six principle actions are recommended in order to prevent and manage childhood obesity. As demonstrated, childhood obesity prevention starts already before the pregnancy (interventions 1-2). During pregnancy (intervention 3), maternal health can influence the fetal development and the risk of a child become obese. Further, promoting physical activity and healthy nutrition with integrated weight management during child’s growth are major pillars for the childhood obesity prevention (interventions 4-6).

As highlighted in red in FIGURE 7 B in order to reduce the obesogenic environment among the most sensitive groups for developing obesity – the school aged children - the creation of a healthier food environment is crucial. Considering the importance of this intervention, this PhD will focus on enhancing the food offer with an improved nutritional and health environment.

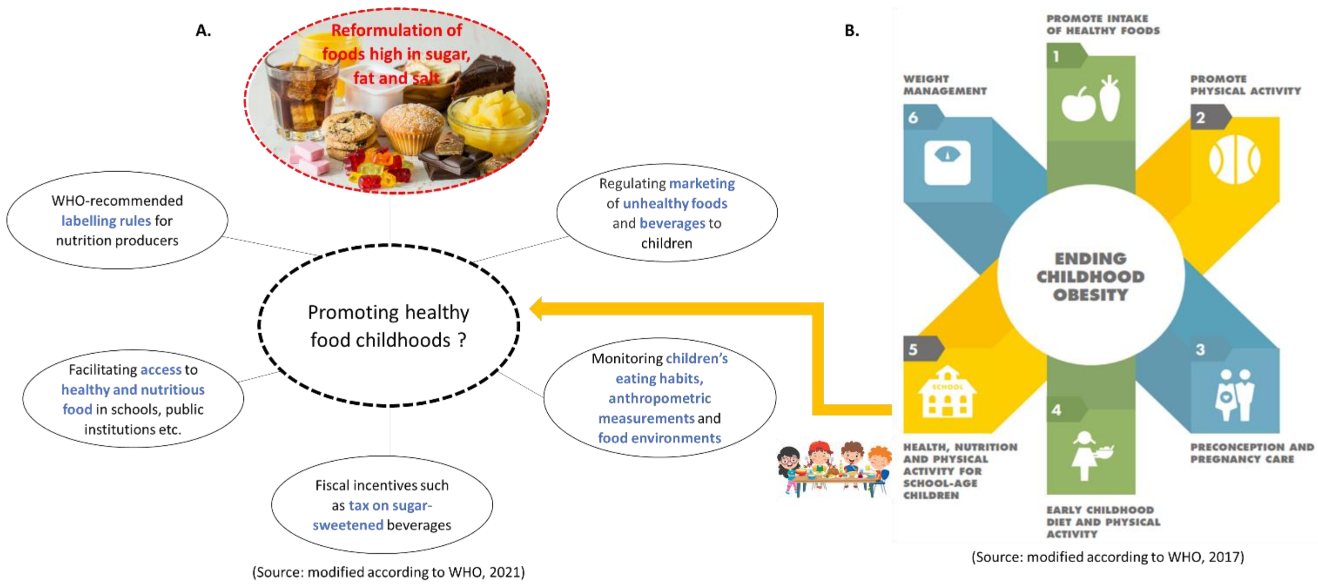


FIGURE 7 : A : Nutrition related leverages to tackle and manage childhood obesity. B: Overall leverages to prevent childhood obesity.

In order to prevent and manage childhood obesity, the energy intake from sugar and fat often coming from highly processed foods should be reduced (Askari et al., 2020; Bogl et al., 2018). FIGURE 7 A summarizes the different strategies that can be used to create a healthier food environment for children. As illustrated, food reformulation is one of the possible leverages to enhance children's food environment and nutrition.

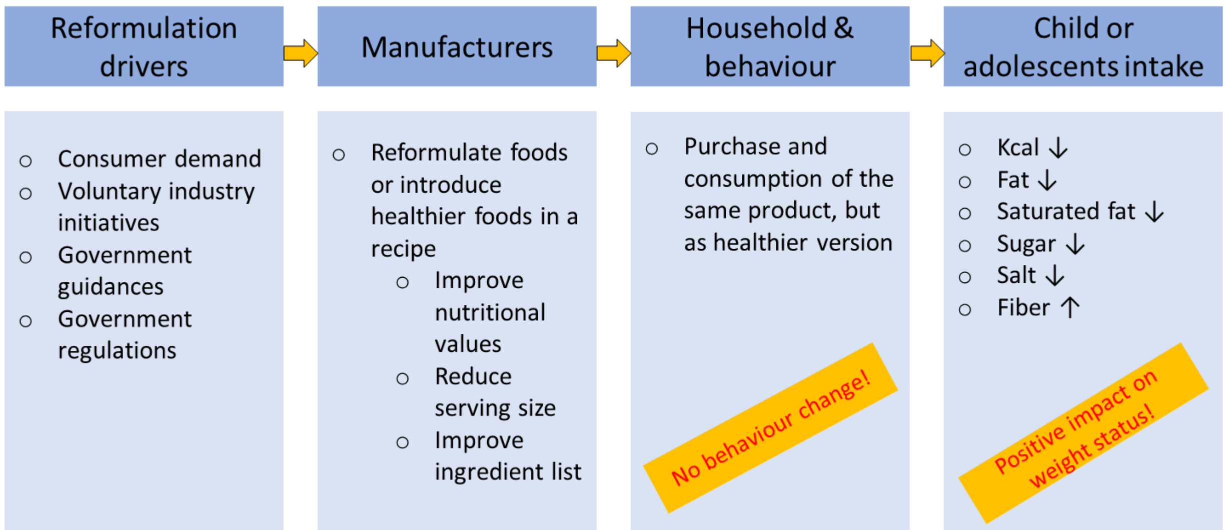
Food reformulation as a leverage to reduce children's obesogenic environment

Food reformulation is an interesting leverage to reduce over-consumed nutrients having negative health effects (sugar, fat, salt) in processed foods. Some works showed that food reformulation can enhance our diet and health (Gressier et al., 2021; Nijman et al., 2007; Raikos & Ranawana, 2019; Spiteri & Soler, 2018). It permits to consume healthier diets without the consumers having to make decisions or modify their consumption behavior (Buttriss, 2013) (FIGURE 8).

Recent modeled food reformulation studies with a multi-nutrient approach showed that food reformulation could lead to a significant reduction in daily energy, fat, sugar and salt intake and to a statistically significant increase in fiber intake among children and adolescents (Combris et al., 2011; Leroy et al., 2016; Masset et al., 2016; Muth et al., 2019). It was shown that a reduction of undesirable nutrients such as trans fatty acids, saturated fat, sodium and sugar of more than 17’000 foods and beverages would lead to a reduced intake of nutrients which are to limit and an improved public health (Nijman et al., 2007). Beyond that, a recent modeling study from Portugal showed that a daily salt intake reduction from 7.6 to 7.1g would led to 610 deaths less per year (Francisco Goiana-da-Silva et al. , 2019). Furthermore, a daily energy consumption reduction from 1911 to 1897 kcal resulted from a sugar reduction would led to 261 death less per year (ebd.).

Especially the reformulation of products targeting on children is high relevant as it was found that products targeting at children do have in several cases a higher sugar content than compared to those of adults (Moore et al., 2020; Rito et al., 2019). Food reformulation was considered as one of the most cost-effective strategies to reduce the sugar intake among children (Macgregor & Hashem, 2014). Several studies showed the possibility to reduce children’s sugar intake and to enhance their diet by reformulating foods into healthier versions while children continued with the consumption of the same product (Hashem et al., 2019; Muth et al., 2019; Yeung et al., 2017).

Sugar and fat should be reformulated both at the same time in sweet baked goods because of the high impact of their overconsumption on children’s’ health (Alessandrini et al., 2019). Reducing the energy density only from sugars in sweetened beverages makes sense (as it is the main energy source), but in baked products fat plays the most important role when it comes to energy density (9kcal per g for fat, 4kcal per g for sugar). Furthermore, an overall fat reduction would as well reduce the saturated fat content, with positive impact on the LDL reduction and the overall health. In the UK for example, biscuits and cakes were not yet included in the calorie reduction program, as this product category was already part of the sugar reduction program (Alessandrini et al., 2019). This highlights the complexity of food reformulation with respect to the policies and regulatory aspects.



(Source: modified according to Muth et al., 2019)

FIGURE 8 : Principe of food reformulation and the possible impact on children's dietary intake.

Reformulation faces many challenges, but different levers and strategies could be imagined. First, when reducing sugar and fat among baked goods, the challenge is to maintain products processability, structure, texture, sensory perception and liking without any health concerns.

2.2 Sweet biscuits (cookies) as the target for reformulation – the role of ingredients and common strategies for a sugar and fat reduction

Sweet bakery products are among the most widely consumed food categories worldwide due to their practicality, good sensory acceptance and long shelf-life period (Albuquerque et al., 2017; Dias et al., 2015). When having a closer look at biscuit categories, we can distinguish between crackers, hard sweet and semi-sweet biscuits, short-dough biscuits and cookies (Davidson, 2018). Each biscuit category also differs in their mixing, forming and baking process (ebd.).

When comparing the nutritional values among 26 cake and biscuits families, cookies showed an increased kcal, fat, sugar and salt content compared to the remaining categories (Oqali 2008). Indeed, cookies are energy dense (high sugar and fat recipe) and play an important role in the children's intake of added sugar (Afeiche et al., 2018; Denney et al., 2017; Elliott & Truman, 2020, Davidson, 2018).

Moreover, cookies belong to children's most preferred snacks and are known and eaten all over the world (CREDOC enquête CCAF, 2013 and Gupta et al., 2011). Cookies are composed with a wide variety of recipes, using different ingredients and inclusions, such as for example chocolate-chips, coconut, peanut butter, raisins, nuts or dried fruits as illustrated in FIGURE 9.

Thus, because of their popularity, relatively low cost, varied taste, ease of availability and processing, high nutrient density and long shelf life, we choose to focus on cookies as target product of interest for our study.

FIGURE 9 : Overview of commercial cookies available in different varieties. (Source: Davidson, 2018).

Their composition and process parameters have strong influence on taste and crispiness (Chappalwar et al., 2013). When processing cookies, it is thus necessary to understand the functions of ingredient and process variables for the industrial production (Mudgil et al., 2017).

The composition of the cookie dough influences dough production and handling, how cookies bake and their final quality (Pareyt & Delcour, 2008). The principal cookie ingredients are flour, sugar and fat. They contribute largely to the desired organoleptic properties and drive consumer liking (FIGURE 10).

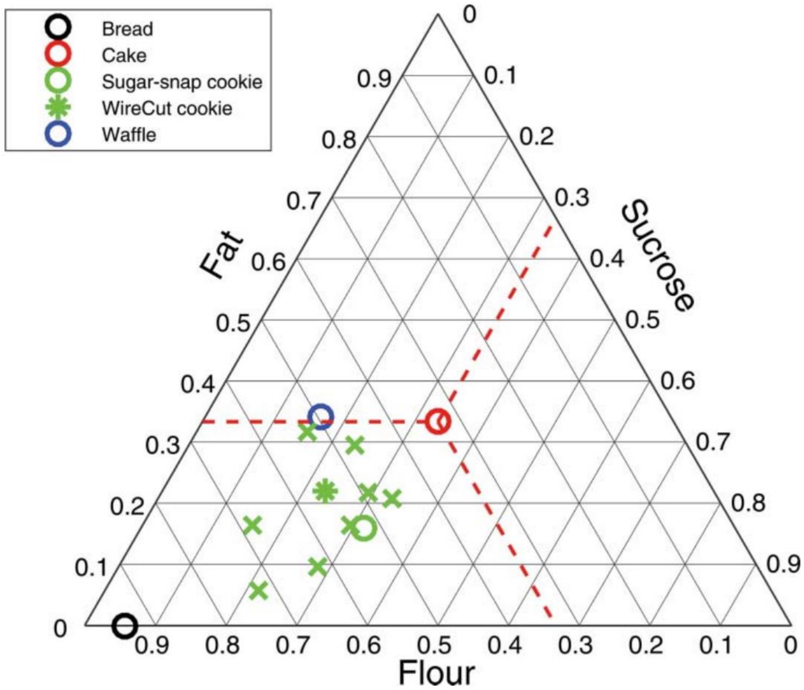


FIGURE 10 : Overview of principle ingredients and their ratios among different bakery products. (Source: Pareyt & Delcour, 2008b; Chevallier et al., 2000; Moiraghi et al., 2011; Laguna et al., 2011; Rodríguez García et al., 2013 in van der Sman & Renzetti, 2019).

The structure of the cookies develops along the process from the dough mixing to the final cookie structure. The dough is considered as a partially aerated mix system depicted as two interpenetrating continuous phases: one lipophilic phase with oil and fat in different states, and the second phase composed of a sugar solution. Depending on the level of added water, sugar may be dissolved or stay with its crystalline structure. Flour particles and starch are dispersed into this system. Some authors consider that lipids may be more emulsified and thus constitute a dispersed phase. During mixing and baking, sugar and fat may change state, from crystal to melted, and may recover partial crystalline structure upon cooling (van der Sman & Renzetti, 2019). Sugar and fat both contribute to the structure of the product, the texture, mouthfeel, volume, color and flavour of sweet bakery products. They have been identified as most relevant ingredients determining the overall acceptability among consumers (Heenan et al., 2010; Manohar & Rao, 1999; Zoulias et al., 2002a). Water is supplemented in limited amounts as a solvent, together with other minor ingredients like egg, baking powder, salt, aroma and emulsifiers. The quality of the final product depends largely on the quantity and the type of all ingredients (Arepally et al., 2020).

2.2.1 Sugar ingredient

2.2.1.1 Role of sugar on structure, texture and sweetness in biscuit

In bakery products such as cookies, sugar is one of the main components, contributing up to 30-40% of the total recipe. Sucrose is considered as the most important sugar in baked products and cookies (Garvey et al., 2020; Maache-Rezzoug et al., 1998; Pareyt et al., 2009). Sucrose is a carbohydrate derived from sugar cane or sugar beet and is composed of two monosaccharides, glucose and fructose (Davidson, 2018). Besides the white sugar, as well the brown sugar is a common ingredient for biscuit making (Manley, 2011). The brown sugar (or raw sugar) is coated with molasses, which colored from golden brown to dark. The darker the color, the more intense the distinctive flavor. Due to the molasse content, brown sugar has an increased moisture con tent (~2-4%) compared to white crystal sugar (~0.04%). Looking at the production of white refined and brown non- or less refined sugar, it is considered that brown sugar has a reduced level of processing. Furthermore, brown non-refined sugar contains a high number of phenols and flavonoids, whereas thermal treatment did not largely affect their antioxidant capacity (Seguí et al., 2015). For these reasons, brown sugar is an interesting sugar to add in the cookie dough.

Sugars' role goes beyond providing sweetness, as this raw material is involved in creating and maintaining products' structure and texture and reduce water activity what can result in an enhanced preservation (Rodríguez et al., 2016). Cookies' texture is especially affected by the sugar level and the type of sugar. Depending on the amount of water present, sucrose in biscuits dough dissolves (or partially) and recrystallizes or forms an amorphous glass after baking (Manley, 2011). Therefore, a high level of sucrose could lead to a harder texture. But as well the size of the sucrose crystals and their dissolution rate can affect the cookie spread, including appearance and crunchiness (Manley, 2011). It was shown that a smaller sugar particle size in cookies led to a harder texture (Boz, 2019). This, because smaller sugar particles might be better dissolved than larger sugar particles. Moreover, sugar is involved to incorporate air into the fat during cookie dough preparation and can decrease dough viscosity (Maache-Rezzoug et al., 1998). Further, dissolved glucose also inhibits gluten development during dough mixing and starch gelatinization during baking, while sugar is competing with the flour for available water (O'Sullivan, 2020). This will lead to a more tender texture (Davidson, 2018).

The sugar level in cookies can affect the sweet taste, dimensions, color, hardness, crispness, volume and surface (O'Sullivan, 2020; Pareyt et al., 2009; Hoseney, 1994). Besides the sucrose, as well syrups are common cookie ingredients, often in form of reducing sugars (Manley, 2011).

Syrups are mostly used in small quantities in order to enhance certain flavours and colors (increased Maillard reaction with the presence of amino acids) or to maintain moisture to prevent the biscuit from being too hard (Manley, 2011; Davidson, 2018). Commonly used syrups are glucose-, cane-, fructose- and invert syrups including malt extract (Davidson, 2018). Moreover, fructose as monosaccharide has a higher perceived sweetness than glucose.

Given the multiple functionalities that sugars exert in foods, the reformulation of bakery products with a substantial reduction in sugars has proven difficult, and goes beyond just changing the sweetness level.

2.2.1.2 Sugar reduction strategy

To overcome processability, structure and perception challenges, sugar is often replaced or substituted with different ingredients or additives. However, although maintaining the sweetness, substitutes or replacers fail to imitate important sucrose roles, such as structural development, functionality and color formation (Struck et al., 2014).

According to a recent review about sugar reduced bakery products, only limited quantity (~10%) of sucrose can be reduced from biscuits and cakes without alternative sweeteners and replacers (Luo et al., 2019). This is because sugar has multifunctional properties in the food matrix. As the sugar is not only providing sweet taste but as well to a high extend responsible for products texture, it is often recommended not to completely replace or substitute the sugar (Markey et al., 2015).

Sugar replacers and substitutes such as polyols or non-nutritive sweeteners (NNS) are commonly used for sugar reduction strategies in industry (Luo et al., 2019; Raikos & Ranawana, 2019). Polyols (sugar alcohols as for example maltitol or erythritol) contain around the half of calories compared to sugar and they provide bulk and sweetness, however to a lower extent than the sugar (Raikos & Ranawana, 2019). Non-nutritive sweeteners (NNS) (for example saccharin, stevia, sucralose, acesulfame potassium Ace-K and aspartame), or as well called as artificial sweeteners, do have no or very few calories and provide a higher sweetness than sugar and are therefore only in very small quantities needed (ebd.). Among the NNS, stevia was identified as the most studied sweetener, whereas maltitol was identified as the most suitable substitute for baked products (Luo et al., 2019). A natural sweetener which is as well frequently used is fructose, with a higher sweetness intensity than sucrose. However, fructose is controversial due to possible negative health outcomes (Hannou et al., 2018).

In the USA, the children's consumption of NNS largely increased, and it is expected to increase further as the sugar reduction programs with partial or fully substitution continue (Sylvetsky et al., 2012). Negative sensory side effects could be a bitter and metallic aftertaste, what can impact children's acceptance (Li et al., 2014, 2015). It was shown that NNS may also have negative effects on children's health, such as an increased body mass index (Karalexi et al., 2018; Swithers, 2015) or negative impact on the gastro-intestinal environment (Suez et al., 2014). Moreover, the frequent consumption of NNS during pregnancy was further associated with increased body mass index in the offspring (Azad et al., 2016).

2.2.2 Fat ingredient

2.2.2.1 Role of fat in structure and texture in biscuits

Butter, vegetable fats and oils are so called shortenings in the biscuit dough (Arepally et al., 2020). They have specific key processing and machinability, functional and sensory roles. For example, fat is providing shortening, richness and tenderness, mouth feel, lubricity and flavour (O'Sullivan, 2020; Zoulias et al., 2002a,b). An important role of fat is the coating of the particle flour during mixing, what inhibits hydration and hinders the gluten development (Davidson, 2018). Further, fat can as well inhibit the leavening action during baking, what result in a softer and finer texture.

Further, fat impacts biscuits' spread and product appearance and it enhances aeration (air incorporation during dough mixing) and volume (Aggarwal et al., 2016; Maache-Rezzoug et al., 1998). Moreover, it was reported that the type of fat affects the biscuit dough and the final biscuits properties (Mamat & Hill, 2014, Jacob, & Leelavathi, 2007). For example it was shown that cookies made with sunflower oil showed a harder and more resistant dough during mixing, an increased spread, and a harder final texture, compared to cookies made with bakery fat, margarine and hydrogenated fat (Jacob & Leelavathi, 2007). The harder final cookie texture with sunflower oil might be explained by a lower air incorporation during the creaming. When solid fat was added to the sunflower oil, the cookie texture resulted in a softer texture (ebd.). This demonstrated that the ratio of the solid phase to the liquid phase, or the ratio of solid fat to the total fat (solid fat index (SFI)) is an important factor when considering the functionality of the fat/shortening in the dough. Butter and palm oil/fat are often used in the bakery industry due to their high solid fat content at room temperature. Fats and oils with a high saturated fat content should be replaced or substituted with lower saturated contents, whether it be for health or environmental reasons.

The solid fat index (SFI) for biscuits shortenings is ideally 21% at 25°C and at 17% at 30°C (Davidson, 2018). Fat plasticity also modulates air inclusion during creaming (Jacob & Leelavathi, 2007). A mixture of liquid and solid fat at the temperature of mixing is essential to enhance aeration. If the SFI is too high, there is too little oil for air incorporation or coating of the gluten (ebd.).

Decreasing the solid fat content of concrete fat increased the spreading of the dough and may decrease the breaking force (Mamat & Hill, 2014) whereas using only oil fat the breaking force of the cookie is increased (Jacob & Leelavathi, 2007).

In bakery products fat is highly important for textural and structural properties, but as well responsible for many sensory sensations (Atkinson, 2011). Further it was shown that fat is most important when it comes to aroma and flavor perception, as fat contains also non polar flavours (Garvey et al., 2020). Especially the presence and combination of sugar and fat play an important role in flavour development and release (ebd.).

2.2.2.2 Fat reduction strategy

Similar to the sugar reduction, common fat reduction strategies involve using fat substitutes and fat mimetics (Thondre & Clegg, 2019). First, fat substitutes (e.g sucrose fatty acid polyester, medium chain triglyceride, diaglycerol, small particle lipids) are physically and chemically very similar to triglycerides (ebd.). Fat substitutes are able to maintain the palatability, the texture and the mouthfeel of a product. Moreover, fat substitutes are heat stable, but they provide not the same flavor to foods (O'Connor & O'Brien, 2016).

Second, fat mimetics on the other hand (often protein or carbohydrate based) can imitate organoleptic or physical properties of triglycerides, but they cannot be fully replaced, as they have a lack of fats' thermal properties. Fat mimetics (modified starch, maltodextrin, dextrin, polydextrose, cellulose) do have an energy density of 0-4 kcal per g and contain a lot of water and are in general suitable for baking, however more heat sensitive than fat substitutes. As well gums (e.g guar, xanthan, locust bean gum, carrageenan, gum arabic and pectins) are common fat replacers, as they bind with water to form gels which mimic the texture and viscosity of fats (O'Connor & O'Brien, 2016).

Another study showed that it was possible to reduce the fat content in cookie formulation up to 30% with wheat and oat bran based fat replacers in for of gels, while maintaining sensory perception (Milićević et al., 2020). This is an interesting approach, as besides the fat reduction as well a fiber enrichment might be achieved, with potential impacts on satiety and satiation.

None of the currently available fat and sugar replacers can provide all the functional and sensory advantages of conventional fats and sugars. Moreover, possible negative influences from substitutions and additives on sensory perception and health must be taken into account. In addition, more and more, consumers demand safer, healthier and more natural foods without artificial additives (Asioli et al., 2017).

2.2.3 Flour ingredient

Wheat flour is the most used flour in biscuits. It is composed of carbohydrates (mainly starch), protein, fat, fiber, ash and trace elements and vitamins (Davidson, 2018). Biscuit flours usually have a moisture content of about 14%, protein content (N x 5.7) of about 7-9%, and starch content of about 70-75% (Mamat & Hill, 2018).

As mentioned, starch (polysaccharide) composed of many glucose units is the principle component of the wheat flour and it counts for around 80% of the total energy content of the wheat flour (Davidson, 2018). The starch molecules are amylose (~20-30%) and amylopectin (~70-80%), whereas starches physical properties are influenced by the amylose and amylopectin ratio in the starch granule (Kim et al., 2013; Lineback, 1999). Amylose contributes to gel formation by creating a viscous gel. A limited amount of water can be absorbed by starch granules what induces a swelling, although starch is not soluble in water. The starch swelling above temperatures of 60-70 °C makes the swelling irreversible and the gelatinization starts (Davidson, 2018). However, the high sugar (competition for water) and fat content in a cookie dough delays the starch gelatinization and prevents the starch from gelatinization. Therefore, a cookie dough high in sugar and fat has low gel viscosity and results in short and soft cookies.

The protein in wheat flour is mainly gluten, such as gliadin and glutenin (Davidson, 2018). The protein content is responsible for the flour “strength”. A so-called weak flour (low protein content) is used for cookies with low protein content, what results in a soft and tender cookie due to the lower gluten development also hindered by high sugar and fat content (Davidson, 2018). Using different types of wheat flours affects the rheological and baking properties of the dough and the final product (Pedersen et al., 2004). Weak and medium flour (lower protein content) have a protein content of around 7%, whereas the protein content of strong flour (with an increased protein content) is around 10% (Davidson, 2018).

2.2.4 Ingredients in smaller quantities: eggs, baking powder, salt and aroma

Further ingredients in smaller quantities could be eggs, baking powder, salt and aroma and flavours. Egg white proteins in the dough can act as foaming agent, including forming a network of air bubbles what contributes to an aerated structure. Due to the high fat and lecithin content in the egg yolk, eggs act as well as emulsifier and contribute to the flavour and aroma development (Arunepanlop et al., 1996; Garvey et al., 2020; Yang and Baldwin, 1995; Davidson, 2018). In addition, eggs are sources of amino acid for the Maillard reaction.

The role of salt in the biscuit dough is mainly due to process (increasing consistency), preservation and sensory reasons (Ayed et al., 2021). Salt contributes to the crust formation and can act as taste and flavour enhancer (Arepally et al., 2020; Ayed et al., 2021). Moreover, leavening agents such as for example baking powder (a mixture of sodium bicarbonate and an acid) produce leavening gases. Those gases are important for products final textural properties (Arepally et al., 2020). The addition of aroma such as for example vanilla aroma can enhance the taste perception and even contribute to the perceived sweetness (Wang et al., 2018).

2.2.5 Cookies processing

Biscuits are manufactured according to three main processing steps (Davidson, 2018): mixing and forming, baking, and cooling.

First, mixing is one of the critical steps of biscuit making. The objective is to make a cohesive dough that can be sheeted or molded and formed. Gluten should form a minimal network, just sufficient for dough handling and forming (van der Sman & Renzetti, 2019). After the dough is obtained, the method of forming can be different for specific types of cookies: semi-sweet biscuits are usually sheeted, while molding is applied for soft dough biscuits.

Then, after forming, the next step in cookies manufacturing is baking associated with physical transition and chemical reaction. During the baking process, important reactions occur such as water evaporation, protein denaturation, dough deformation, partial starch gelatinization, browning through Maillard and caramelization reactions (Chevallier et al., 2000; Mohsen et al., 2009). All those reactions strongly influence the structure, the texture, the digestibility and the transformation of sensory attributes.

During the baking important thermal reactions and other interactions among the food matrix occur, which strongly contribute to the aroma formation and the final product characteristics (FIGURE 11).

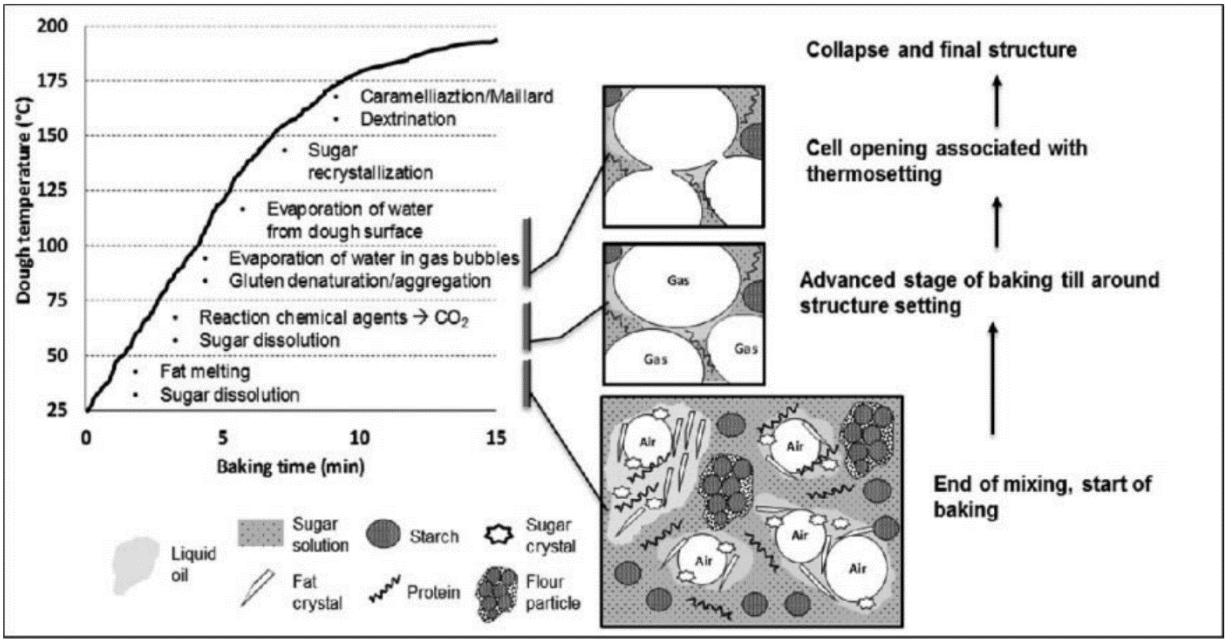


FIGURE 11 : Overview of most important stages of baking in biscuits, including their structure development (Source: van der Sman & Renzetti, 2019).

The Maillard reaction is a non-enzymatic reaction what occurs during heating with the presence of reduced sugars and amino acids (Garvey et al., 2020). The Maillard reaction contributes to the flavour, aroma and the color of the baked product.

Besides the Maillard reaction, as well the caramelization reaction plays an important role when it comes to aroma and color development (Lee & Lee, 1997; Zhang et al., 2012). During the caramelization the sugar decomposition occurs at temperatures above 120°C and is associated with brown color and "caramel" odour.

Cookie formulations, ingredients functionalities and physical-chemical transformation involved in the different steps of biscuit manufacturing play key roles in their structure and sensory properties. Any modification of formulation implies sensory and physicochemical changes in cookies.

2.3 Barriers to food reformulation

As previously described, sugar and fat are the principal ingredients with multifunctional properties in the biscuit dough. The production of bakery products is depending on processing conditions (temperature, moisture, time) and formulation (presence of sugar and fat) (Hough et al., 2001). Consequently, any sugar and fat reduction may lead to technological-, sensory-, liking- and finally economical constraints (FIGURE 12).

Most companies reported as main barrier the fear of a reduced taste and lower product quality (Van Gunst et al., 2018). This due to the replacement of functional ingredients. As a consequence, cost increases due to alternative ingredients or changes in production (Van Gunst et al., 2018). Another problematic is the fact that the food reformulation is often done on a voluntary basis, and that consumers can still switch or prefer the supplier with the enhanced taste induced by a higher sugar and fat content. This can lead to a potentially disadvantaged position for the reformulation company, whereas the non-reformulation company has an advantage (Van Gunst et al., 2018). Improving biscuits nutritional quality impacts biscuits' physicochemical, sensory and liking properties. This will be described in the next sections.

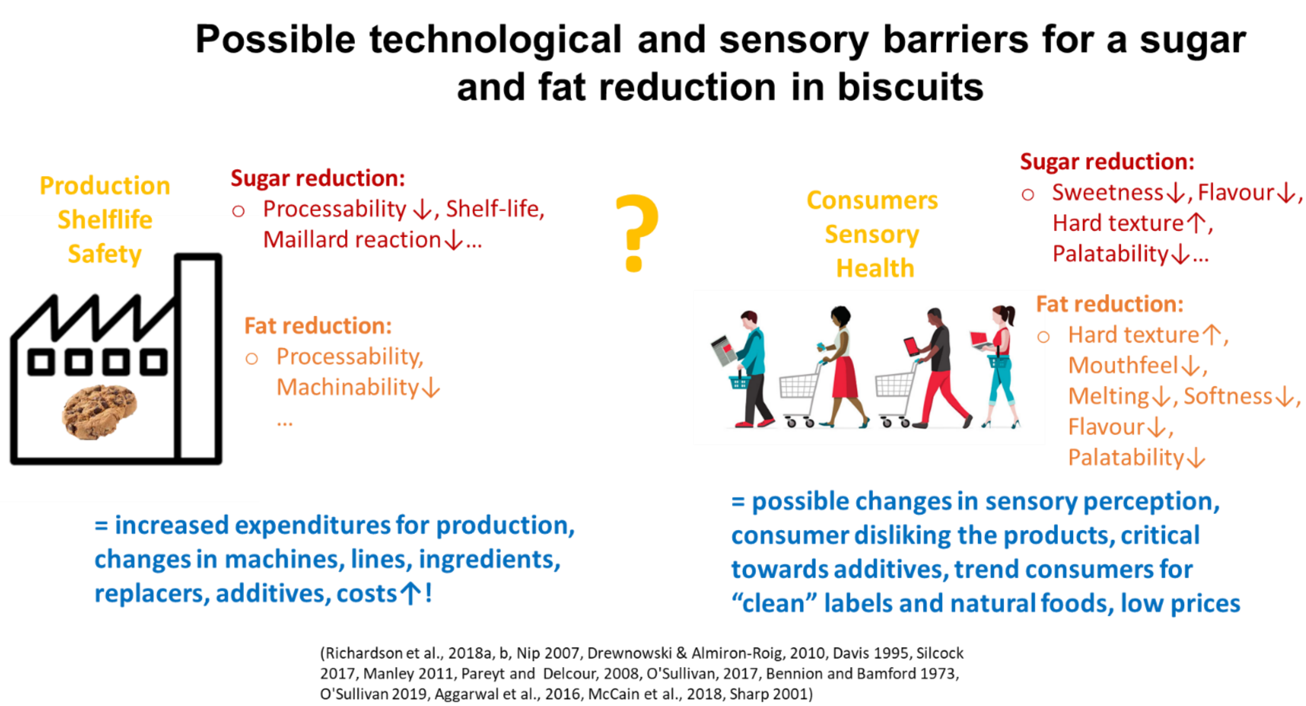


FIGURE 12 : Overview of possible technological and sensory barriers when reducing sugar and fat in the biscuit.

2.3.1 Changes in physicochemical properties as possible barriers

As already mentioned, only few studies were available which investigated “only” the impact of sugar and fat reduction on physicochemical and sensory properties without replacers, substitutes or additives (Luo et al., 2019; Pareyt et al., 2009). Indeed, modifying the proportion of any component in the recipe, will automatically change the ratios of other ingredients.

As shown in FIGURE 13 when investigating the physicochemical properties of different fat levels (8.7-15.8%) among cookies it was shown that decreased in fat level led to increased cracks on the cookie surface. This might be explained by the higher proportion of the sugar in the recipe resulted from the fat reduction. Therefore, the increased sugar recrystallization on the cookie surface during baking can be responsible for the increased cracks (Zoulias et al., 2002b). In addition, it was reported that a fat reduction in biscuits was associated with an increased dough stiffness (Zoulias et al., 2002b).

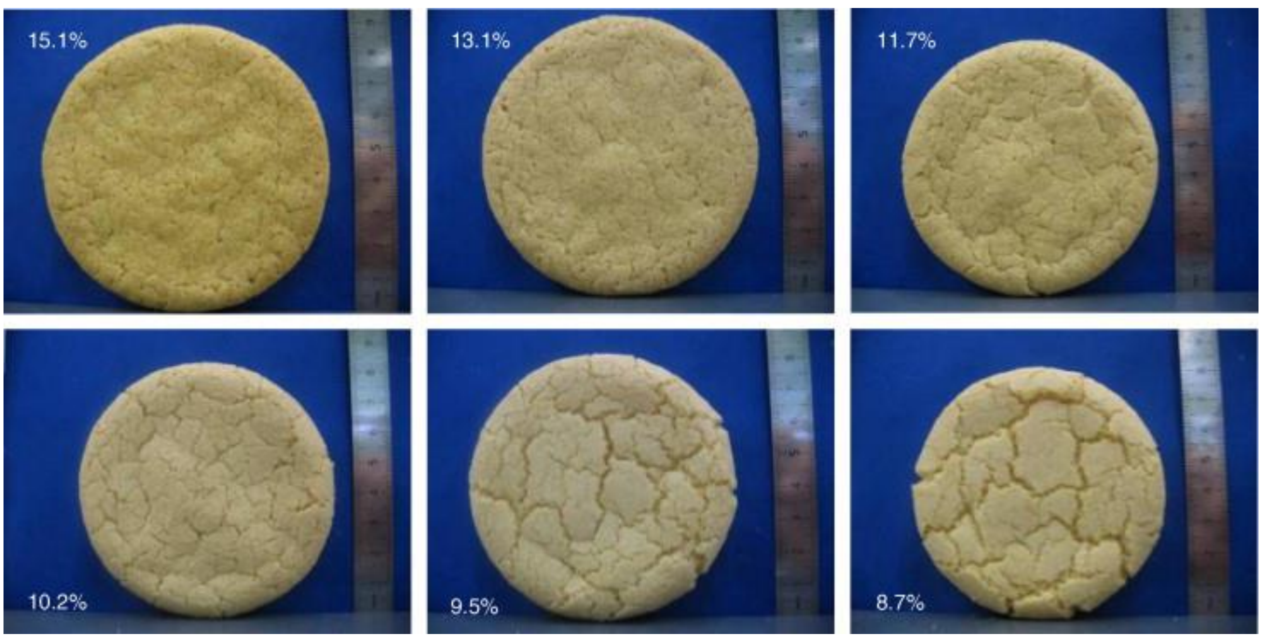


FIGURE 13 : This figure shows cookies with different fat levels and surface cracking pattern, whereas a reduced fat level resulted in more cracks with a lower spread (Source: Pareyt et al., 2009).

Furthermore, the impact of different sugar levels (17.6-31.2%) on cookies physicochemical properties were studied (Pareyt et al., 2009). Overall, a decreased sugar level led to a reduced spread and diameter. In addition, cookies’ breaking strength increased with a higher sugar content.

Same trends were observed elsewhere (Gallagher et al., 2003). The sugar level influenced the porosity, the cell size, the cell wall thickness and the distribution. Therefore, cookies' baked structure is highly affected by the sugar level, whereas the sugar level might impact dough viscosity during baking (Pareyt et al., 2009).

FIGURE 14 highlights the impact of the sugar level on cookies' cracks on the surface. A higher sugar level was associated with increased cracks, whereas a lower sugar level resulted in a smoother surface.

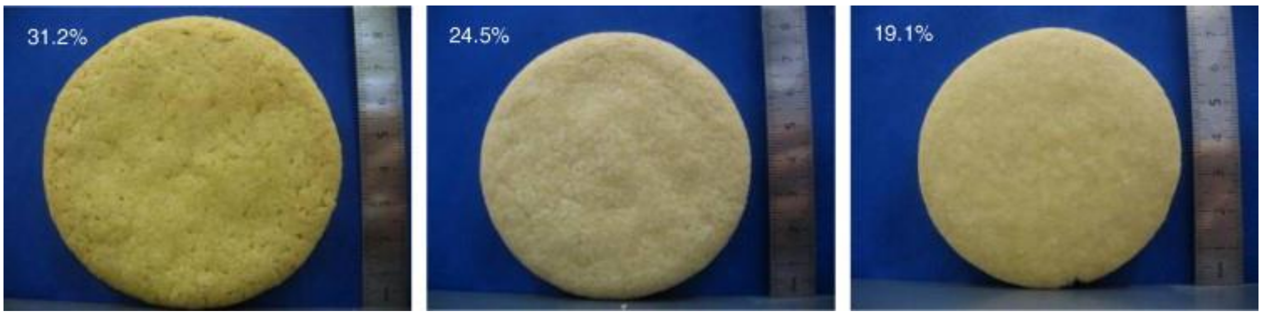


FIGURE 14 : Impact of the sugar level on the cookie surface cracking pattern (Source: Pareyt et al., 2009)

Besides a sugar and fat modification, as well the incorporation of oat fiber influenced the measured texture. The measured texture showed an increased hardness and the cookie color was getting darker, more yellow and red (Majzoobi et al., 2013; Sahin et al., 2021).

2.3.2 Changes in sensory properties as possible barriers

Besides providing sweet taste, sugar has multifunctional properties in the food matrix and any modification might impact the sweet taste and biscuits' structure and texture. Sugar is a driver of preference and any change might have negative consequences on the pleasure experience, liking and consumers loyalty (Marty et al., 2018; Nguyen et al., 2015). A recent study stated that it might be only possible to reduce the sugar content less than 10% among baked products to maintain sensory perception and textural properties (Luo et al., 2019). However, another study found that consumers had difficulties in discriminating several sucrose levels among biscuits with high sugar and fat levels (Holt et al., 2000). This might be promising for future biscuit reformulation. As already mentioned, reducing sugar without replacers or substitutes is challenging, however the use of artificial sweeteners can cause negative sensory response and even health risk.

As different studies have shown, a sucrose reduction in cookies led to a reduced buttery flavour (Laguna et al., 2014). Heenan et al. also found that replacing sugar with isomaltose in bakery products led to lower buttery and caramel flavour perception (Heenan et al., 2010). This flavour loss was explained by the interaction of sugar and the thermal process during the baking. A sugar reduction lead to a lower availability of monosaccharides for the Maillard and caramelization reaction.

Fat reduction in cookies was associated with a less crispy, crumbly and with decreased brittle texture, what results in a chewier biscuit (Zoulias et al., 2002b). This was confirmed elsewhere, where biscuits with a lower fat content were perceived as harder than those with a higher fat level (Laguna et al., 2014). Besides the level of fat, as well the type of fat affects the sensory perception. It was shown that a butter replacement with inulin and olive oil led to a decreased caramel and butter odour, a lower butter flavour and a lower perceived sweetness (Giarnetti et al., 2015).

According to Biguzzi et al., who compared the impacts of sugar and fat reduction on sensory perception of commercial biscuits, fat reduction might be more feasible and to a higher extent than a sugar reduction (Biguzzi et al., 2014, 2015). However, caution is advised when reducing the fat content, as a fat reduction might still induce a reduction of the sweet taste (Biguzzi et al., 2014). On the other hand, a sugar reduction caused only weak effect on the fat perception in the biscuits (Biguzzi et al., 2014).

Addition of fiber into the biscuit dough also leads to sensory changes. A fiber addition into the biscuit dough led to changes in crispness (Singh et al., 2015). Moreover, an increased fiber content was associated with a harder perceived texture (Priyanka et al., 2019).

As already mentioned, sensory and physicochemical analyses are crucial to guide the reformulation process and to have a better understanding of products' characteristics.

Changes in sensory perception and physicochemical properties are potential barriers to reformulation, with the risk of inducing disliking and losing customers. Therefore, sensory and physicochemical measures are crucial to reformulation in order to anticipate possible hindrances and find optimal pathways for reformulation.

2.3.3 Possible consequences on liking

As sugar and fat are drivers of liking, any change of food properties and sensory perception as a result of reformulation can induce a possible disliking (Marty et al., 2018; Nguyen et al., 2015).

2.3.3.1 Impact on liking

It was reported that hedonic ratings are usually lower for sweet bakery products when fat was reduced or replaced (Psimouli & Oreopoulou, 2013; Rodriguez-Garcia et al., 2014; Singh & Kumar, 2018). The acceptability for the perceived aroma and flavor was lower. Lower liking scores were also observed for sugar reduced sweet bakery products, (Cavalcante & Silva, 2015; Karp et al., 2016; Zahn et al., 2010).

Children tend to have preferences for fatty and sweet foods (Albataineh et al., 2019; Ambrosini et al., 2015; Marty et al., 2018; Moore & Fielding, 2016; Nguyen et al., 2015; van Buul et al., 2014). Therefore, fat and sugar reduction in cookie dough are expected to have a strong negative impact on children's hedonic ratings (Biguzzi et al., 2015).

Changes in food texture due to formulation changes also affect children's acceptance and preferences (Laureati et al., 2019; Schwartz et al., 2021). Foods rich in fiber can result in texture disliked by children, because they have difficulties to orally manipulate them, although fiber is important for a healthy diet and can help to prevent overweight in children (Hörmann-Wallner et al., 2021).

Nevertheless, maintaining children's level of liking for reformulated product is possible, as shown by recent studies that aimed at reducing the sugar content in various product categories (Lima et al., 2019; Reed et al., 2019; Velázquez et al., 2020a,b). For products with a high sugar level it might even be possible to dramatically reduce the sugar (up to 40%) content without affecting the liking (Velazquez Mendoza et al., 2021a,b). However, most of the successful reformulation studies were conducted on food and drinks with a lower food matrix complexity (such as sweetened beverages and dairy products) (Velazquez Mendoza et al., 2021a,b). More research is needed on complex food matrices such as bakery products, where sugar and fat do have multifunctional properties, including textural and structural functions (Sahin et al., 2019; Struck et al., 2014). Further, different food preferences among individuals have been reported and must be therefore integrated in the reformulation process (Laureati et al., 2019; Drewnowski, 1993; El-Sohemy et al., 2007). Variations in food preferences might be as well a chance for industries to apply different reformulation strategies on target consumers.

2.3.3.2 Impact on children behavior

Food liking and familiarity with foods are strong drivers of food intake in children (Bergamaschi et al., 2016). In particular, food texture are key determinants of food intake, and can impact individual oral processing skills and behavior during a meal.

As mentioned in the literature, texture perception of children are dependent on their age, and relates to the development of mouth muscles, jaw and teeth (Lukasewycz & Mennella, 2012; Rose et al., 2004a, 2004b; A. S. Szczesniak, 1972; Zeinstra et al., 2010). Those factors may indeed affect children's' chewing capacity and could thus be important indicators of whether children do like or dislike a certain food texture (Narain, 2005). Indeed, the masticatory function changes throughout childhood. The final development of the dentition and the transition to adult-type mastication takes place between 10 and 14 years of age (Almotairy et al., 2018).

The effect of food texture on satiety has only been little studied in children. Contrary to observations in adults, one study showed that the texture of an apple offered at the beginning of a meal had no impact on the amount of total calories consumed during a snack (Schwartz et al., 2021), but some links between chewing abilities and speed of ingestion have been demonstrated, showing the role of food texture on the oral processing and the consequences on satiety in children.

For example, overweight children were reported to have a 'fast eater' profile (Fogel et al., 2017, 2018). Further it was reported that children aged 4.5-year-old described as 'fast eaters' took larger bites of food, had low level of chewing and finally consumed more energy than children characterized as 'slow eaters' (ebd.). Therefore, a possible way to fight against obesity is to reduce the portion size of food eaten and to play on the speed of consumption, which is largely impacted by food texture (Forde et al., 2013).

Besides, it should also be noted that some children may be very sensitive to certain textures which can affect their neophobia (Coulthard & Blissett, 2009).

Thus, a supplementary challenge is observed for reformulation, when a focus is proposed on a targeted population as children. Methodologies and constraints of development must be adapted.

2.4 Innovative food reformulation approaches as a leverage to reduce children's obesogenic environment

In order to maintain sensory perception and the important functionality of single ingredients in the food matrix, it is possible to play on food structure and texture properties. For example, a sugar reduction while maintaining food sweetness might be achieved by: 2.4.1) Multimodal interactions, playing on sensory interaction between odour and taste, as using vanilla aroma with the principle of the congruency model

(Velázquez et al., 2021a; Wang et al., 2019), 2.4.2) Oral processing impacts texture and structure of food, introducing heterogeneity to food structure and thus modifying food oral processing (Stieger & van de Velde, 2013) or 2.4.3) Modifying granulometry and properties of ingredients (Richardson et al., 2018; Tyuftin et al., 2021). Texture is an important driver of preference and therefore a relevant lever to make a product more desirable among consumers (Brown & Braxton, 2000; Jeltema et al., 2015). Besides, food texture may have positive effects on eating behavior and kcal intake (Chambers et al., 2014; de Graaf, 2012; Hogenkamp & Schiöth, 2013; Stribiţcaia et al., 2020).

2.4.1 Multimodal interactions

First, in the case of food flavor, the multimodal integration of chemosensory cues can induce crossmodal perceptual interactions. For example, the perception of a tastant may affect the perceived intensity of an odorant, and vice versa (Delwiche, 2004). A series of studies showed that some odors can modulate the intensity of particular tastes and that these odor-induced changes in taste perception are both odor and taste specific (Clark & Lawless, 1994; Frank, 2003; Frank & Byram, 1988; Schifferstein & Verlegh, 1996; Stevenson et al., 1999). As an example, the strawberry aroma enhanced the sweetness of the sweet whipped cream, whereas the peanut butter aroma did not (Frank & Byram, 1988). Recent studies investigated the possibility to reduce the sugar content in milk desserts with a cross modal interaction between vanilla aroma and starch, while maintaining sensory perception and liking (Alcaire et al., 2017; Velázquez et al., 2020). It was shown that addition of vanilla aroma increased both the sweet taste and the vanilla flavor (Alcaire et al., 2017). With this cross modal interaction it was possible to reduce the sugar content up to 40% in milk desserts, while maintaining children's liking (Velázquez et al., 2020).

2.4.2 Oral processing impacts texture and structure of food

Besides the question about what consumers eat, it is also important to consider "how" they eat their products (Bolhuis & Forde, 2020). Manipulating food's structure can help to make a biscuit healthier, by increasing the food oral processing, satiation and satiety and reducing its glycemic index (Anttila et al., 2004; Bolhuis et al., 2014; Daou & Zhang, 2012; Jia et al., 2020; Roberts, 2003).

Highly processed foods contribute to the obesogenic environment with their low texture properties, highly palatable and weak satiation and satiety effects (Forde, Mars, & de Graaf, 2020; Hall et al., 2019).

The so called “obesogenic eating style” was therefore characterized with a reduced oral processing time induced by a larger bite size etc., where the texture was identified as most important factor influencing the food oral processing (Fogel et al., 2017, 2018). Besides nutrients modification trough food reformulation, the literature also shows that it is possible to reduce the total energy intake by enhancing the satiation and satiety thanks to changes in texture and the oral process (Fogel et al., 2017; Forde et al., 2013; Krop et al., 2018; Quah et al., 2019). In particular, it was shown that texture modification might be successful to decrease the ‘obesogenic’ eating style among children, which is associated with faster eating rates. This was achieved through larger bites, reduced chewing and shorter oral exposure time (Fogel et al., 2017).

FIGURE 15 presents an overview from the literature about possible reformulation levers related to foods’ texture, structure and properties with impact on food oral processing, satiation and satiety and weight management. For example, when increasing foods’ viscosity (for example with fibers), this might lead to a longer food oral processing time, due to a smaller bite size, a higher number of bites, chews and swallows. At the same time, this can impact hormones which are responsible for the hunger perception. When the food stays longer in mouth, exposition to stimuli is further increased, which can decline the level of hunger. More viscous textures can induce a lower eating rate and a better satiation and satiety, which might affect the energy intake and help weight management. Furthermore, foods with a lower glycemic index may inhibit the rise of blood glucose and insulin response after consumption, which impacts the perceived hunger level. Based on FIGURE 15 it is therefore clear that foods’ texture plays an important role in the whole food oral processing, including hormone responses and energy intake which may largely impact consumers’ behavior and their eating habits.

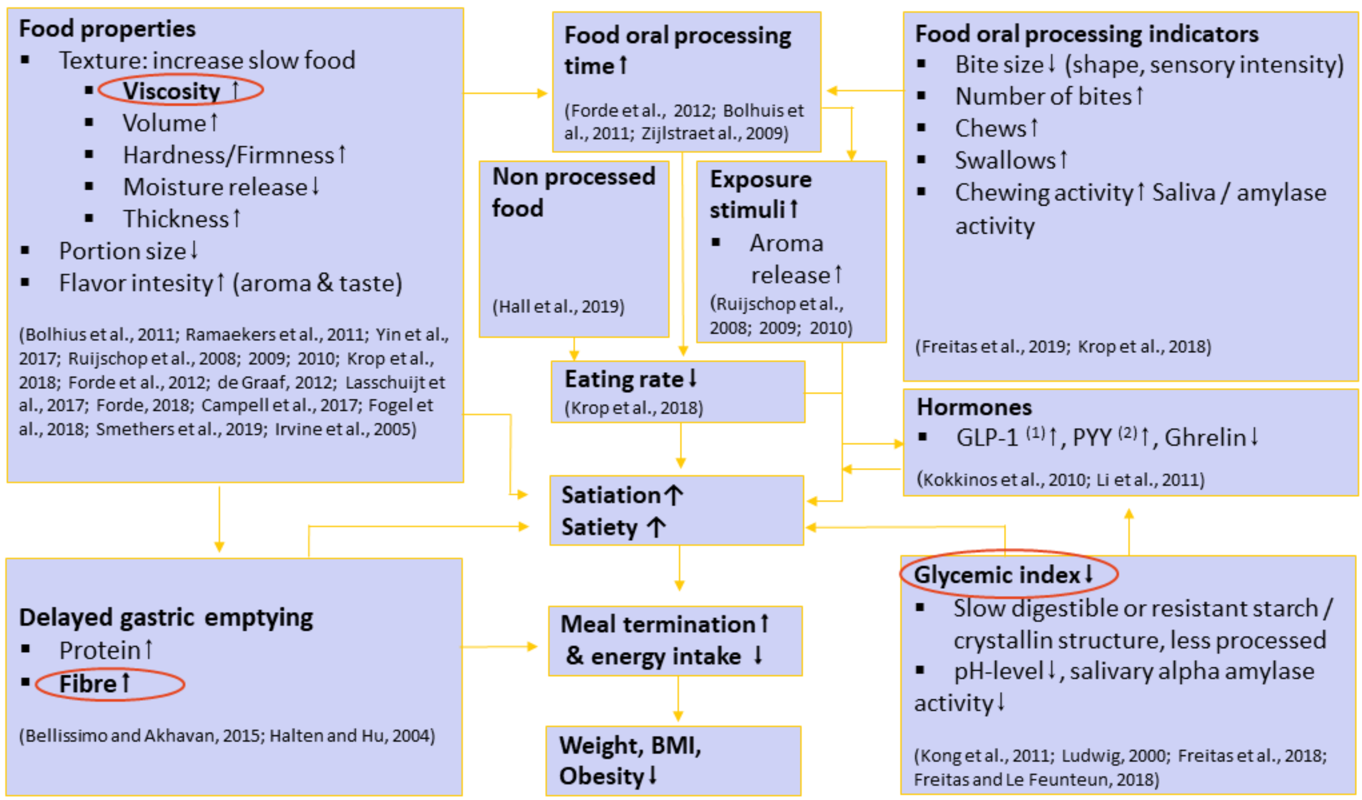
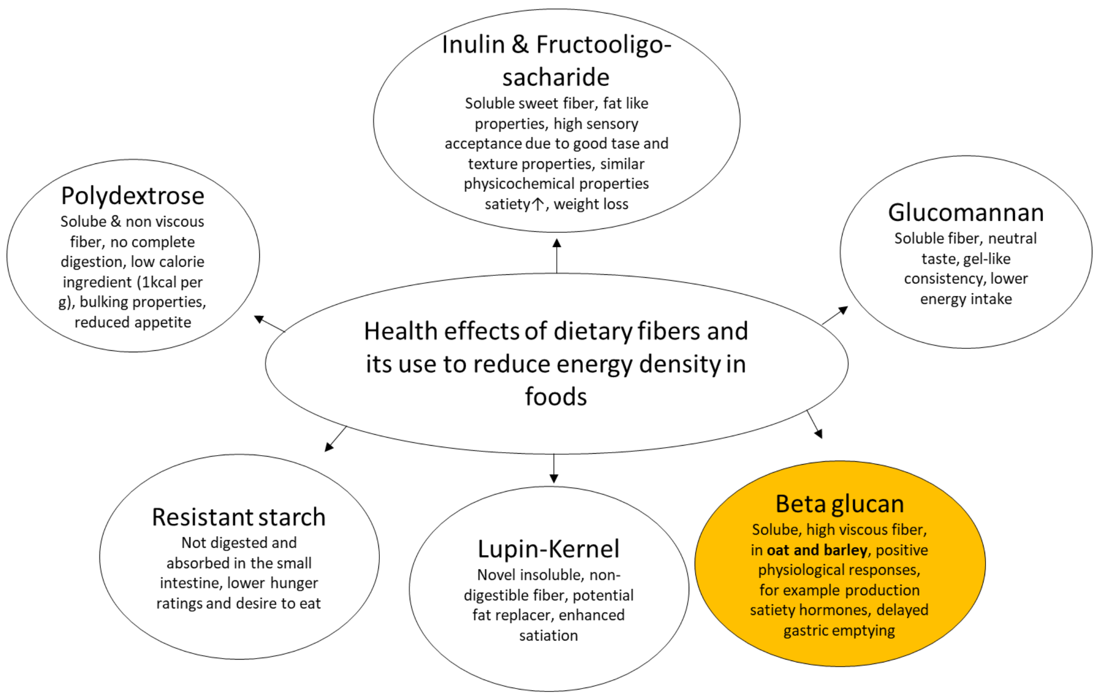


FIGURE 15 : Texture and food property reformulation levers to impact food oral processing, satiation and satiety, energy intake and weight management.

As, shown in FIGURE 15, fibers, or cereals rich in fibers, have positive effects on gastric emptying and may therefore impact the satiation and satiety. However, fibers positive effects on health goes beyond this sole mechanical effect (FIGURE 16 and FIGURE 17). In food reformulation, fibers can act as fat replacers while maintaining texture and mouthfeel (Conforti et al., 1997; Lee & Inglett, 2006; Milićević et al., 2020; Thondre & Clegg, 2019; Zoulias et al., 2000a,b). Besides that, fibers can increase foods' viscosity and therefore increase food oral processing, with impact on satiation and satiety (Pentikäinen et al., 2014; Priyanka et al., 2019, Erinc et al., 2018; Thondre & Clegg, 2019). Food high in fiber demonstrated a longer oral processing time compared to low fiber food and was therefore associated to higher satiety (Zijlstra et al., 2008) and also a positive effect on health and weight management. Furthermore, the incorporation of fiber rich cereals to foods might contribute to lower the predicted glycemic index (Jia et al., 2020). Moreover, fibers might inhibit the increase in humans blood glucose level and can reduce the insulin response, which positively affects satiety (Anttila et al., 2004; Daou & Zhang, 2012; Roberts, 2003).

Unfortunately, the fiber content of many packed foods is reportedly too low (Bonsmann et al., 2019). However, it was shown that there is a large potential to increase the fiber content of cereal products targeting on children, while maintaining their liking (Herbreteau et al., 2019). That study showed that it was possible to increase the fiber content with micronized wheat bran and inulin up to +30%, respectively up to 67% while maintaining children's acceptance (ebd.). This highlights the potential to increase the fiber content among packed foods targeting on children, while without losing their liking.



(Source: Ibarra et al., 2016; Higgins 2014; Liber and Szajewska 2013; Au-Yeung et al., 2018; Clegg and Thondre 2014, do Carmo et al., 2016; Laguna et al., 2013; Morais et al., 2014; Rebello et al., 2016; Vitaglione et al., 2010; Archer et al., 2004)

FIGURE 16 : Overview from the literature for different dietary fiber sources and their impact on health.

Beta glucan is a very interesting fiber. It is a viscous, water soluble polysaccharide consisting of glucose units and is found in the endosperm (Jane et al., 2019). B-glucan is therefore a functional ingredient with several potential health benefits. Those benefits might be explained by its physicochemical properties such as the viscosity and the molecular weight (Ahmad et al., 2012; Daou & Zhang, 2012). Beta glucan enriched biscuits have been shown to lead to an increased satiety and fullness ratings (Vitaglione et al., 2010); Pentikäinen et al., 2014).

Moreover, use of beta glucan might lead to an increased bolus viscosity (increase in oral process), a delayed gastric emptying (increase in satiation and satiety) and a limitation of the starch hydrolysis (decrease in glycemic index, increase in satiety and satiation) (FIGURE 17).

Likewise, soluble oat fiber can delay blood postprandial glycemic and insulinemic responses, with positive impact on hunger feelings and kcal intake (Anttila et al., 2004; Daou & Zhang, 2012; Roberts, 2003). A key role thereby plays the physicochemical properties of beta glucan with an increased viscosity, what lead to a delayed absorption of glucose in the intestine (Anttila et al., 2004). Furthermore, beta-glucans' viscosity in foods and in the food digest depends on solubility, concentration and molecular weight.

Oat bran- a by-product of oat grain processing - is a natural, commercial available ingredient which is rich in fiber and contains beta glucan. Based on different varieties and cultivation conditions, the composition of oat bran vary with 15-18% protein, 10-15% starch and sugars, 5-10% fat, 10-40% dietary fibers and 5-20% β-glucan (Dhinda et al., 2011; Sontag-Strohm et al., 2008). Oat bran is characterized with a half to two times higher soluble fiber content compared to whole oats, whereas β-glucan is the main component of the soluble fiber.

Recent studies showed, that it was possible to incorporate around 10% of oat bran or oat fiber into biscuits, while maintaining its sensory and physicochemical properties (Parvez, 2015; Sandhu et al., 2018). Another study highlighted it was possible to incorporate oat bran into biscuits up to 15% while maintain sensory perception (Majzoobi et al., 2013).

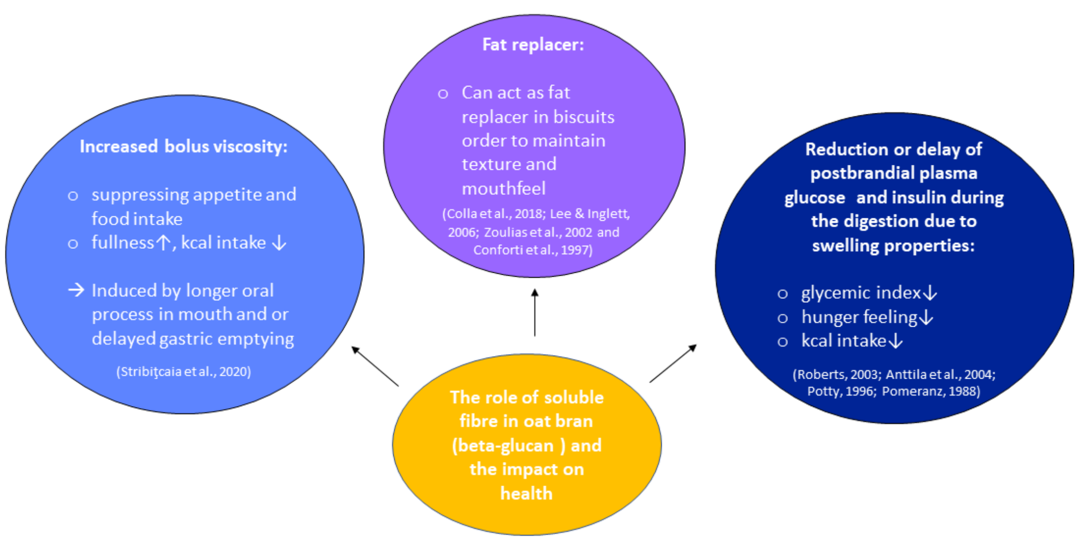


FIGURE 17 : Overview from the literature about the possible health aspects of beta glucan.

2.4.3 Modifying granulometry and properties of ingredients

As previous mentioned, the manipulation of sugar particle size impacts biscuits texture. For example, when reducing the sugar particle size, it was shown that the biscuit became harder (Boz, 2019). This on the other hand might be an opportunity to increase the food oral processing time, as harder textures were associated with a longer oral processing time (Bolhuis et al., 2014) (FIGURE 15). Besides the impact of the sugar particles size on the texture, the particle size can as well impact the perceived sweetness. Smaller sugar particle size increased the perception sweet taste intensity by adult consumers (Richardson et al., 2018). Besides the improved perceived sweetness, as well brownies' softness and moistness were improved. The impact of the sugar particle size on liking were also obtained for shortbread biscuits (Tyuftin et al., 2021). This study showed that mixing control sugar (102-378 µm) with medium particle size sugar (228-377 µm) was preferred to the control sugar or the finer particle size sugar (124 to 179 µm) for shortbread biscuits.

Innovative solutions can be proposed to reduce the sugar and the fat content among foods. It was possible to play on food reformulation beyond manipulating macronutrients, with impact on humans' food oral processing parameters with improved foods' textures. However, the reformulation success among certain mentioned foods might be only valid for the specific food category. Therefore, those strategies must be tested on other food categories, including foods with more complex textures. To achieve this, an in-depth understanding of the food matrix and ingredients' interactions are highly important. Including besides composition as well sensory, physicochemical and liking information in the reformulation process is therefore crucial.

2.4.4 Analyses and statistical tools necessary for a sensory-led multicriteria reformulation approach

2.4.4.1 Sensory and physicochemical characterization

Food reformulation is a multidimensional approach with interactions among ingredients in a food matrix. Therefore, food reformulation can impact food's structure, texture, sensory perception and liking. To anticipate those interactions and to limit barriers of reformulation, an in depth know how of products properties are needed.

To obtain thus a holistic view of products characteristics, pertinent approaches are based on different analyses, such as sensory and physicochemical measures, and adapted to each food category. Sensory measures are an essential tool, as they are most close to consumer's perception of the final product. Sensory analysis involves the discrimination and description of food products (Meilgaard et al., 2016; Murray et al., 2001). In particular, sensory quantitative descriptive analysis is a referent method, to describe and quantify the sensory properties a specific product category (Lawless & Heymann, 2010; Stone et al., 1974). By using sensory methods, it is possible to pinpoint differences among products or conditions, to identify drivers of consumer hedonic responses, and to examine relationships between sensory and chemical characteristics (Tuorila & Monteleone, 2009; Venturi et al., 2016). In addition, they have a multidimensional character, as sensory analyses take into account several dimensions of the product, unlike instrumental measurements which often measure only one dimension of the product. However, sensory analysis requires to constitute a panel of consumers/experts and it may take several weeks or months.

Physicochemical measures are more accessible and realizable in shorter time and they can help to anticipate sensory responses as well. Further, they can provide important nutrition (for example in vitro starch hydrolysis) or texture information (for example viscosity) which are relevant for food oral processing. Furthermore, physicochemical measures can help to anticipate sensory response (Gilbert et al., 2013). But depending on the food matrix and analysis selected, enough time must be spent to validate the specific protocol, including the measures in triplicates. Furthermore, conducting sensory and physicochemical measures at the same time may be a useful approach to check if the obtained results followed the same trend.

2.4.4.2 Preference mapping: linking preferences of consumers with products properties

Preference mapping was introduced by Carroll in 1972. It is a tool to link the sensory attributes but as well physicochemical and composition product characteristics to the preferences of consumers.

Often a PCA (Principal Component Analysis) is performed on the sensory descriptors of interest or a MFA (Multiple Factor Analysis) is performed on the sensory, physicochemical and composition variables. The first two factorial axes are often chosen as they best represent the information. Preference mapping consists of a linear regression of the ratings on the main components (generally the first two components) and the ratings on the second component (the second component). The result is a model linking the combinations of sensory descriptors/physicochemical/composition parameters and consumer ratings of the consumers.

In a second step, all the models obtained for each consumer are discretized in order to define individual preference zones and then aggregated in order to obtain a surface of responses for all consumers. A gradient from 'warm' to 'cool' colors allows a quick reading of areas of high and low consumer preferences.

2.4.4.3 Experimental design, multicriteria modeling and optimization

Applying an experimental design within the frame of a multicriteria reformulation approach is a promising approach, as this allows to study different recipe variations taking into account the interactions between ingredients and product properties and limiting the number of tests performed (Chanlot, 2004). Further, experimental design is a method of experimentation that allows several factors to be varied at the same time, in order to achieve the set goals. This makes it possible, among other things, to finding the optimal recipes, studying a greater number of factors and identifying most influential factors, and optimizing the models and the results (goals). Via sensory engineering (Moskowitz, 2000) and modeling, it will be possible to optimize recipes while improving key sensory properties (perceived intensities evaluated from the quantitative descriptive analysis) and relevant nutrition or physicochemical parameters (Mao, 2007). A possible sensory engineering goal is for example to optimize a recipe towards a healthier product (reducing sugar, fat etc.) while matching a consumer profile, which is determined by sensory attributes and liking information.

When it comes to formulation or reformulation of foods, mixture designs are of relevance (Abdullah & Cheng, 2001; Delgado-Pando et al., 2019; Los et al., 2020). The particularity of the mixture plan is that the factors are dependent on each other and that is possible to set constraints for ingredients/mixture. Indeed, the factors of study are the proportions of the components of the mixture. The content of each component is between 0 and 100%, and the sum of the proportions is always equal to 100%. Thus, the variation of the proportion of an ingredient will necessarily imply the variation of the proportion of another ingredient of the proportion of another ingredient at least (Goupty, 2001).

When the number of criteria and factors increases, it is necessary to use multicriteria approaches. This type of approach allows a large number of factors to be taken into account, such as ingredients, interactions between ingredients, process parameters, etc. and to look at their influence on several criteria such as physicochemical and sensory parameters for example.

The more criteria and factors there are, the more difficult it will be to find the ideal combination of factors to meet expectations. Acceptable zones for the criteria must be determined in order to find the best compromise zone. In this zone, the desirability function can be introduced. It first transforms each response into an individual desirability function, ranging from 0 to 1. If the predicted value is unacceptable then di = 0. If the value is at its optimum level, then di = 1. This function is flexible because it allows the experimenter to define how desirability degrades as the value moves away from the target. Then the total desirability, D, is constructed by calculating the geometric mean of the individual desirabilities (Mao, 2007).

Thus, a real challenge exists to choose the most relevant methods and data processing to achieve a reformulation based on multiple constraints.

2.5 Key points of the state of the art and outlook for the considered strategy for this PhD

This literature review underlined the urgent need for innovative solutions in order to manage and prevent childhood obesity. One important causing factor for the ongoing childhood epidemic is the shift in the diet towards highly processed foods, which are often energy dense from sugar and fat. One of the causes for the high intake of sugar and fat is the fact that packed foods are not suitable for children's' diet, due to a high sugar and fat content. Data from different European regions show that the product category "biscuits and cakes" largely contributes to children's daily kcal intake. Within this product category, cookies have a particularly high energy density from sugar and fat. Within this context, cookies were select as product of interest for this PhD.

One of the possible leverages to improve children's diet is to improve the food offer. The so-called food reformulation – aiming at the reduction of overconsumed nutrients sugar, fat and salt – is a pertinent approach to improve the quality of the food offer without largely changing consumers' behaviour. However, food reformulation of bakery products is challenging because of the multifunctional roles of sugar and fat in the biscuit dough and their impact on processability, structure, sensory perception and liking. Many food reformulation approaches in the past focused on sugar and fat reduction with replacers and substitutes.

However, non-nutritive sweeteners are controversial because of their potentially negative health consequences. Consumers thus increasingly demand more natural, “clean label” foods. Understanding specific ingredients properties and foods’ texture can help to improve nutritional and sensory quality. Thereby, trying to reduce the obesogenic environment, increasing the food oral processing time induced by foods’ texture (oat fiber) is a further interesting reformulation leverage. The physicochemical properties of beta glucan are especially interesting. Beta glucan can indeed be used to increase the measured viscosity of the biscuit, with a positive impact on food oral processing, satiety and glycemic index.

However, as described, any sugar and reduction or fiber incorporation might have consequences on processing, structure, sensory perception, physicochemical and liking properties of the biscuits.

The question is how it is possible to overcome all these multiple constrains while improving the nutritional and sensory quality? (FIGURE 18). To address this challenge, an innovative reformulation approach based on multiple criteria is proposed in order to taken into account all these mentioned barriers. This approach might help to reinforce voluntary food reformulation and to identify new efficient pathways for successful reformulation among commercial products in order to improve the food offer and children’s diet.

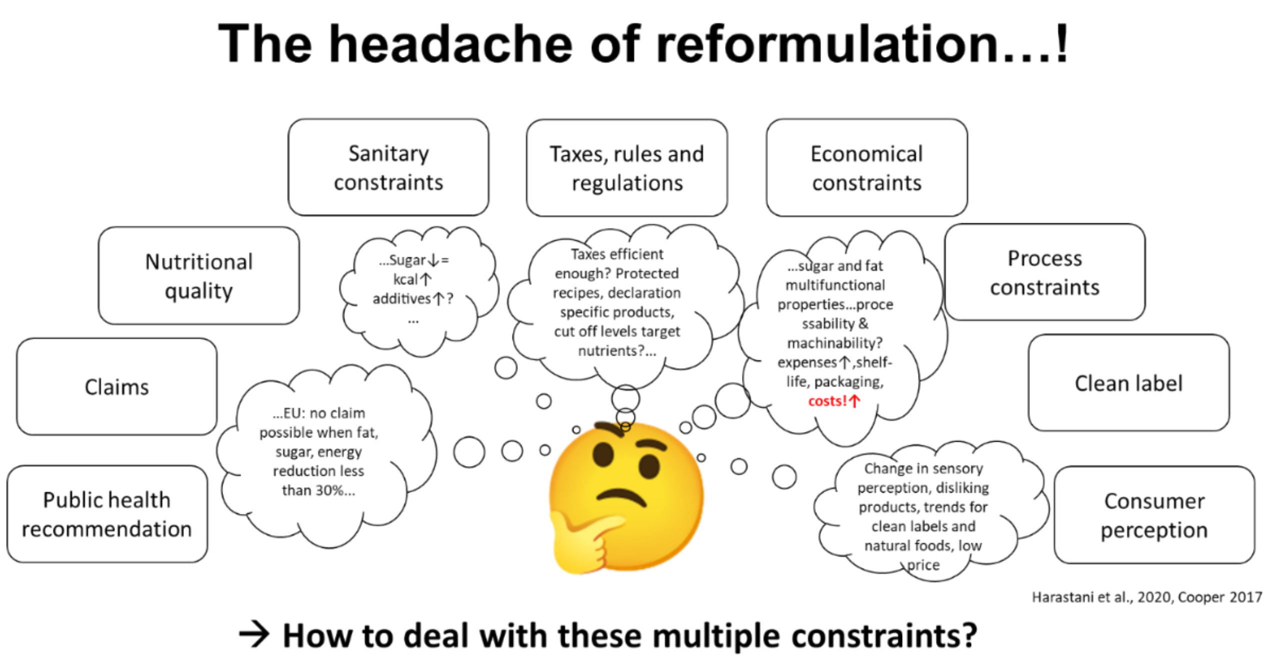


FIGURE 18 : Multiple constraints for food reformulation.

3.Chapter 3

Context

Research Questions

Overall Strategy

3 Chapter : Context, Research Questions, Overall Strategy

3.1 Context and the European STOP project

Since 1975, the global childhood obesity rate increased tenfold (NCD Risk Factor Collaboration NCD-RisC), 2017). Especially affected are school aged children (FAO, 2019). Among 35 European countries or regions, around 27.3% are suffering from overweight while 10.5% are affected from obesity (WHO, 2018). Besides the serious negative physical and psychological health outcomes, childhood obesity also has social and economic implications, which will obviously affect children's future (Sassi et al., 2016; Segal et al., 2020.). In order to tackle the childhood obesity pandemic in Europe, the project "Science and Technology in Childhood Obesity Policy" was launched in 2018, with a duration of four years. This PhD work is a part of a project that has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 774548. STOP aims at first to better understand the contributing factors of the spread of childhood obesity with scientific, novel and policy relevant evidence (STOP, 2017). Second, the goal is to provide technological and organizational based solutions with policy options to address the childhood obesity problem. Within this project, 31 organizations from the health and food sectors from 16 European countries are involved (FIGURE 19 A).

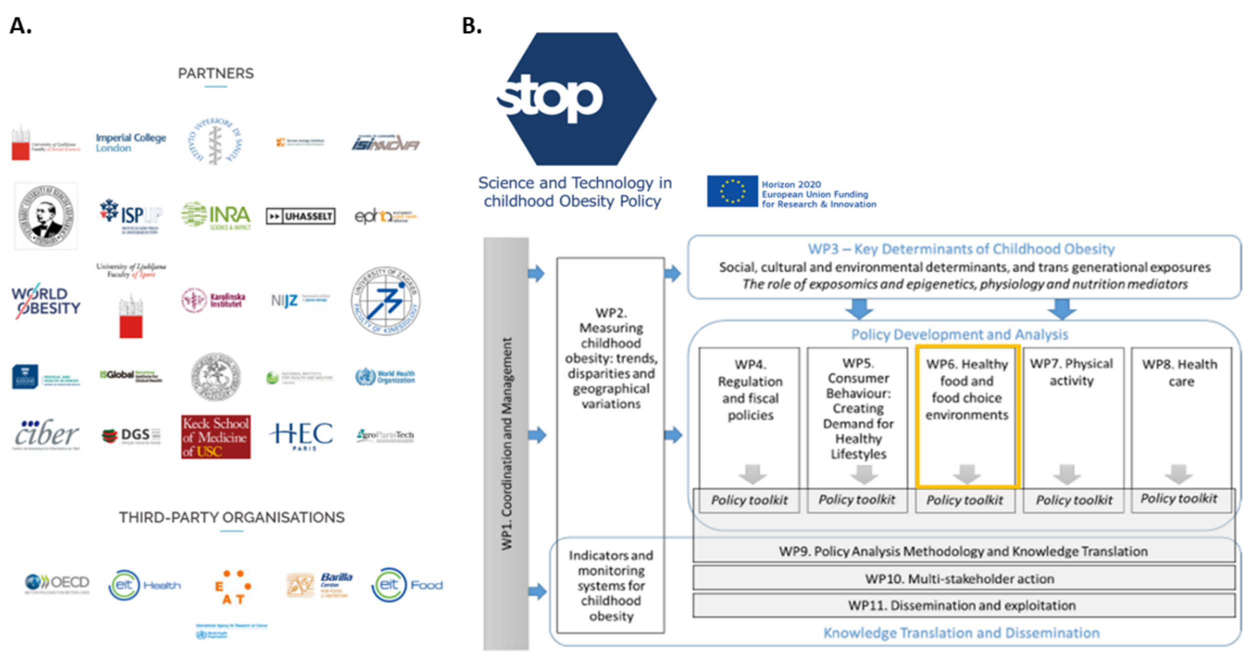


FIGURE 19: Overview of the European STOP project which aims to manage and to reduce the childhood obesity. This project was financed from EU Horizon 2020. A: All partners involved. B: The STOP structure with total 11 work packages (WP), whereas this PhD contributed to WP6, Healthy food and food choice environment.

Actors from the food sectors, scientists, health professionals, government policy makers, national health agencies, international organizations, civil society and business organizations are represented. The STOP project follows an integrated approach by including total 11 work packages (WP) from different fields (FIGURE 19 B). This PhD contributed to the WP6, as yellow highlighted. The WP6 consists of four main objectives such as reducing the use of ingredients that may promote obesity, increasing the use of healthy ingredients, reducing the overall kcal content and changing food properties to make healthy food more attractive for children (STOP, 2017).

3.2 Research questions

In this context, this PhD aims to investigate the levers to improve the nutritional quality of the food offer for commercial products while improving or maintaining their key sensory properties and the liking. As mentioned previously, biscuits and in particular cookies are very energy dense with a high sugar and fat content, consumed in high quantities and overall liked among children. Therefore, cookies are is the target product category in our study.

Further, this work aims to understand the impact of the reformulated products on health relevant indicators, such as the biscuits' predicted glycemic index and the self-reported hunger level for children aged 10-13 years old. For that, we hypothesize that products' composition, structure and texture may impact childrens' drivers of preferences, the self-reported satiety and food oral processing among adults (time in mouth before swallowing).

Therefore, three principal hypotheses (H) with five research questions (RQ) can be derived:

<u>H1:</u> With focus on the food offer, an in-depth understanding of a whole product category would provide more information about the products composition, sensory and liking and increase the chances of success for reformulation.

- **RQ1.1:** It is possible to identify reformulation paths by studying the diversity of a commercial food product category?
- **RQ1.2:** Is it possible to select a subset of commercial products representative of the diversity of the product category
- **RQ1.3**: Is it possible to derive reformulation opportunities and to investigate the frame in which is possible to reformulate while maintaining the liking on the select subset?

H2: A multicriteria approach using the product category as a starting point will help to better understand ingredients' interactions in the food matrix and optimizations possibilities for recipes, sensory attributes, nutrition and physicochemical parameters based on different consumer profiles and preferences.

- **RQ2:** Is it possible to adopt a sensory led-strategy including multiple criteria to answer this reformulation challenge?

H3: Cookies' composition, structure/texture and oral processing behavior impact perception, satiety and predicted glycemic index.

- **RQ3.1:** Is it possible to reformulate a healthier cookies while maintaining children's liking?
- **RQ3.2:** Does the reformulation drive a lower predicted glycemic index and allow increase satiety?
- **RQ3.3:** Does the reformulation strategy allow to change the oral processing?

3.3 Overall strategy

To answer to these scientific objectives, FIGURE 20 summarizes the overall approach used for the PhD, from step 1 (literature review, selection product category & market inventory) to the final step 5 (validation and impact of formulated cookies on health relevant indicators).

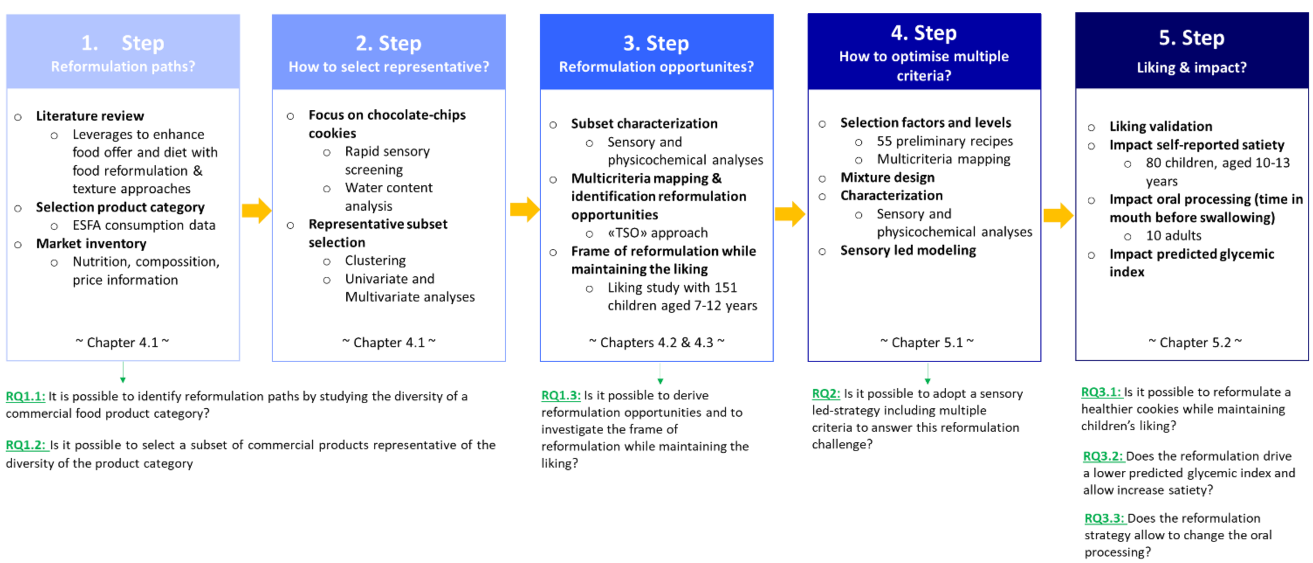


FIGURE 20: Overview of the global strategy of this PhD with RQ (research questions) 1.1-3, containing five steps.

The first step consists of a literature review about possible leverages to enhance the food offer and the diet. Then an extensive market inventory followed to first explore the selected product category for this PhD work and then to apply the studied leverages **(step 1).** To obtain an actual view of the obesity pandemic, a literature review containing obesity trends, consequences and determinants with possible interventions with impact on health and obesity was conducted. In order to highlight the potential impact of reformulation on children's diet and health, we aimed to select a product category that has a strong impact on children's' diet in terms of total kcal, sugar and fat contribution and intake. Consumption data per product category (EFSA, 2011) was analyzed. Then, a comprehensive market inventory was conducted to study and identify the product diversity and potential reformulation possibilities for existing commercial products. However, besides, composition information, gaining in-depth information of products structure, texture and sensory properties is crucial as they are key drivers of the liking and behavior among children.

In order to conduct in-depth sensory and instrumental characterization, we suggested to work on a subset of products that would be representative of the diversity of the food offer in this category **(step 2).** Thanks to the subset selection, it is possible to investigate the diversity of existing products via multicriteria mapping in order to identify potential reformulation opportunities.

Further sensory and instrumental analyses allowed to obtain a more complete view of the products **(step 3).** On this basis, a multicriteria mapping followed by an outlier approach allowed to identify reformulation opportunities based on commercial chocolate-chip cookies.

With the knowledge of the identified reformulation opportunities, preliminary recipes were thus created in order to define the factors (ingredients) and levels to be used in a mixture design **(step 4)**. In order to better understand the impact of the independent factors on the products' structure and texture, sensory perception with relevant nutrition and physicochemical parameters were also conducted on all 30 formulated cookies. Then, modeling of sensory responses allowed to optimize recipes while maintain sensory perception and liking. As a last step, a selection of reformulated cookies was evaluated to study their influences on predicted glycemic index and children's behavior in snacking evaluation conditions **(step 5).**

All codings of the used commercial chocolate-chips cookies and reformulated chocolate-chips cookies within this PhD work were shown in SUPPLEMENTARY TABLE 1 & SUPPLEMENTARY TABLE 2.

4.Chapter 4

Result Part

with commercial cookies

4 Chapter results part: Research with commercial cookies

4.1 "How to Select a Representative Product Set From Market Inventory?" A Multicriteria Approach as a Base for Future Reformulation of Cookies."

General introduction

Food reformulation would be a powerful leverage to enhance the food offer and our diet, but due to many hindrances (changes in structure, texture, sensory perception or liking), the success stays limited. Therefore, new innovative reformulation approaches must be developed, in order to consider food reformulation as a holistic approach, starting from the food offer targeting on one product category. This approach aims to provide a holistic view of the market which could benefit the industries by evaluating their competitors' products and ultimately gaining a better understanding of their own product positioning. But the food market is complex to analyze, with many different recipes from many different manufacturers. An investigation of the product category under consideration is thus a first necessary step to identify the diversity of existing products. Trying to limit the reformulation constraints, this recently published article proposed a guide on how to create a solid base for future reformulation based on a multicriteria approach, by going beyond nutrition information on the packaging. Therefore, besides easily available composition and price information on the packaging, further sensory and physicochemical analyses were considered.

Within this frame, the first aim was to create a database with the help of a comprehensive market inventory on French cookies with inclusions. The second aim was to define a subset of products that would be representative of the market, based on various composition, sensory and economic criteria. The subsets' representativity was then checked with multivariate and univariate analyses.

The comprehensive market analysis with focus on a single product category allowed to obtain a broad view of the product diversity. Results showed a broad variety of chocolate chips cookies with large nutritional, compositional, water content, and sensory differences. Further, based on multiple criteria, a representative subset of 18 cookies could be selected from the obtained cookies clusters. These results highlighted the first paths for future reformulation in this product category. They showed the importance to include sensory and physicochemical product information beyond the information on the packaging to identify some reformulation opportunities, in order to improve product nutritional quality.

For that and to go further, it is now necessary to determine complementary sensory and physicochemical analyses among the selected subset, to propose some pertinent reformulation levers, which target some products properties with, as example, unchanged sweet perception or hard texture. This objective will be developed in the next study, to identify pertinent reformulation opportunities among commercial cookies, under clean label criteria.

"How to Select a Representative Product Set From Market Invento-ry?" A Multicriteria Approach as a Base for Future Reformulation of Cookies."

Published Research Paper, Frontiers in Nutrition, https://doi.org/10.3389/fnut.2021.749596

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Abstract

Consuming too much fat, sugar, and salt is associated with adverse health outcomes. Food reformulation is one possible strategy to enhance the food environment by improving the nutritional quality of commercial products. However, food reformulation faces many hindrances. One way to alleviate some of these hindrances is to embrace a multicriteria approach that is based on a market inventory. In this objective, additional sensory screening and water content analyses allow going beyond nutrition and composition information on the packaging. However, due to feasibility reasons for later in-depth analyses, it is necessary to work with several reduced and manageable products. To the best of the authors' knowledge, in the literature, there is no sample selection approach taking into account multiple criteria as a base for future food reformulation. The overall aim of this paper is to propose a method to select the best representative products from the market base, for future reformulation by going beyond nutrition and composition information on the packaging. This approach considered therefore nutrition, composition, economic, water content, and sensory information with the example of the cookies market.

The first step is the creation of an extensive cookie database including sensory and water content information. In total 178 cookies among the French market were identified, then focus was placed on 62 chocolate chip cookies only. Sensory screening and water content analyses of all 62 products were conducted. The second step is to make an informed subset selection, thanks to a cluster analysis based on 11 nutrition, composition, and water content variables. A representative subset of 18 cookies could be derived from the obtained clusters. The representativity was evaluated with statistical uni- and multivariate analyses. Results showed a broad variety of chocolate chips cookies with a large nutritional, compositional, water content, and sensory differences. These results highlighted the first paths for future reformulation in this product category and showed the importance to include physical product information beyond the information on the packaging. This complete database on the selected cookies constituted a solid base for identifying future reformulation levers, in order to improve the nutritional quality and health.

Keywords: Market inventory, Multiple criteria, Sample selection, Food reformulation, Nutrition, Health

4.1.1 Introduction

Food reformulation is an interesting lever to reduce over-consumed nutrients (such as sugar, fat and salt) and to enhance our diet and health (Gressier et al., 2021; Spiteri & Soler, 2018). A successful reformulation makes it possible to move towards a healthier food offer without largely changing consumers eating habits. It was shown that a reduction of undesirable nutrients such as trans fatty acids, saturated fat, sodium and sugar of more than 17’000 foods and beverages would lead to a reduced intake of nutrients which are to limit and an improved public health (Nijman et al., 2007).

However, a recent study across 20 European countries showed that many packaged foods and drinks still have a too high fat, sugar and salt- and a too low fiber content (Bonsmann et al., 2019). These results of concern are surprising as the link between overconsumed adverse nutrients and negative health outcomes is well known (Afshin et al., 2019). For example in the UK, most of the companies between 2015 and 2018 did not reach an overall sugar reduction of 5% among the top 5 product categories which contribute the most to the high sugar intake (biscuits, cereal bars, breakfast cereal, chocolate and sugar confectionery, yoghurts) among the UK population (Bandy et al., 2021).

These findings underline the fact that food reformulation still has a lot of unused potential, very likely due to many technological and sensory barriers. Indeed, reformulating biscuits is challenging.

For instance, decreasing sugar and fat content is difficult because of their multiple functional properties in food matrix, and in particular in sweet bakery products (Ghotra et al., 2002; Miller et al., 2017; Pareyt et al., 2009). Moreover, sugar and fat are strong drivers of preferences. Any modification might have huge consequences on liking, pleasure experiences and food choices (Marty et al., 2018; Nguyen et al., 2015). This may contribute to the hesitant willingness for voluntary food reformulation on the part of the food industry as cost and time effectiveness are not immediately granted.

To overcome these barriers and to encourage industries to reformulate healthier versions of their products, we argue that is necessary to see food reformulation in a comprehensive way because of the multi-factorial nature of the determinants of food preferences and of the multiple interactions between food components in the food matrix (Batista et al., 2021; Marty et al., 2018; Monnet et al., 2019; Nguyen et al., 2015; Vasanthakumari & Jaganmohan, 2018). Focusing only on nutritional and compositional changes would thus inevitably lead to dead-ends or missed opportunities. Improving the nutrition quality by food reformulation is complex and needs to integrate different dimensions such as food composition, physico-chemical properties and sensory perception. To address this challenge, it would be useful to create a solid base relying on multiple criteria in order to anticipate possible interactions and to achieve a successful reformulation in the long term.

This article proposes a guide on how to create such a base for future reformulation. Cookies were chosen as a case study of prime relevance. The first aim was to create a database with the help of a comprehensive market analysis, taking into account multiple criteria by going beyond nutrition and composition information on the packaging. This multicriteria approach considers easily available information from the packaging (nutrition, composition, and price) and adds complementary information obtained thanks to simple analyses such as water content measurement and rapid sensory screening. It aims to provide a holistic view of the market which could benefit the industries by evaluating their competitors’ products and ultimately gain a better understanding of their own products positioning. But the food market is complex to analyze, with many different recipes from many different manufacturers. An investigation of the product category under consideration is thus a first necessary step to identify the diversity of existing products. Then, further in-depth analyses are usually needed to gain greater knowledge of the existing recipes and to guide reformulation. To make these analyses realistic and compatible with experimental constraints, a second step in the proposed approach is to define a subset of products that would be representative of the market and yet be of manageable size. In this objective, we suggest to make an informed selection based on a multicriteria analysis. To the best of the authors' knowledge, there is a lack of a common subset selection method adapted to food reformulation and that takes into account multiple variables.

4.1.2 Material and Methods

This section describes the four steps used for this multicriteria approach, from the analysis of the cookie market to the subset selection and the representativity checks (FIGURE 21, **steps 1-4**). First of all, to identify the potential for reformulation and to explore the diversity of recipes of the "commercial cookies" product category, an online analysis of the French market was conducted **(step 1).** The focus was set on a uniform cookie variety. In order to identify possible levers for food reformulation in a later step, it is important to first have a broad view of products' characteristics. For this, we needed to select a representative subset of products while maintaining a good vision of the market diversity. Therefore, some rapid sensory and physicochemical analyses were first conducted on all chocolate chip cookies **(step 2).** Then, the cookies were clustered based on available nutrition, composition and physicochemical data. A subset of products was then proposed based on additional 11 composition, sensory and economic criteria ranked for their importance in the selection **(step 3).** Finally, a check of the subset representativity was performed with uni- and multi-dimensional statistical analyses **(step 4).**

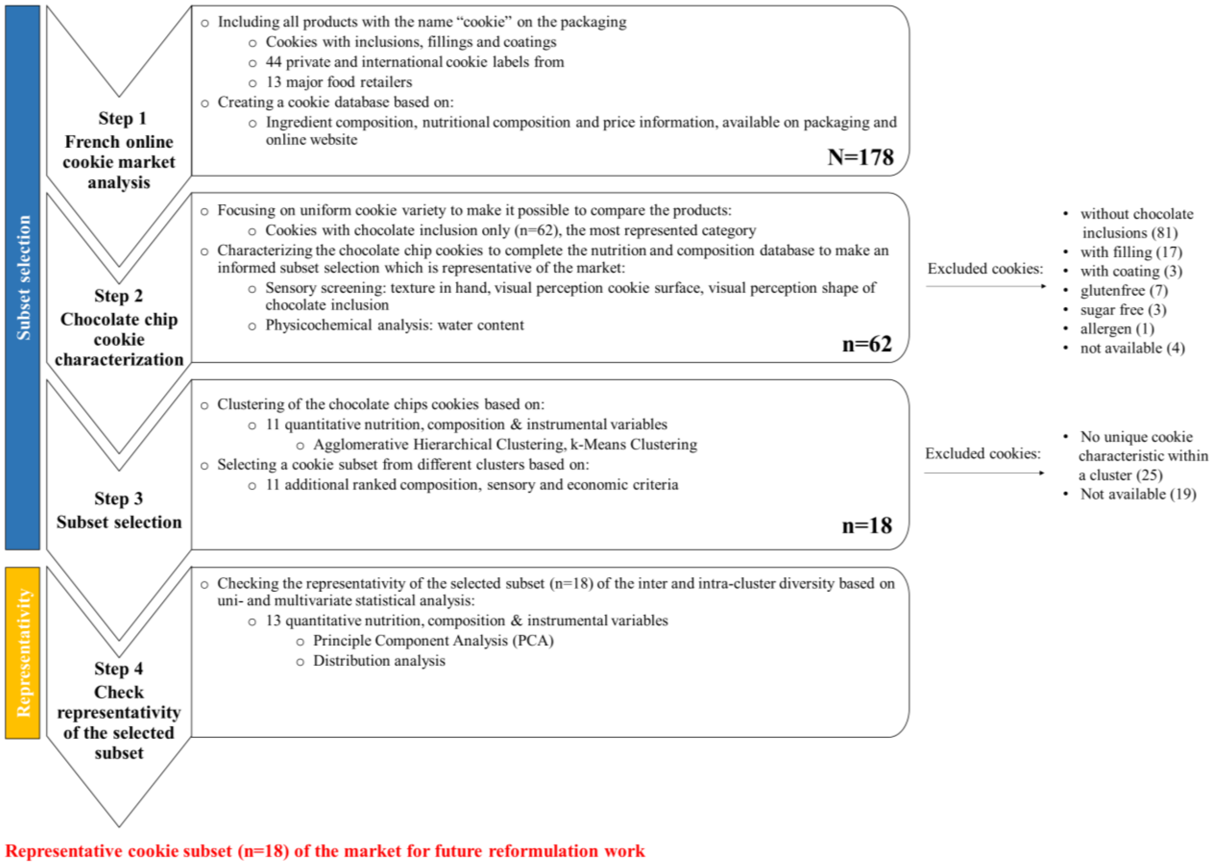

FIGURE 21 : Overview of the four steps from the online cookie market inventory to the selected subset and its check of the representativity.

4.1.2.1 Cookie market analysis (Step 1)

All the cookie brands available in 2019 on the online French market with the specific mention "Cookie" on the packaging were included in this study (FIGURE 21, step 1). All the different varieties were initially considered: cookies with inclusions, fillings and coatings. A database with a total of 178 cookies was created, using information from the packaging and websites. Available nutrition, composition and price information from the packaging and online websites were collected. In addition to that, the Nutri-Score (letters A-E) was calculated based on the Rayner computation for each product (Rayner, 2017).

4.1.2.1.1 Focus on uniform cookie category: chocolate chip cookies

We aimed to focus on a uniform cookie variety in order to work on a homogeneous product set and to make future reformulation work consistent.

Cookies with chocolate inclusions showed the broadest range and greatest diversity within the market offer. Therefore, decision was made to consider cookies containing chocolate inclusions. Besides, it is worth noting that chocolate chips are important carriers of sugar and fat which makes them a potentially interesting lever for reformulation. We excluded all cookies without chocolate inclusions, those with fillings and coatings, and specialties cookies such as gluten-free, sugar-free, and allergen-free cookies. Finally, a total of 62 cookies with chocolate inclusions were included in this study (FIGURE 21, step 2 excluded cookies).

4.1.2.2 Variables and criteria among the chocolate chip cookie database

Beside the cookie information from the packaging and from online websites, the chocolate chip cookie database was further completed with physicochemical analysis and sensory screening (texture in hand, visual perception shape chocolate inclusion and cookie surface) of the 62 cookies. All quantitative variables were included for the clustering analyses and representativity checks, whereas additional ranked criteria were considered for the subset selection among clusters. All variables and criteria used for the chocolate chip cookies database are presented in SUPPLEMENTARY TABLE 3 and SUPPLEMENTARY TABLE 4.

4.1.2.2.1 Quantitative variables

Thirteen quantitative nutrition, composition and physicochemical variables were used to constitute the database: kcal, fat, saturated fat, carbohydrates, sugar, protein, fiber and salt content per 100g, number technological additives (important for baking and conservation properties such as baking powder, emulsifier, thickening agents, antioxidants and humectant), number sensory additives (important for sensory properties such as colorings and artificial sweeteners), number additives (technological & sensory additives), number ingredients, water content and the calculated Rayner score.

Eleven variables (fat, saturated fat, carbohydrates, sugar, protein, fiber and salt content per 100g, number technological additives, number sensory additives, number ingredients and water content) were included for the clustering and twelve variables (kcal, fat, saturated fat, carbohydrates, sugar, protein, fiber and salt content per 100g, number additives (technological & sensory additives), number ingredients, water content and the calculated Rayner score) were included for the representativity check.

4.1.2.2.2 Additional ranked criteria

Eleven additional composition, sensory and economic criteria with their 40 subgroups were also included in the database (FIGURE 22). Cookies availability was not included as a criterion but as constraint, as for obvious practical reasons products must be available for further analyses. All 11 criteria were ranked according to their possible impact on the food structure, sensory perception and liking. In addition to these criteria, product availability at the time of the study was a strong constraint and was taken into account for the final selection.

Obviously, composition criteria such as major cookies ingredients and chocolate ingredients were considered as most impactful on the food matrix due to their high quantity in the recipe. The weight of the cookie and price were included as well. These two criteria lesser impact reformulation, sensory perception and liking. However, the cookie weight might play an important role into portion size and kcal intake. Besides, as healthier reformulated products should be available for all, we also included the price that is an important determinant of purchasing behavior.

Seven criteria contained qualitative information (type of flour, type of sugar, type of fat, type of chocolate inclusion, shape of chocolate inclusion, surface cookie and brand), whereas 5 criteria contained quantitative information (amount of chocolate and cacao powder, amount of chocolate inclusion, texture cookie, weight of cookie and price per kg cookie).

All 11 qualitative and quantitative criteria were considered as categorial criteria with subgroups. For the 5 quantitative criteria, we calculated their quintile rank in order to obtain five subgroups of equal frequencies such as very low, low, middle, high and very high. For the criterion texture in hand, we calculated the tertile rank for the score in order to distinguish between three main textures (soft, intermediate and hard) (TABLE 1).

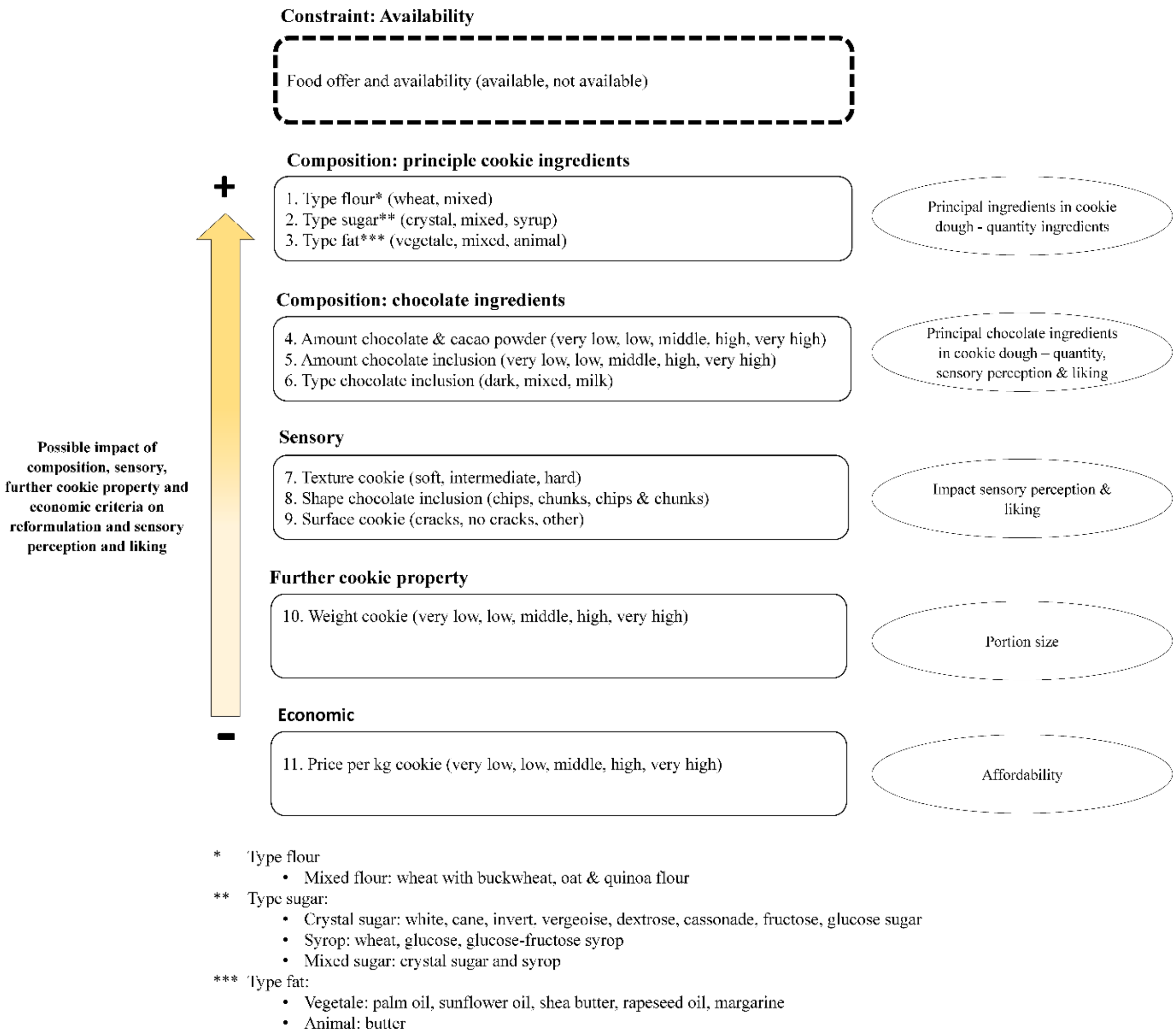

FIGURE 22 : Overview of the 11 additional ranked criteria with their 40 subgroups (in brackets) and the availability as constraint.

TABLE 1 : Rank calculation of the quintiles and tertile of the subgroups.

Criteria (quintiles)	Very low (%)	Low (%)	Middle (%)	High (%)	Very high (%)
Amount chocolate & cocoa powder in % (per 100g)	1.3-2.3	2.4-2.6	2.7-3.1	3.2-5.7	5.8-15.3
Amount chocolate inclusion in % (per 100g)	5.5-22.6	22.7-28	28.1-30.5	30.6-37	37.1-40
Criteria (quintiles)	Very low (g)	Low (g)	Middle (g)	High (g)	Very high (g)
Weight cookie in g	3.12-16.5	16.6-16.6	16.7-23	23.1-25	25.1-70
Criteria (quintiles)	Very low (€)	Low (€)	Middle (€)	High (€)	Very high (€)
Price per kg cookie	2.9-4.5	4.6-7.5	7.6-10.4	10.5-16.7	16.8-29.3
Criterion (tertile)	Soft		Intermediate		Hard
Texture in hand (score 0-10)	0-5		5.1-7.2		7.3-9.4

4.1.2.3 Chocolate chip cookie characterization (step 2): sensory screening and physicochemical analysis

Further analyses were conducted in order to go beyond composition and nutritional values from the packaging, and to better understand major sensory and physicochemical characteristics of the products (FIGURE 21, step 2). Three sensory screenings (perceived texture in hand; visual perception cookie surface and shape of chocolate inclusion) were performed. The goal of the sensory screening was to categorize the cookies according to their most striking visual and texture characteristics. This type of evaluation is relatively easy and differences between the cookies were expected to be quite obvious. Under such conditions, it is thus possible to reach sufficient power, even with a very small number of panelists. Besides the sensory screening, the water content was measured for all 62 chocolate chip cookies. Measuring the water content among baked bakery products will provide information about cookies physicochemical properties, including structure and texture characteristics.

4.1.2.3.1 Screening of the texture in hand

In order to gain insights into product texture, three trained subjects evaluated the hardness of all chocolate chip cookies. They were told to break the cookies in two halves by hand and to report their perceived hardness on an unstructured scale from 0-10, where 0 indicated soft and 10 hard. The evaluation took place over six sessions and was conducted in sensory booths in a sequential monadic way, following a balanced order over the panel and sessions. Samples were coded with random three-digit numbers and presented in blind.

4.1.2.3.2 Screening of the cookie surface and the shape of the chocolate inclusion

Cookies' surface aspect and the shape of the chocolate inclusions were evaluated by a cookie expert who was trained over one year with all 62 chocolate chip cookies. The visual perceived cookie surface was grouped into the qualitative subgroups "cracks", "no cracks" and "other" what means neither cracks nor no cracks. The visual perceived shape of the chocolate inclusion was grouped into three qualitative subgroups "chips", "chunks" and "chips and chunks".

4.1.2.3.3 Water content

The water content was determined by oven drying method and adapted from (Upadhyay et al., 2017). First, all chocolate chip cookies were crushed and grinded with a mortar during 15 seconds. After grinding, 3 g of grinded cookies were weighed in a round aluminum dish. It was further put in the oven (EM10, Chopin, France) for 18 hours at 103 °C. The time was set by 18 hours as the weight after drying did not change anymore. The sample was then placed in a desiccator for 1 hour before weighing. All measurements were performed in triplicate among three different cookies and the results averaged.
The mass loss was determined by weighing the sample before and after drying to constant weight:

$$\boldsymbol{water\ content\ in}\ \% = \frac{\boldsymbol{weight\ (g)\ cookie\ before\ oven - weight\ (g)\ cookie\ after\ oven}}{\boldsymbol{weight\ (g)\ cookie\ before\ oven}} * \mathbf{100}$$

4.1.2.4 Subset selection (Step 3)

In order to best represent the market diversity and to make an informed subset selection, cookies were clustered based on 11 nutrition, composition, and water content variables defined in section Quantitative Variables (FIGURE 21, step 3). This allowed the selection of cookies from each cluster with different cookie characteristics. In sensory science, Agglomerative Hierarchical Clustering (AHC) and K-means clustering are possible methods to group product characteristics or consumers in the same clusters based on their similarities and is, therefore, a suitable tool to contribute to decisions for product development (Alves et al., 2013; Pagliuca & Scarpato, 2014).

The subset selection from each cluster was done with the help of 11 additional ranked criteria defined in section Additional Ranking Criteria. As well other authors have used several ranked criteria for product selection (Mora et al., 2018; Thompson et al., 2004). Within a cluster, those cookies with unique characteristics (subgroup) were selected. Please find more detailed information in SUPPLEMENTARY TABLE 5. Cookies that were marked as "not available" were excluded. The cookie numbers per cluster are shown in SUPPLEMENTARY TABLE 6.

4.1.2.5 Statistical representativity check (step 4)

In order to evaluate the representativity of the selected subset, we applied multi-dimensional analysis with 12 quantitative nutrition, composition and physicochemical variables. To check the subset based on their intra- and inter cluster diversity, a PCA was performed on the 12 variables. To validate the representativity of the subset, we compared the distribution of the 62 chocolate chip cookies and of the 18 selected cookies based on the 12 variables.

4.1.3 Data analysis

All statistical analyses (K-means clustering, Principle Component Analysis, Histogram and Linear Regression) were conducted with XLSTAT version 2018.1.1 (Addinsoft, New York, USA), where needed with a significance level alpha=0.05.

4.1.3.1 Cookie clustering (step 3)

To characterize and cluster cookies according to their nutrition, composition, and water content characteristics, we first ran an AHC with Euclidean distance, Wards' Method, and centered and reduced data. This analysis allows to visually define the optimal numbers of clusters. Data from the AHC were organized in a table with 11 columns (nutrition, composition, and water content analyses) and 62 rows (commercial chocolate chips). Defining the "good" number of cookies clusters is a matter of balance between precision (the higher the number of clusters or products to be selected, the higher the precision of the selection) and feasibility (the higher the number of products, the more difficult to run additional analyses). Once the number of clusters was selected, K-means clustering was applied (Trace (W) criterion on reduced and centered data the differences among the seven clusters was evaluated with an ANOVA). Conducting first an AHC followed by K-means is a common method in sensory science to obtain robust clusters.

4.1.3.2 Validation with multi-dimensional statistical analysis (step 4)

To visualize the seven clusters from the K-means clustering, the 10 active and two supplementary quantitative variables were plotted on a 2-dimensional map by using PCA. This allowed us to evaluate and check the multivariate nutrition, composition, and water content variables based on their intra- and inter-cluster diversity. For the PCA, we used Pearson correlation with a significance level alpha = 0.05 and standardized (n) data. Missing data were replaced by mean or mode. For the validation axes, F1 and F2 were considered. To evaluate the relationship between the texture in hand and cookies' water content, a linear regression was applied. The PCA is a convenient tool to visualize and plot obtained clustering data to detect class diversity (Baxter, 1995). To check the representativity of the selected subset, we visually compared the distributions of all 62 chocolate chip cookies and the 18 selected cookies based on the 12 quantitative variables thanks to histogram plots.

4.1.4 Results

4.1.4.1 Cookie varieties and compositional diversity among the entire cookie database with private and international labels

The results showed that three main cookie varieties were identified from the whole database with 178 cookies: 158 (88.8%) cookies with inclusions, 17 (9.5%) cookies with fillings, and 3 (1.7%) cookies with coatings. Among the cookies with inclusions, products with chocolate chips 77 (48.7%), nuts 42 (26.6%), nougat, caramel, and gianduja 25 (15.8%), and dried fruits 14 (8.9%) were the most represented cookies on the market. Around 20 (11.2%) cookies do have fillings and coatings, while more cookies have fillings than coatings. The vast majority of cookies on the French market thus have chocolate inclusions with dark chocolate or nuts inclusions with almonds. FIGURE 23 presents detailed information about the different inclusions, fillings, and coatings of commercial French cookies.

As shown in TABLE 2 (A), the ranges (from the minimum to maximum values among the 178 cookies) for nutritional values (per 100 g) were: 183 kcal, 27 g sugar, 22.8 g carbohydrates, 16.4 g fat, and 16.4 g saturated fat. The calculated Rayner score showed that 170 (95.5%) cookies had a Nutri-Score of E, while 6 (3.3%) cookies had a Nutri-Score of D and 2 (1.2%) cookies had a Nutri-Score of B.

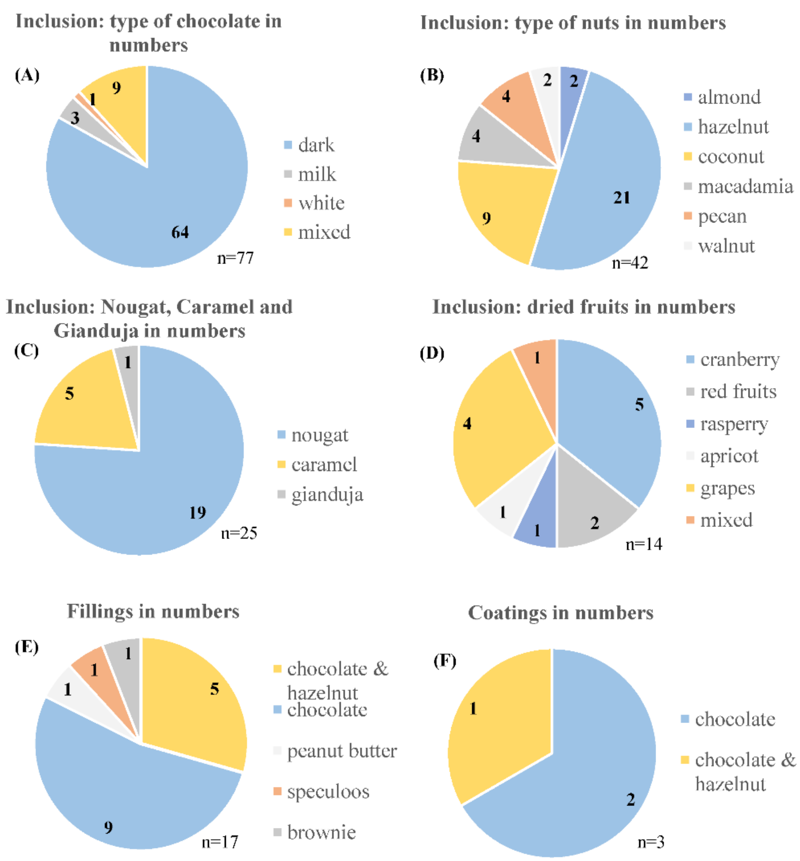

FIGURE 23 : Cookie varieties from the online French market inventory in 2019. Cookies (A–D) are cookies with different inclusions and cookies (E) and (F) are cookies with fillings and coatings.

TABLE 2 : Nutritional values of the entire- (A) and chocolate chip cookie database (B).

	Databases A: 178 cookies B: 62 cookies	Min. value	Max. value	Difference Min. & Max. value	Mean ± SD
Kcal	A	389	572	183	499.5 ± 25.5
	B	433	518	85	495.4 ± 15.2
Fat (g)	A	16	32.4	16.4	25.4 ± 3.1
	B	17.1	28	10.9	24.3 ± 2.0
Saturated fat (g)	A	3.6	20	16.4	12 ± 3.3
	B	5.9	18	12.1	12.6 ± 2.7
Carbohydrates (g)	A	48	70.8	22.8	59.6 ± 3.8
	B	57	70.8	13.8	61.6 ± 2.5
Sugar (g)	A	0*	43	27	32.1 ± 6.0
	B	27	41.8	14.8	34.5 ± 3.0
Protein (g)	A	3.5	13	9.5	6.2 ± 1.1
	B	4.5	7.6	3.1	6 ± 0.8
Fiber (g)	A	0.8	10	9.2	3.9 ± 1.5
	B	1.8	5.7	3.9	3.6 ± 0.9
Salt (g)	A	0.03	2	1.97	0.7 ± 0.4
	B	0.2	1.5	1.3	0.8 ±0.3

* for sugar free cookies

4.1.4.2 Nutrition, physicochemical and sensory diversity among the chocolate chip cookie database

In this study, we set the focus on 62 cookies with chocolate inclusions, representing 27 different private labels and international brands gathered from 12 retailers. As shown in TABLE 2 (B), the broadest ranges for nutritional values per 100 g were found for kcal (85), sugar (14.8 g), carbs (13.8 g), saturated fat (12.1 g), and fat (10.9 g). Additionally, cookies with chocolate inclusion (B) demonstrated a slightly higher mean content of saturated fat, carbohydrates, sugar, and salt content, whereas we found a slightly lower mean content of protein and fiber compared to the whole cookie database (A). For cookies with chocolate inclusions, 61 cookies (98.4%) have a Nutri-Score E and only one (1.6%) cookie a Nutri-Score D. The Rayner score ranged between 14 (Nutri-Score D) and 28 (Nutri-Score E).

The mean value of the measured water content among the 62 cookies was 3.9 ± 1.7%, whereas the values ranged from min. 2.1% to max. 9.3%. For the perceived texture in hand, the mean value was 5.6 ± 2.5, with a range from min. 0 and max. 9.4 on a scale from 0 to 10 (0: soft; 10: hard) (SUPPLEMENTARY FIGURE 1). As expected, a significant negative correlation ($p < 0.0001$, $r = -0.773$, $r2 = 0.579$) was observed between the variable texture in hand and the water content.

The numbers of cookies for the additional ranking criteria “texture in hand,” “shape chocolate inclusion” and “surface cookie” are shown in FIGURE 24 with their subgroups. Among the 62 chocolate chip cookies, most products had chips as a chocolate shape and most of the cookies' surfaces were characterized with cracks. All types of cookie textures are well distributed, in soft, intermediate, and hard. All criteria with their subgroups are shown in SUPPLEMENTARY TABLE 4.

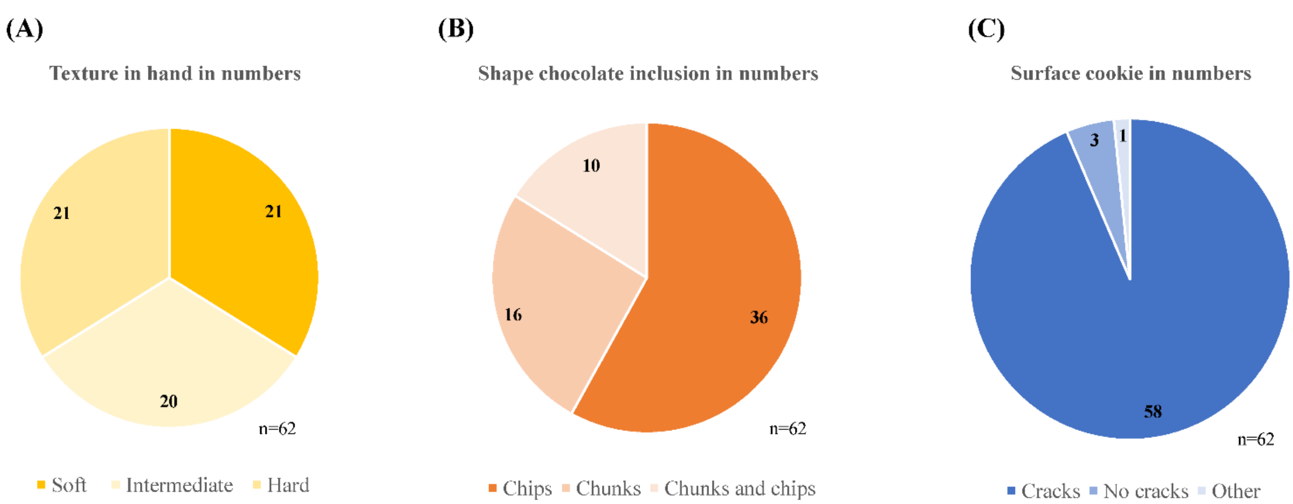

FIGURE 24 : Results of the three sensory screenings on all 62 chocolate chip cookies with the additional ranked criteria (A) texture in hand, (B) shape of the chocolate inclusion and, (C) the surface of the cookie. Those three criteria are part of the 11 additional ranked criteria in order to be able to make an informed subset selection which is representative of the market.

On the PCA score map in FIGURE 25 A, the cookies were grouped and represented with different colors based on seven clusters, obtained by K-means clustering. The broadest variability was explained by axes F1 and F2 with a variance of 49.12%. Results of a conducted ANOVA demonstrated significant differences between almost all clusters ($p < 0.05$), except for the smallest ingredient components fiber and the salt content.

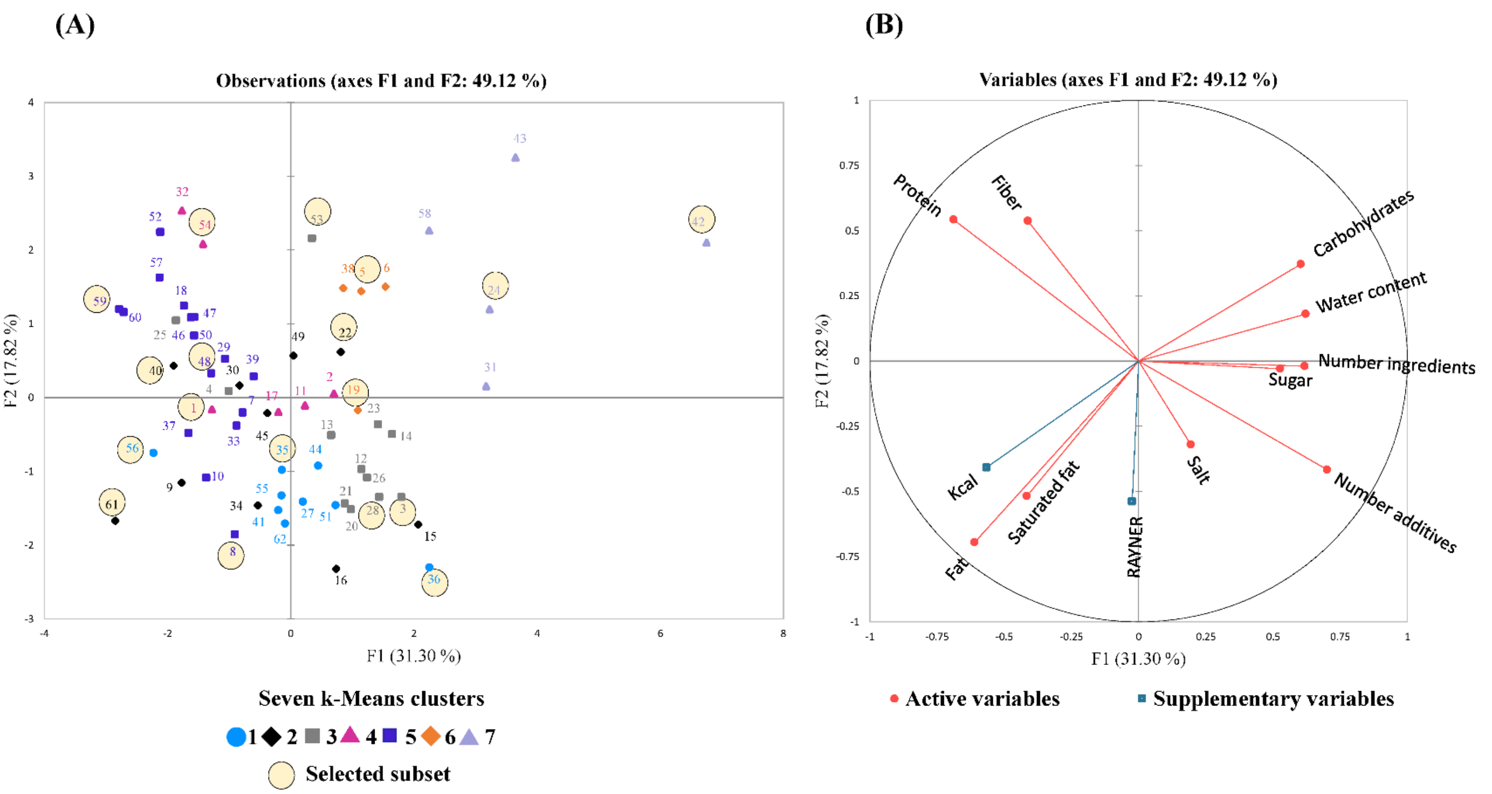

FIGURE 25 : Principal component analysis (PCA) with axes F1 and F2. (A) observation plot including 62 cookies with chocolate inclusion colored based on seven different K-means clusters and the 18 selected cookies for the subset in black circles, representative of the market. (B) PCA correlation matrix with 10 active nutrition, composition, and water content variables (Fat, saturated fat, carbohydrates, sugar, protein, fiber and salt in g per 100 g, water content in %, number ingredients and number additives), and two supplementary variables (Rayner score, Kcal).

The loadings in FIGURE 25 B show the relationships between 10 active and two supplementary variables. The strongest positive correlations were found between the fat and kcal content ($r = 0.828$), between the Rayner score and the number additives ($r = 0.538$), and between the Rayner score and the salt content ($r = 0.447$). On the other hand, the strongest negative correlations were found between the kcal and water content ($r = −0.793$), the protein content and the number of additives ($r = −0.659$), and between the fat and the water content ($r = −0.603$). FIGURE 25 A shows broad nutrition, composition, and water content diversity among the 62 chocolate chip cookies. Some cookies on the right side of the plot (axis F1) are characterized by a high carbohydrate, sugar, and water content and a higher number of total additives (technological and sensory) and ingredients.

On the left side (axis F1), some cookies are characterized by their high protein and kcal content. Furthermore, cookies on the bottom (axis F2) had higher fat and saturated fat content with a higher Rayner score. Cookies on the top (axis F2) tend to have a higher fiber content. Moreover, and as expected, the Rayner score showed a positive correlation with fat content (r = 0.288), saturated fat (r = 0.538) and salt content (0.447), and a negative correlation with the fiber content (r = −0.281). Cookies of clusters 1 and 3 had a high Rayner score with high fat, saturated fat, and lower fiber content. On the other hand, most of the cookies belonging to clusters 5, 6, and 7 presented a lower Rayner score with higher fiber content, and lower fat and saturated fat content than other cookies. Cookies from cluster 5 showed the highest kcal content, while those of cluster 7 were characterized with high sugar content.

FIGURE 26 : This figure shows 62 pictures of the commercial chocolate chip cookies, including the selected subset of 18 cookies.

FIGURE 26 presents all 62 commercial chocolate chips cookies. Although this study concentrated on a single product category only, we can observe a broad visual cookie variety. Notably, they differ in their size, their dough color, the shape of the chocolate inclusion, the quantity of the chocolate inclusion appearing on the surface, or the cracks on the cookie surface.

4.1.4.3 The selected subset and its representativity

To best represent the diversity of all chocolate chip cookies, a subset of 18 cookies was also proposed. This accounts for almost a third of the initial 62 cookies. In total, 3 cookies were selected in each cluster 1,2,3 and 5 and 2 cookies were selected in the clusters 4,6 and 7 (FIGURE 25 & SUPPLEMENTARY TABLE 6).

4.1.4.3.1 Labels and retailers

The subset of cookies included 13 different private and international labels from 7 retailers. In comparison to the entire cookie database with 178 products, this is almost on third (29.5%) of all labels and more than half (53.8%) of all retailers. Considering the chocolate chip cookie database, the subset included about half (48.1%) of all labels and more than half (58.3%) of all retailers (FIGURE 27).

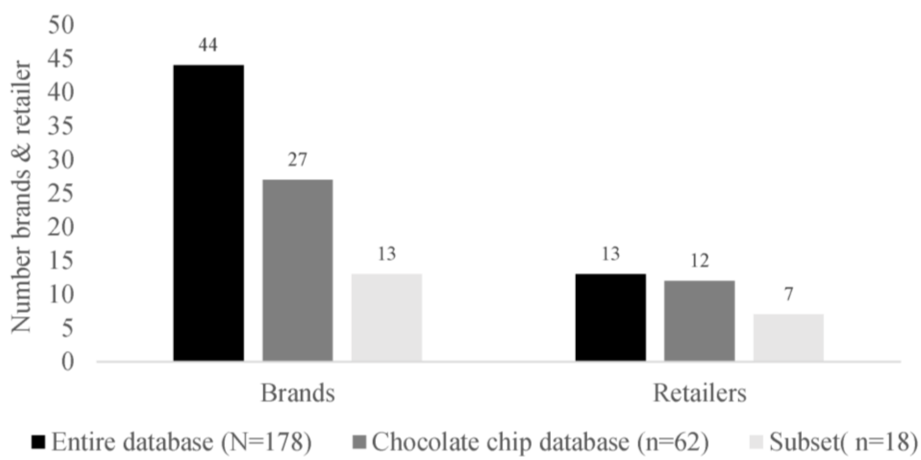

FIGURE 27 : Representativity of the brands and retailers of the selected subset.

4.1.4.3.2 Quantitative nutrition, composition and physicochemical variables

The 18 selected cookies are highlighted on the PCA of the 62 chocolate chip cookies in FIGURE 25 A. The subset shows broad nutrition, composition, and water content diversity based on 12 plotted variables. Moreover, the selected cookies of each cluster showed a balanced distribution of extreme cookies within and between clusters based on axes F1 and F2. As can be seen in FIGURE 28 we observed a similar distribution between the chocolate chips cookies and the selected subset for almost all variables. The subset led to a slightly different distribution for the kcal, fiber, protein, salt, and water content. The subset also accounted for minimal and maximum values for most of the variables.

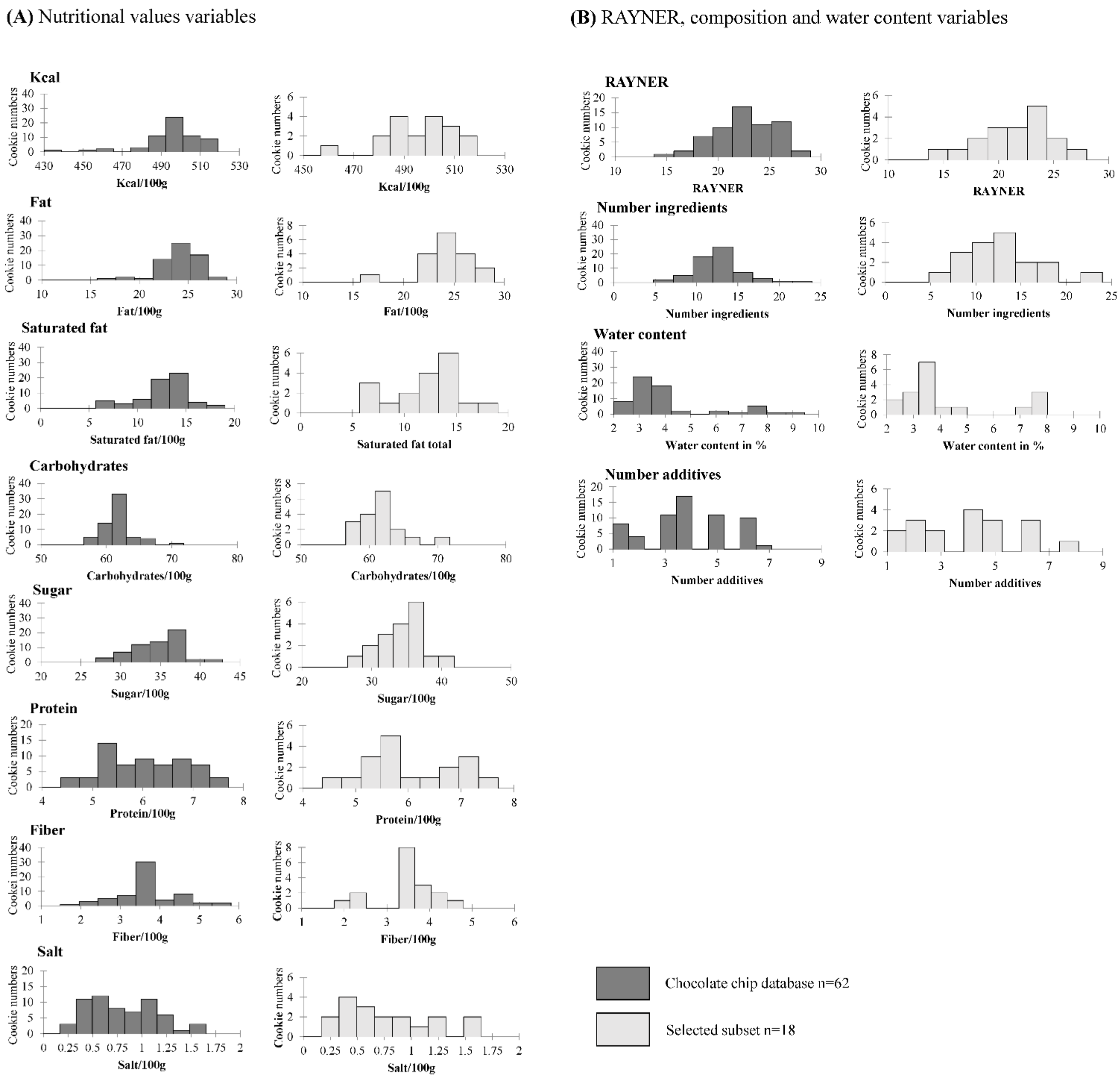

FIGURE 28 : Comparison of 12 nutrition, composition and water content variables among chocolate chip cookies and the selected subset based on distributions with (A) nutritional values variables and (B) Rayner score, composition, and water content variables.

4.1.4.3.3 Additional ranked criteria

As shown in SUPPLEMENTARY TABLE 7, the selected subset considered 37 out of the 40 subgroups. Three subgroups (criterion type sugar: syrup, criterion amount chocolate, and cacao powder: middle and criterion weight cookie: high) remained unrepresented. Although we did not seek strict representativeness in terms of group sizes, it can be noted that larger subgroups in the chocolate chip cookie database also had more products in the selected subset. The selected subset contained cookies as well with smaller subgroups in the chocolate chip cookie database, such as the subgroup “type of flour, mixed,” several subgroups from the criteria “amount chocolate and cacao powder” and “surface cookie” and as well the subgroup “type of chocolate, milk.” In addition, each additional ranked criterion was considered when selecting the cookies from the seven clusters.

4.1.5 Discussion

Focus on a single product category (cookie) and specific cookie variety (chocolate chip cookies)

Inventorying one product category only is not so frequent in the field of food reformulation. Further, sensory studies often usually deal with a small number of products without considering the full diversity of the market. However, this study showed that working with a single product category has several advantages.

First of all, focusing on a single product category allows to increase the product number in a database, what will lead to an increased product diversity what is important for the later reformulation. As well conducting analysis implies to work on physically available products from the market, as those information are not available on the packaging.

Moreover, it is possible to compare food products’ nutritional, sensory and physicochemical characteristics. Although this study focused on chocolate chip cookies only, it was shown that this product category provided a large nutrition, composition, physicochemical and sensory diversity. Those various characteristics are necessary to better understand the links between products’ composition, perception and liking in a later step. Although focusing on cookies only, the measured water content ranged from 2 to almost 10%, with significant consequences on the perceived texture in hand. Further, it was observed that cookies with an increased kcal content had a lower water content and were perceived as more hard in hand. A possible explanation might be due to baking parameters, with a higher water loss during baking leading to an increased kcal content and more hard texture.

At opposite, cookies with a higher water content had either a lower baking time or temperature, what lead to a lower kcal content with a more soft texture. Besides the baking parameters, an increased sugar content as for clusters 7 might as well lead to a more soft texture as sugar is bringing moisture to the cookie dough. Therefore, we suggest that the water content provides important information when it comes to food reformulation among baked cereal products.

A past study showed difficulties in comparing the kcal content and setting cut-offs for nutritional values among different product categories, as the products' composition and the portion sizes were too different (Nijman et al., 2007). Comparing only one product category would make it possible to compare all nutritional values and might help therefore setting pertinent cut off levels for reformulation.

Focusing on cookies with chocolate chips and excluding the other types of cookies, presents the advantage to have realistic overview of the range of products, but also led to a slightly decreased ranges for minimum and maximum nutritional values in this study. The used approach might be more inclusive compared with other studies that usually focus on a specific product or a specific ingredient category (Pearson et al., 2020; Sune et al., 2002). Moreover, other studies prioritized leading brands, high price segments or premium and private label brands for their dataset (Martínez et al., 2002; Schouteten et al., 2018). Considering only market leader brands, might have relieved cookies availability in our study. However, we suggest that especially recipes from different brands, including leader and niche brands, may provide a more diverse product variety and represents the current market for one specific product category.

The selected subset and its representativity

This study illustrated how representative subset of products can be selected from a detailed market analysis, including multiple criteria by going beyond the nutrition and composition information on the packaging. The selected subset of 18 cookies in this study is representative for 23 variables and criteria. Including different retailers, private labels and international brands might contribute to a broader range of recipes and product diversity in the subset as when only focusing on selected retailers and international or private labels.

This PCA permits to visually assess that the selected subset was representative of the market, with the presence of "extreme" cookies within a single cluster but as well between the seven clusters. However, only two cookies were selected from cluster 7, although this cluster showed the highest variance. Due to the unavailability of some of the corresponding brands on the market, it was not possible to select more cookies from cluster 7. To avoid this situation, we could have excluded cookies that are difficult to purchase from the start. However, this would have limited our knowledge of the market.

In addition to this multifactorial analysis, the unidimensional distributions confirmed the good representativity of the subset for almost all 13 variables.

The results in this study showed that almost all subgroups were represented in the selected subset. Several subgroups remained unselected, although they were higher ranked than the remaining criteria. However, these subgroups had already a low representativity in the chocolate chip cookie database, what increases the difficulty to be selected. One possible approach to increase the chance for a selection even for weak represented subgroups would be to create subgroups based on extreme values, rather than the calculation of balanced quintiles ranks. Moreover, each criterion was considered for selecting cookies among the clusters. However, the selected cookie numbers were not higher among criteria which were higher ranked. Instead, more cookies were selected on lower ranked criteria. A possible way to solve this disbalance would be to set higher numbers of cookies to be selected at higher ranked criteria and lower numbers of cookies to be selected at lower ranked criteria.

The representativity step is a critical step as the main purpose is primarily to help industrials and decision makers to anticipate the levers of reformulation. Therefore, working with a reduced subset which is representative of the market is required to conduct further in depth sensory, physicochemical and liking analyses.

Potential for reformulation among the product category commercial "chocolate chip cookies" and prospects for the future reformulation work

We found a large heterogeneity among the chocolate chip cookies in terms of nutritional, compositional, physicochemical and sensory aspects. Large ranges for minimum and maximum values for fat and sugar indicate a potential for certain commercial cookies to reduce their fat and sugar content. Likewise, we identified the potential to increase the fiber content among certain cookies. Moreover, most of the cookies were graded at the highest Nutri-Score (E), which is associated with poor nutritional quality food. However, this study identified commercial cookies with a reduced Rayner score (but only one cookie with a reduced Nutri-Score D), which is associated with a lower fat, saturated fat and a higher fiber content. This rise the question if the Rayner respectively the Nutri-Score is an optimal tool to reformulate among a product category which is known to have very high sugar and fat contents, as the effect of the sugar and fat reduction on the score itself might be low. On the other hand, a sugar and fat reduction in too large steps implies many constraints. Therefore, besides nutritional values, further parameters such as the level of processing and the number of additives should be considered for reformulation.

Sweet biscuits are important contributors to children's unhealthy diet, composed of high caloric, highly processed and palatable foods (Bandy et al., 2021; Costa et al., 2018; Forde, Mars, & de Graaf, 2020; Hall et al., 2019). Our data confirm the interest and the possibilities of reformulation among the commercial "chocolate chip cookies" product category. There clearly is scope for improvement of some cookies nutritional profile, especially by reducing fat and sugar content and increasing fiber content.

Besides the nutritional diversity, we identified three types of cookie textures: soft, intermediate and hard. Texture properties play a key role for sensory perception and as driver of preferences for food choices (Brown & Braxton, 2000; Jeltema et al., 2015). Moreover, besides nutrients manipulation, studies have shown that texture modification might be successful to decrease the 'obesogenic' eating style. Indeed, food oral processing, impacted by texture, could influence satiety and satiation of individuals with faster eating rates and shorter oral exposure time (Fogel et al., 2017). This confirms the high interest to expand nutritional and compositional databases with physicochemical and sensory criteria.

Eventually, we will use the selected subset to identify future reformulation levers, while maintaining sensory perception and liking. This will imply further in-depth sensory and physicochemical analyses, in order to better understand the link between products composition, sensory and physicochemical properties. This understanding is crucial for a successful reformulation, as this multi-criteria approach anticipates potential limitations among the reformulation process.

4.1.6 Conclusion

The creation of a database based on a comprehensive market analysis with focus on a single product category and that considers multiple variables allows to describe and compare the diversity of products. It also sets the bases for future reformulation. Besides nutrition and composition information collected from packaging, simple additional characterizations are useful to better assess product diversity. This allowed to make an informed and representative subset selection whose representativity was checked by uni- and multi-variate analyses.

Thanks to this subset selection, it will be possible to conduct in depth sensory, physicochemical and hedonic investigations that are required to successfully reformulate the products as one possible answer to the improvement of the food offer. Besides nutrients modification, texture modification with possible impact on the oral process, satiation and satiety is a further promising reformulation lever. It is also necessary to create multi criteria database to ideally identify some healthier formulation solutions which minimize changes in sensory perception, liking and cost effectiveness. Increasing the potential for voluntary reformulation among industries on one hand and providing a tool to drive public policies on the other hand, might strengthen the reformulation as an even more impactful lever to enhance our food environment.

4.2 "Multicriteria analysis of a product category to identify reformulation possibilities: a case study using commercial chocolate chip cookies."

General Introduction

There is a clear and pressing need to identify innovative solutions for facilitating food reformulation, such that industry actors can more easily developed healthier reformulated versions of their products. In order to be the most possible in line with consumers expectations, one possibility is for food reformulation to propose some products with sensory properties similar to older products or possibly improved, including some criteria in accordance with texture and improved consumption behavior. To help address this need, we have developed a new strategy for exploring food reformulation possibilities based on multifactorial approach. This strategy uses commercial products as a starting point and aims to realistically reduce overall calorie content and levels of certain nutrients by multicriteria analyses.

This submitted article, in a peer reviewed journal, described a multicriteria reformulation approach based on commercial cookies, with depth and complementary sensory and physiochemical analyses of a select subset of 18 commercial chocolate-chips cookies. For that, a sensory quantitative descriptive analysis on all the cookies was carried out with 12 trained panelists and physicochemical analyses such as texture (stress and strain), density and spread ratio measures were performed. Then, in order to study the diversity of the cookie properties and to select key composition and sensory variables, a multicriteria mapping (Multiple Factor Analysis) with 10 composition, 5 physicochemical and 20 sensory variables was carried out. In total 39 pairs of composition and sensory variables were then selected and studied. Then, to identify reformulation opportunities such as improving the nutritional profile while improving sensory perception, a "TSO" (Trends, Scatters, Outliers) approach based on linear regression was applied. Different pertinent regressions were also selected based on 5 ranked criteria (p-value, potential for outlier, nutrition, partial least square regression, r2) to highlight some proposition of reformulation variables and levels, and described in this result part.

Our overall findings highlighted the theoretically feasibility to reformulate commercial chocolate chip cookies while maintaining their sensory attributes, such as sweetness, hardness, crispness and perceived chocolate-chips quantity. Based on the commercial cookies diversity, the following reductions and enhancements were shown as possible with the "TSO" approach: sugar -13.3%, fat -17.9%, chocolate chips -73.8% and fiber +53.8%. Furthermore, optimization possibilities for a Rayner-, processing score and additive reduction were identified, including the use of more environmentally friendly ingredients. We also found that cookie texture must be considered during reformulation and that the specific properties of cookie ingredients could help maintain sensory attributes, based on sensory and physicochemical interactions.

This work opens on research questions about the consequences of these nutritional improving on liking among children, which is the targeted population of the PhD work. Therefore, the next section will investigate the drivers of liking and disliking among a selection of eight commercial cookies derived from the subset described in part 2 and among children with different sociodemographic information and BMI group.

”Multicriteria analysis of a product category to identify reformulation possibilities: a case study using commercial chocolate chip cookies.”

Research Paper, Manuscript submitted to Food Quality and Preferences

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Abstract

Food reformulation could be used to improve dietary quality without having to act upon consumer behaviour. However, this tactic is challenging, given the complex role played by each ingredient in the food matrix and, particularly, their impacts on sensory attributes and preferences. Therefore, it is important to take a holistic approach to food reformulation by considering composition, physicochemical characteristics, and sensory attributes in tandem. Here, a multicriteria approach was applied to chocolate chip cookies with a view to improving their nutritional profiles while maintaining their sensory attributes, work that highlighted potential reformulation hurdles.

First, we characterised the physicochemical characteristics and sensory attributes of 18 commercial chocolate chip cookies, which were chosen to be representative of the broader product category. Second, we selected the most relevant pairs of compositional properties and sensory attributes; multicriteria mapping was performed using 35 key variable pairs. Third, we utilised a trends, scatters, and outliers (TSO) approach based on linear regression to identify reformulation possibilities that maintained sensory attributes.

We identified ways to reduce calorie content—notably by diminishing sugar (-13.3%), fat (-17.9%), and chocolate chips (-73.8%)—and increase fibre (+53.8%), all while maintaining cookie sensory attributes. Cookie texture emerged as a major potential hurdle in product reformulation.

This multicriteria approach could be applied to other food types and might facilitate food reformulation by predicting possible challenges in efforts to improve nutritional and dietary quality.

Keywords: Food reformulation, Cookies, Multicriteria, Nutrition, Sensory, Physicochemical, Health

4.2.1 Introduction

Over recent decades, there has been a shift towards unhealthy diets that contain highly palatable, highly caloric, and ultra-processed foods. As a consequence, a large number of adults and children are suffering from obesity worldwide (NCD Risk Factor Collaboration, 2017) (Costa et al., 2018; Forde, Mars, & de Graaf, 2020; Hall et al., 2019).

One strategy for enhancing food nutritional quality while continuing to respect consumer preferences is food reformulation, which involves reducing a product's levels of sugar, fat, and salt (Gressier et al., 2021; Raikos & Ranawana, 2019; Spiteri & Soler, 2018). Research has shown that the sugar content of drinks can be reduced while maintaining their sensory experience (dairy products = up to 27% and grape nectar = up to 21.6%; Lima et al., 2019; Velazquez Mendoza et al., 2021a). However, there are differences in food matrix complexity between drinks and foods. In the latter, sugar and fat play a significant role in mediating changes when levels of any ingredients are reduced.

Many product types could benefit from reformulation and, indeed, voluntary food reformulation agreements have been established in various industries (Belc et al., 2019; Breda et al., 2020). Nonetheless, this strategy remains rarely employed. Surmounting technological and sensory challenges is often economically prohibitive. In particular, decreasing sugar and fat is challenging because both play multiple functional roles in the food matrix, especially in baked goods (Ghotra et al., 2002; Miller et al., 2017; Pareyt et al., 2009). Indeed, any reduction in sugar and fat can lead to the dough becoming harder to process and to shorter shelf life. Additionally, sugar and fat content strongly drive consumer preferences, and any decreases in their levels generally alter sensory attributes and decrease appreciation (Marty et al., 2018; Nguyen et al., 2015, Cooper, 2017). Moreover, most companies have indicated that the main barriers to product reformulation are concerns over reduced palatability; lower product quality resulting from functional ingredient replacement; and higher costs due to the use of alternative ingredients or changes in production (Van Gunst et al., 2018). Another problem is that food reformulation often takes place on a voluntary basis and only focuses on individual products. As a result, consumers can simply select other, unreformulated products on the market (Van Gunst et al., 2018).

These challenges translate into the limited use of reformulation by the food industry. A recent study conducted across 20 European countries showed that many packaged foods and drinks still have excessively high levels of fat, sugar, and salt as well as extremely low levels of fibre (Bonsmann et al., 2019).

For example, in the UK between 2015 and 2018, most companies did not achieve a targeted 5% reduction in overall sugar content in the top 5 product categories (i.e., cookies, cereal bars, breakfast cereals, chocolate and sugar confections, and yoghurts) that contribute most to the population's sugar intake (Bandy et al., 2021). Food scientists and food engineers are thus facing a number of hurdles, which may also contribute to the food industry's hesitancy to adopt voluntary food reformulation, given that the changes are not immediately cost and time effective (Cooper, 2017; Harastani et al., 2020; Lacey et al., 2016; Vagnoni & Prpa, 2022; Van Gunst et al., 2018).

Consequently, there is a clear and pressing need to identify innovative solutions for facilitating food reformulation, such that industry players can more easily developed healthier, reformulated versions of their products. One possibility is for food reformulation to be applied more uniformly within product categories, instead of tackling one product at a time. Consumers would thus have less to gain by switching products; brands would be less likely to lose consumers to competitors; and consumer food intake habits and dietary quality would likely improve.

To help address this need, we have developed a new strategy for exploring food reformulation possibilities that applies a multifactorial approach to a product category of interest. This strategy uses commercial products as a starting point and aims to realistically reduce overall calorie content and levels of certain nutrients. By conducting multicriteria analyses of both composition and nutritional properties, it is possible to characterise product recipe diversity. Theoretically, this approach should have a greater likelihood of success because it utilises the range of existing products for an entire product category.

To test the strategy, we performed a case study using chocolate chip cookies. In general, cookies play a major role in children's diets because of their frequent consumption and poor nutritional properties (Alessandrini et al., 2019; European Food Safety Authority, 2011).

Cookie structure is highly dependent on both processing conditions (temperature, moisture, duration) and formulation (sugar and fat content). Thus, reformulation must take into account the food's multiple dimensions in order to anticipate shifts in physicochemical and sensory interactions (Hough et al., 2001). However, food packaging information often only lists composition and nutritional properties. In some cases, the front packaging also provides indications of texture, such as "soft cookies" or "crisp cookies".

In addition to ingredient quantities, the origin of the raw materials used may impact cookie structure and texture; it can thus affect reformulation possibilities, sensory attributes, and palatability.

Indeed, texture often drives food preferences (Drewnowski, 1997; Scott & Downey, 2007), and food categories and product families may contain foods that differ greatly in texture (Brown & Braxton, 2000; Helgesen et al., 1997). Thus, it would be useful to have physicochemical information for products within a given food category. Past research indicates the types of data that are best correlated with cookie texture. First and foremost, cookie fracture properties can affect sensory perception during mastication (Baltsavias et al., 1997). Describing the relationship of cookie texture with strain at rupture (proxy for softness) and stress at rupture (proxy for hardness) is helpful. Furthermore, cookie spread (final product size and proportions) might impact visual sensory attributes and preferences. Finally, a cookie's volume and fraction of air affect its structure and fracture properties (Baltsavias et al., 1997; Pareyt et al., 2009), which means measuring density is crucial.

In addition to physicochemical analysis, it is essential to measure how products are perceived by consumers. A helpful approach is quantitative descriptive analysis (QDA), where a group of panellists are asked to describe the sensory attributes of products within a specific food category (Civille & Lawless, 1986). Cookie structure is known to heavily influence perceived texture, flavour, and taste during mastication (Foegeding et al., 2015). Thus, by combining physicochemical and sensory data, it may be possible to improve a food's nutritional profile while simultaneously maintaining its sensory attributes and palatability for children.

The goal of this study was to identify reformulation possibilities for chocolate chip cookies by analysing the suite of physicochemical and sensory properties represented within the product category. First, we characterised product and recipe diversity by measuring these two sets of properties (FIGURE 29, Step 1) for a subset of 18 chocolate chip cookies, found to be representative of this food category in a previous study (Liechti et al., 2022, 4.1). Second, we identified which compositional and physicochemical variables were most likely to influence sensory attributes (FIGURE 29, Step 2). Third, we identified specific reformulation possibilities that would maintain product sensory attributes using a trends, scatters, and outliers (TSO) approach based on simple linear regression (FIGURE 29, Step 3).

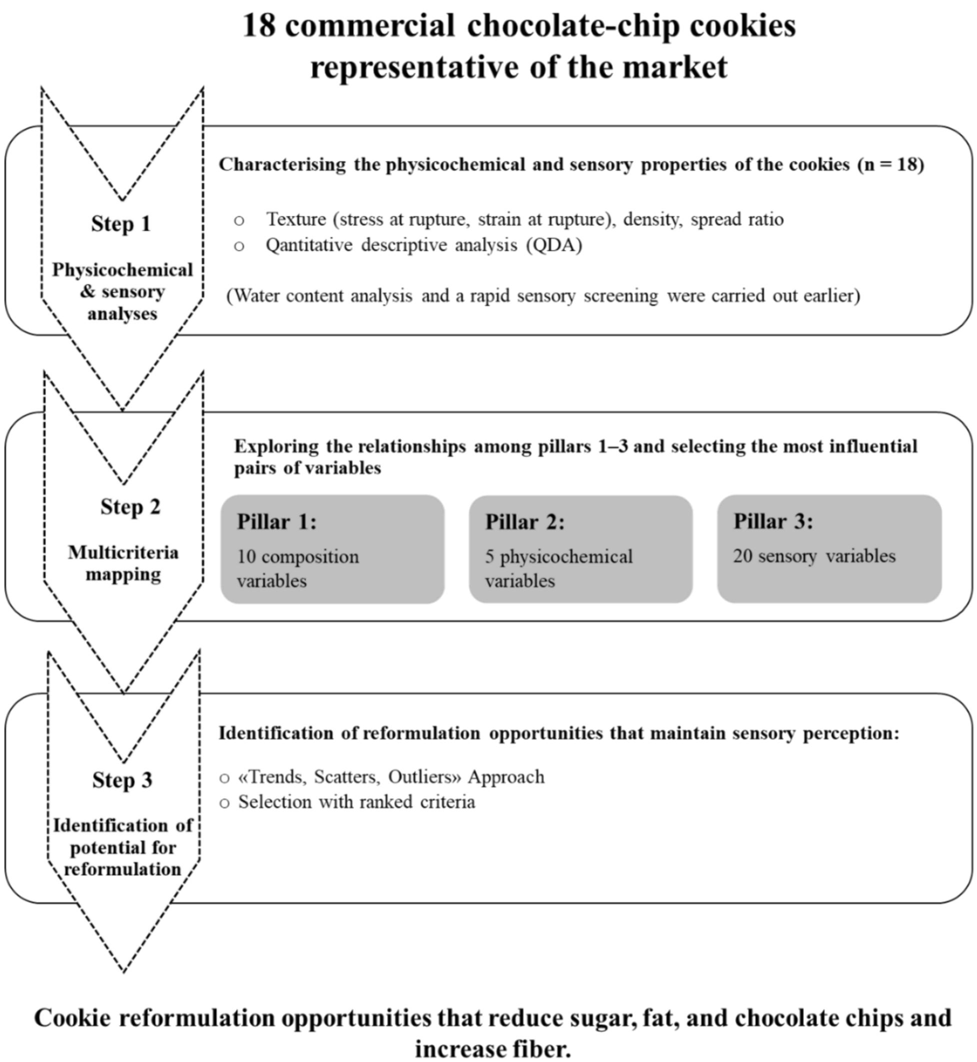


FIGURE 29 : Overview of our multicriteria reformulation approach (Steps 1–3) that utilised compositional, physicochemical, and sensory data for 18 commercial chocolate chip cookies.

4.2.1.1 Trends, scatters, and outliers approach

This section describes the TSO approach, which was used in this study to identify reformulation possibilities based on linear regression analyses between compositional properties and sensory attributes. For the compositional properties, we focused on nutrients and ingredients that can contribute to adverse health outcomes when consumed at excessive levels (sugar, fat, and chocolate chips) or at meagre levels (Bonsmann et al., 2019). For the sensory attributes, we selected 11 properties associated with food perception and preference that display shifts due to reformulation-related changes in the food matrix.

Among them were texture in mouth, taste, aroma, and visual attributes related to the perceived quantity of chocolate chips.

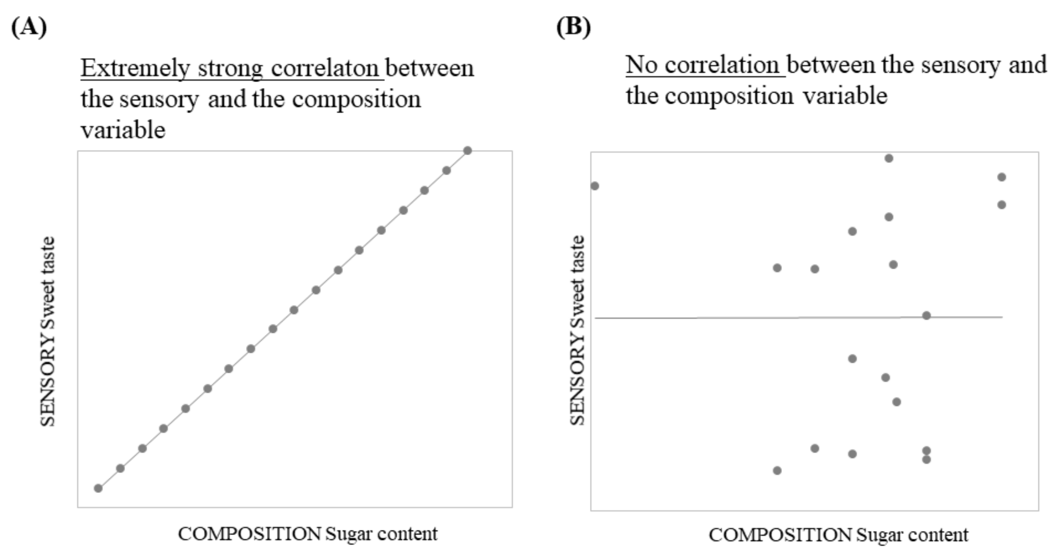
4.2.1.2 Underlying principle

The TSO approach aims to facilitate the process for identifying food reformulations that could improve a product's nutritional profile while maintaining its sensory attributes. Note that, depending on the nutrient or ingredient, improvement results from reducing or increasing content. In traditional reformulation approaches, the starting point is most often a single existing product. In contrast, we suggest that the product category must be analysed as a whole so as to 1) identify the compositional properties that do and do not affect sensory attributes across a range of products and 2) determine whether leeway exists for reformulation. In other words, if a weak link occurs between a compositional property and certain sensory attributes, it means that it would be possible to change this property without provoking a change in sensory attributes. The same applies for outliers. The existence of any product that displays a strong departure from a linear relationship between compositional properties and sensory attributes can successfully undergo a shift in composition. While the reformulation process might not be straightforward, the presence of either a weak correlation or outliers indicates that at least one solution exists. Furthermore, food engineers can define reformulation strategies by analysing an outlier's composition, physicochemical characteristics, and sensory attributes. This approach could thus pave the way for reverse-engineering the product recipe.

The TSO approach is illustrated by three examples (A, B, and C; FIGURE 30) that show three possible linear relationships between the sensory attribute sweetness and the compositional property sugar content. In the first two cases, there are no outliers because there is either a high degree of correlation (FIGURE 30 A) or a complete absence of correlation (FIGURE 30 B).

In the third case, a somewhat weak relationship exists between the two variables (FIGURE 30 C): they display a significant positive relationship where the coefficient of determination (R^2) is low. In other words, although higher sugar content is generally associated with greater perceived sweetness, some cookies are found quite far from the linear regression line. Such a pattern could result, for example, from differences in ingredients or composition as well as from the presence of certain aromas and additives. Taken together, they can lead to differences in cookie structure, texture, and sensory perception. One of the outlier cookies (highlighted in FIGURE 30 C) could potentially be reformulated to have a lower sugar content but retain its sweetness, given the prediction of the regression line. Furthermore, cookie number 15 could be used as a reasonable model during reformulation, given its proximity to the line. The closer a cookie is to the line, the greater the probability that it will display a positive relationship between sugar content and sweetness. In this example, it appears possible to reduce the sugar content by 18.7% to obtain the same level of sweetness.

To apply the TSO approach, we performed linear regression analyses using compositional properties and sensory attributes that had been selected via multicriteria mapping. Almost all the analyses were able to be conducted for the 18 study cookies. However, we could only perform the linear regressions between the compositional property fat content and the sensory attributes hardness in mouth, crispness, sandiness for the hard cookies (n = 14) because the soft cookies (n = 4) were extreme outliers.



(C)

Optimal correlation between the two variables – sugar content could be reduced while maintaining the sweet taste.

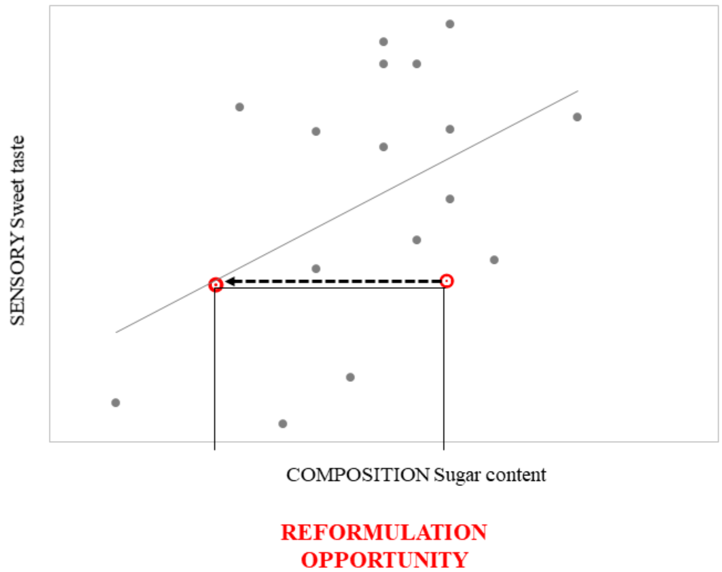


FIGURE 30 : Example application of the TSO approach to identify reformulation possibilities for commercial chocolate chip cookies (n = 18). Linear regressions between the sensory attribute sweetness and the compositional property sugar content indicate whether sugar content could be reduced while maintaining sweetness. (A) The two variables are highly correlated, and there are no outliers. (B) The two variables are uncorrelated, so there are no outliers. (C) The correlation is neither too strong nor too weak, making it possible to identify potential outliers that could reformulation targets.

4.2.1.3 Identification of reformulation opportunities that maintain sensory attributes

Thirty-nine pairs of variables (39 linear regressions) were obtained during Step 2 (FIGURE 29). We applied five criteria to determine which pairs were the most informative from a reformulation perspective. All the linear regressions were conducted similarly (i.e., those with 18 vs. 14 cookies), except in the case of the partial least squares (PLS) regressions described below (Step 4).

As noted above, the relationship between variables should be neither too weak nor too strong to yield outliers of interest. For the 39 linear regressions, we established a cut-off threshold of $p < 0.2$.

Thus, the **first step** was to exclude all linear regressions where $p > 0.2$ (around one-third of the 39). From the results, it is apparent that there was little to no relationship between the variables in these regressions, which means there was no potential for cookie outliers (SUPPLEMENTARY FIGURE 2 C and D). In contrast, regressions below the threshold (e.g., example A in SUPPLEMENTARY FIGURE 2) contained clear outliers.

The **second step** was to focus on cases where reformulation might be possible (e.g., reducing sugar and fat while increasing fibre, while nonetheless maintaining sensory attributes.

The **third step** was therefore to select the cookies whose composition provided an evident opportunity for improvement, focusing on nutrients and ingredients with either excessively high or low levels based on nutritional guidelines (Bonsmann et al., 2019). In the former case, we prioritised those that contribute most to overall calorie content, notably sugar, fat, and chocolate chips. In the latter case, we focused on fibre. Other nutrients were less relevant to our objectives (e.g., salt, saturated fat, and protein) and were therefore ignored.

The **fourth step** was to identify the possible impacts of physicochemical characteristics and compositional properties on sensory attributes using PLS regression (components 1 and 2)**.** One PLS regression was conducted using the full set of study cookies (n = 18). A second PLS regression was conducted with the hard cookies only (n = 14). In both analyses, hardness in mouth was the sensory attribute most significantly influenced by physicochemical and compositional variables.

4.2.2 Materials and Methods

4.2.2.1 Market inventory and cookie selection (Step 0)

A subset of 18 study cookies were chosen based on a comprehensive market inventory that examined a total of 178 commercial chocolate chip cookies (Liechti et al., 2022, section 4.1). This inventory obtained nutritional and compositional information from product packaging. Water content analysis and rapid sensory screening were carried out for a preliminary group of 62 cookies. Based on multiple criteria (i.e., nutritional characteristics, composition, water content, sensory attributes, and pricing), we chose 18 chocolate chip cookies that were representative of the market as a whole (FIGURE 31). These study cookies displayed a broad range of recipes (SUPPLEMENTARY TABLE 8, SUPPLEMENTARY TABLE 9, SUPPLEMENTARY TABLE 10) nutritional characteristics (i.e., in kcal, fat, saturated fat, carbohydrate, sugar, protein, fibre, and salt levels), compositional characteristics (% cacao and chocolate powder, % chocolate chips, number of additives, and Rayner score [Rayner, 2017; Rayner et al., 2005]), processing scores (Maurice et al., submitted), water contents, and sensory attributes (e.g., texture in hand, cookie surface, and chocolate chip quantity and visibility) (SUPPLEMETNARY TABLE 11). Consequently, there was definite potential for nutritional profile improvement. Nearly all the cookies had the worst Nutri-score (E) except for one (D).

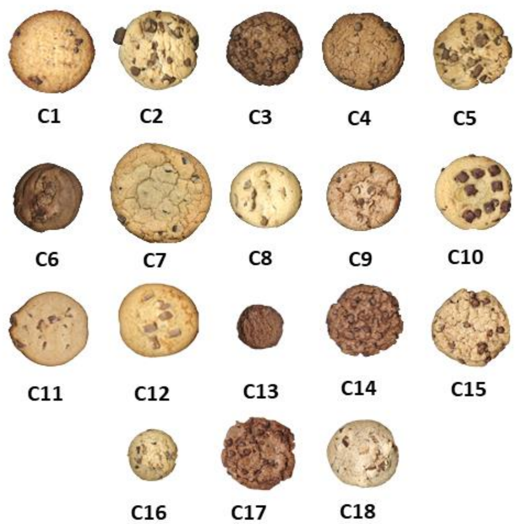


FIGURE 31 : Pictures of the 18 commercial chocolate chip cookies (C1–C18) used in this study. This cookie subset is representative of the broader market.

4.2.2.2 Physicochemical analyses

4.2.2.2.1 Density

The density of the 18 study cookies was measured using a VolScan Profiler (Stable Micro Systems, Surrey, UK), which has been used in previous research on baked goods and baking ingredients (Mäkinen et al., 2013). The test conditions were as follows: rotation speed of 1 rps and vertical scan increment of 2 mm. Cookie density was calculated by dividing cookie mass by cookie volume. All measurements were obtained in triplicate.

4.2.2.2.2 Texture

The texture of the 18 study cookies was measured using a three-point bending test carried out with a TA.HDplusC Texture Analyser (StableMicrosystems, Surrey, UK). The machine was controlled via Exponent Connect software. The experimental conditions were as follows: the distance between the pins was 14 mm, the trigger force was 0.5 N, the probe travel distance was 30 mm, the pretest speed was 1.0 mm/s, test speed was 0.2 mm/s, and post-test speed was 1 mm/s. All measurements were obtained in triplicate.

Stress at rupture (σr) (1) and strain at rupture (εr) (2) were calculated (Baltsavias et al., 1997) in the following way:

(1) $$\sigma_r = \frac{3 \times F_r \times L}{2 \times l \times h^2} \quad (kN/m^2)$$

(2) $$\varepsilon_r = \frac{6 \times h \times y_r}{L^2} \quad (\%)$$

where L = the distance between the two fixtures of the plane on which the cookie rests (m), l = cookie width (m), h = cookie height (m), F = force (N), Fr = breaking force (N), and yr = rupture distance (m).

4.2.2.2.3 Spread ratio

The spread ratio for the study cookies was calculated by dividing cookie diameter by cookie height. The latter was measured in the cookie's middle and was based on the cookie dough (chocolate chips excluded). Cookie diameter was measured using a Vernier calliper. All measurements were obtained in triplicate.

4.2.2.3 Quantitative descriptive analysis

4.2.2.3.1 Panelists and testing conditions

Sensory evaluation of the 18 study cookies was performed using QDA (Stone & Sidel, 1993). Twelve volunteers served as panellists (10 women and 2 men; 21–64 years old). They were recruited at AgroParisTech (Massy, France) in 2020. Before taking part in the study, they signed a consent form and received compensation for their participation. Samples of the study cookies were placed on a white paper plate and were designated by randomly attributed three-digit numbers. The samples were presented using a sequential monadic design. Sample evaluation order was balanced over the panel using a Williams Latin square design to account for potential order and carry-over effects. Panellists were asked to rinse their mouths with mineral water (Evian, France) between samples.

4.2.2.3.2 Procedure

In total, each panellist took part in 14 QDA sessions. First, we organised four 45-min sessions that were dedicated to generating, refining, and selecting sensory attributes. During the first session, panellists generated a list of 303 descriptors for sensory attributes. They spanned attribute families such as visual perception, odour, taste, aftertaste, texture in hand, and texture in mouth. Through discussions, a subset of 20 sensory attributes were chosen and clearly defined. Evaluation protocols were then developed (see the scale anchors in SUPPLEMENARY TABLE 12). The attributes belonged to five attribute families: aspect (8), texture (6), aroma (3), taste (2), and odour (1). Four sessions were subsequently organised to train panellists to evaluate the attributes on a 10-cm unstructured scale; attribute intensity was then evaluated using external reference products. Finally, across 6 evaluation sessions, the panellists evaluated the 20 sensory attributes for the 18 study cookies (6 cookies per session).

4.2.2.4 Multicriteria mapping

We performed multicriteria mapping for the 18 study cookies using the data obtained for 10 compositional properties, 5 physicochemical characteristics, and 20 sensory attributes (FIGURE 29, Step 2). The loading plots were used to select pairs of compositional and sensory variables of interest. All the compositional properties were considered, except those for which no threshold nutritional value could be chosen and those that contained unique ingredients (only a concern for a small number of cookies). With regards to the sensory attributes, we choose to focus on taste, aroma, and texture in mouth. Odour, texture in hand, and visual attributes were excluded for these analyses. Once pairs of compositional and sensory variables had been selected, the next step was to identify reformulation possibilities using the TSO approach (see above).

4.2.2.5 Statistical analysis

All the statistical analyses were conducted using XLSTAT (v. 2018.1.1; Addinsoft, New York, USA). Significant differences in the cookies' physicochemical characteristics and sensory attributes were determined using ANOVA, where $\alpha = 0.05$. To visually explore differences in the results, we carried out principal component analysis (PCA) on a correlation matrix; the data were averaged across replicates and panellists. To visually explore differences in the multicriteria results, we performed multiple factor analysis (MFA) (centred by group; Pearson type; PCA type: correlation; coefficient: n; missing data: replace by mean). The data for each criterion were averaged across replicates and/or panellists.

Three tables were created containing quantitative values for compositional properties (10 variables), physicochemical characteristics (5 variables), and sensory attributes (20 variables). MFA is a useful tool for dealing with multidimensional data in the sensory sciences. Moreover, it makes it possible to visualise and interpret the relationships among different data types, such as compositional properties, physicochemical characteristics, and sensory attributes.

To analyse the sensory profiling data, we performed a three-way ANOVA for each attribute, which included product, replicate, and panellist as the main effects and all their first-order interactions. Panellist performance was also assessed based on the participants' ability to differentiate among the cookies and score repeatability. In the TSO approach, linear regressions were used to analyse the relationships between pairs of sensory and compositional variables. PLS regression with two interaction levels was employed to identify significant associations among compositional, physicochemical, and sensory variables (fast algorithm, reduced and centred data; method: PLS-R; 95% confidence interval; missing data: mean or mode; filter: N first rows). In the models, sensory attributes were the dependent variables, and compositional properties (10) and physicochemical characteristics (5) were the independent variables.

4.2.3 Results

4.2.3.1 Cookie physicochemical diversity

The 18 study cookies displayed significant differences in the five physicochemical characteristics ($p < 0.05$; TABLE 3 and SUPPLEMENTARY FIGURE 3). The cookies could primarily be differentiated based on spread ratio, water content, and stress at rupture (SUPPLEMENTARY FIGURE 3: axes F1 and F2). Most of the cookies tended to have higher stress at rupture, lower water content, and lower density; only a few cookies had greater water content and density. Significant correlations were found between density and water content ($r = 0.562$) and between water content and stress at rupture ($r = -0.548$). The density and water content values might convey key information about processing. Notably, higher density and water content could indicate that baking time or temperature was lower. Moreover, the negative relationship between water content and stress at rupture might mean that water content plays a role in cookie texture, particularly in hardness or softness. The mean values of all the physicochemical characteristics are provided in SUPPLEMENTARY TABLE 13.

TABLE 3 : Differences in physicochemical characteristics among the 18 study cookies (means ± SD, F values, and p-values). Significance was determined using α = 0.05.

Physicochemical characteristics	F	p-value	Mean ± SD
Strain at rupture	17.33	< 0.0001	0.288% ± 0.515%
Stress at rupture	20.72	< 0.0001	0.145 kN/m^2 ± 0.092 kN/m^2
Density	12.66	< 0.0001	0.736 ρ ± 0.090 ρ
Spread ratio	30.96	< 0.0001	5.774 mm ± 1.718 mm
Water content	38.435	< 0.0001	4.118% ± 2.049%

4.2.3.2 Cookie sensory diversity

Based on the panellists' evaluations, the 18 study cookies differed significantly in all 20 sensory attributes ($p < 0.05$; TABLE 4). Overall, panellists scored most of the attributes in a consistent and repeatable way. The interaction effects were negligible compared to the product effects. In general, Fisher values were lower for sweetness, butter aroma, salty aftertaste, and time in mouth.

Moreover, the cookies displayed a high level of sensory diversity (SUPPLEMENTARY FIGURE 4), with the most differentiation arising from texture-related attributes, such hardness in mouth, crispness in mouth, and hardness in hand (axes F1 and F2). Chocolate-related attributes played a role as well, notably chocolate aroma, odour, and aftertaste. In addition, the cookies tended to have either a chocolate or butter aroma. Cookies with higher hardness in mouth had higher perceived numbers of chocolate chips (0.604) and smaller sized chocolate chips (-0.613). Furthermore, crispier cookies displayed a shorter time in mouth (-0.508), and hardness and crispness in mouth were strongly correlated (0.948). The mean values of all the sensory attributes are provided in SUPPLEMENTARY TABLE 14.

TABLE 4 : The 20 sensory attributes of the 18 study cookies evaluated via QDA by the 12 panellists. In bold are the significant F and p-values for the variables panellist, product, repetition, and their interactions. Abbreviations for attribute family: O = odour, H = in hand, T = taste, A = aroma, At = aroma after taste, M = in mouth, and V = visual appearance.

Attributes	**Panellist**		**Product**		**Repetition**		**Panellist * Product**		**Panellist * Repetition**		**Product * Repetition**	
	F	p-value	F	p-value	F	p-value	F	p-value	F	p-value	F	p-value
Chocolate (O)	2.37	**0.01**	26.26	**<0.01**	0.71	0.40	1.36	**0.04**	0.83	0.61	2.30	**<0.01**
Hardness (H)	2.81	**<0.01**	64.86	**<0.01**	0.35	0.56	1.26	0.10	1.60	0.11	3.82	**<0.01**
Brittleness (H)	3.72	**<0.01**	23.24	**<0.01**	1.77	0.19	1.03	0.43	0.79	0.65	2.05	**0.01**
Sweetness (T)	12.75	**<0.01**	4.33	**<0.01**	0.89	0.35	1.69	**<0.01**	0.87	0.57	1.20	0.28
Chocolate (A)	4.89	**<0.01**	21.83	**<0.01**	0.11	0.74	1.23	0.12	1.50	0.14	2.49	**<0.01**
Butter (A)	17.99	**<0.01**	7.46	**<0.01**	0.41	0.52	1.81	**<0.01**	2.49	**<0.01**	0.95	0.52
Chocolate (At)	5.60	**<0.01**	18.23	**<0.01**	0.57	0.45	1.21	0.14	0.71	0.73	2.38	**<0.01**
Salty (At)	11.00	**<0.01**	2.13	**0.01**	0.23	0.63	1.21	0.14	1.01	0.44	2.17	**<0.01**
Crispness (M)	4.64	**<0.01**	38.15	**<0.01**	0.18	0.68	0.90	0.73	0.80	0.64	4.50	**<0.01**
Sandiness (M)	3.57	**<0.01**	25.14	**<0.01**	2.80	0.10	1.20	0.16	1.12	0.35	3.23	**<0.01**
Hardness (M)	9.00	**<0.01**	45.55	**<0.01**	9.00	**<0.01**	1.74	**<0.01**	0.95	0.50	2.74	**<0.01**
Time (M)	5.06	**<0.01**	5.44	**<0.01**	0.62	0.43	1.72	**<0.01**	2.31	**0.01**	0.64	0.85
Dough colour (V)	3.11	**<0.01**	55.98	**<0.01**	2.16	0.14	1.05	0.39	0.72	0.71	2.34	**<0.01**
Chocolate visibility (V)	4.69	**<0.01**	39.84	**<0.01**	0.36	0.55	1.33	0.06	0.98	0.47	3.49	**<0.01**
Chocolate quantity (V)	2.96	**<0.01**	41.13	**<0.01**	1.63	0.21	1.03	0.44	1.61	0.11	5.25	**<0.01**
Chocolate size (V)	6.28	**<0.01**	30.00	**<0.01**	3.34	0.07	1.54	**<0.01**	0.68	0.75	3.74	**<0.01**
Contour regularity (V)	5.58	**<0.01**	22.30	**<0.01**	0.36	0.55	1.24	0.11	0.99	0.46	3.80	**<0.01**
Cookie size (V)	4.11	**<0.01**	29.06	**<0.01**	0.18	0.67	1.10	0.29	0.84	0.60	6.62	**<0.01**
Crackliness (V)	5.13	**<0.01**	44.26	**<0.01**	1.07	0.30	1.67	**<0.01**	2.86	**<0.01**	2.56	**<0.01**
Cookie height (V)	8.48	**<0.01**	49.27	**<0.01**	1.68	0.20	1.56	**<0.01**	0.74	0.70	2.37	**<0.01**

4.2.3.3 Multicriteria mapping

The multicriteria mapping found marked diversity in the compositional properties, physicochemical characteristics, and sensory attributes of the 18 study cookies (FIGURE 32).

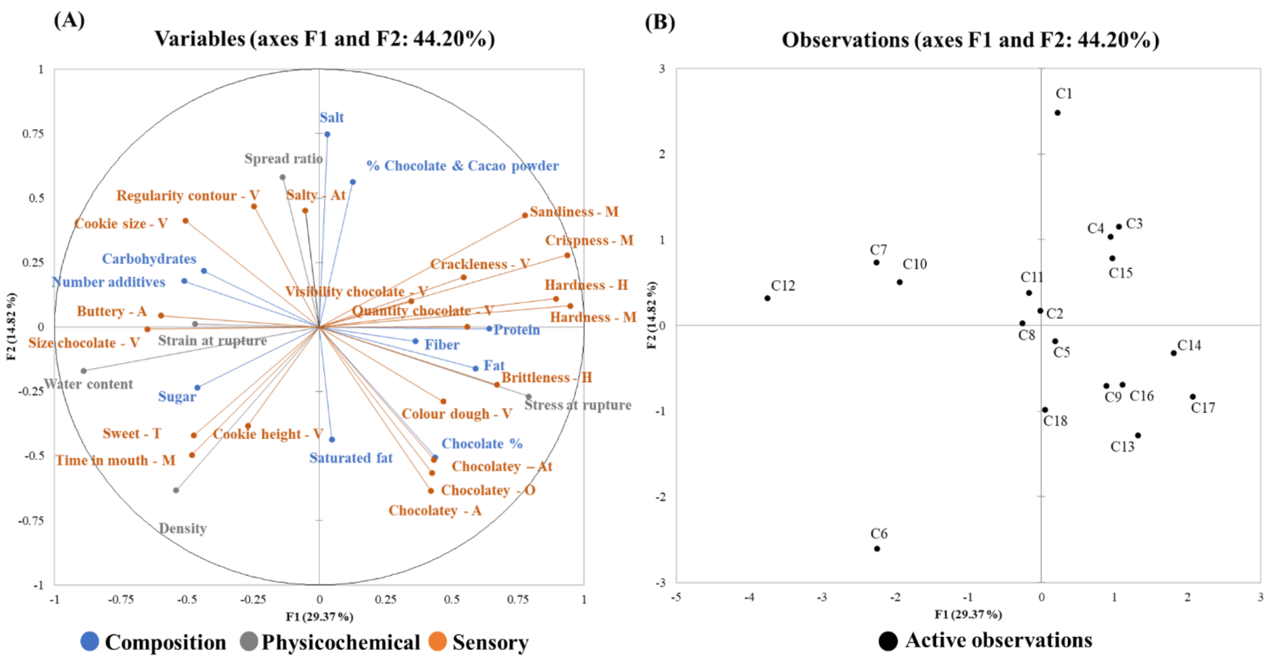


FIGURE 32 : MFA results for axes F1 and F2 (explaining 44.2% of the variation). (A) Correlation matrix including 35 variables related to compositional properties (blue), physicochemical characteristics (grey), and sensory attributes (orange). (B) Plot of the 18 commercial chocolate chip cookies (C1–C18).

The main differences occurred between the soft cookies (C12, C7, C10, C6) (FIGURE 32: axis F1 to the left) and the hard cookies (FIGURE 32: axis F1 to the right). The hard cookies tended to have higher calorie, fat, and chocolate content, while the soft cookies tended to have higher sugar levels and lower fibre and protein content. Moreover, the soft cookies had a larger number of additives and higher water content. A relationship was found between hardness in mouth and stress at rupture. Indeed, cookies perceived as less hard in the mouth had higher water content and greater strain at rupture. Given this relationship between sensory attributes and physicochemical characteristics, the next step was to focus on the relationships between sensory attributes and compositional properties.

In this regard, there were two general groups: cookies tending to have higher salt, chocolate powder, and cacao powder content but lower density (FIGURE 32: top of axis F2) versus cookies with lower salt, chocolate powder, and cacao powder content but higher density (FIGURE 32: bottom of axis F2).

Taking all these results together, we were able to choose pairs of compositional and sensory variables of interest that showed reformulation potential. Eight of the 10 compositional properties were retained. The number of additives, chocolate powder content, and cacao powder content were excluded.

We focused on 11 sensory attributes in the families of aroma (3), taste (2), texture in mouth (4), and visual appearance related to chocolate chips (2). The remaining nine attributes in the families of odour (1), texture in hand (2), and visual appearance (6) were not included.

We then proceeded to apply the TSO approach. In total, 39 pairs of compositional and sensory variables were identified as having reformulation potential (TABLE 5 and TABLE 6). Thirty-six came from the subset of all the study cookies (n = 18), while 3 came from the subset of hard cookies (n = 14). Within the compositional properties, we focused on levels of sugar, fat, saturated fat, protein, fibre, salt, and chocolate chips. Within the sensory attributes, we focused on two taste variables, sweetness and salty aftertaste; three aroma variables, butter aroma, chocolate aroma, and chocolate aftertaste; four texture-in-mouth variables, crispness, hardness, sandiness, and time in mouth; and two visual variables, chocolate chip quantity and chocolate chip visibility.

*TABLE 5 : Thirty-six influential pairs of compositional and sensory variables obtained from the multicriteria mapping of the 18 study cookies and the resulting reformulation possibilities. The linear regression statistics (correlation coefficient, p-value, R^2), the presence of outliers, and the number of significant influences ($p < 0.05$) from the PLS regression are indicated. In italics are the final selected pairs of variables. *significant linear regression (α = 0.05).*

Reformulation possibility and compositional property	Sensory attribute	Outliers	Correlation coefficient	p-value	R^2	No. significant influences
Sugar↓	*Sweetness*	Yes	0.679	0.002*	0.461	0
	Time in mouth	Yes	0.46	0.055	0.211	5
	Hardness in mouth	Yes	-0.309	0.212	0.096	25
	Crispness	Yes	-0.416	0.086	0.173	15
	Sandiness	No	-0.451	0.06	0.203	12
% Chocolate chips↓	Chocolate aroma	Yes	0.619	0.006*	0.383	0
	Chocolate aroma in mouth	No	0.565	0.015*	0.319	0
	Chocolate chip visibility	No	0.379	0.121	0.144	0
	Chocolate chip quantity	Yes	0.637	0.004*	0.406	2
	Sweetness	No	0.349	0.156	0.122	0
	Hardness in mouth	Yes	0.465	0.052	0.217	25
	Crispness	No	0.346	0.159	0.120	15
	Sandiness	No	0.184	0.465	0.034	12
Fat↑	Butter aroma	No	0.001	0.995	0.000	0
	Sweetness	Yes	-0.394	0.106	0.155	0
	Time in mouth	No	-0.359	0.143	0.129	5
Saturated fat↓	Butter aroma	No	0.354	0.149	0.126	0
	Sweetness	No	-0.333	0.177	0.111	0
	Time in mouth	No	-0.021	0.934	0.000	5
	Hardness in mouth	No	-0.093	0.714	0.009	25

	Crispness	No	-0.052	0.836	0.003	15
	Sandiness	No	-0.138	0.584	0.019	12
Salt↓	Salty aftertaste	Yes	0.685	0.002*	0.469	0
Protein↑	Hardness in mouth	Yes	0.606	0.008*	0.368	25
	Crispness	No	0.581	0.011*	0.338	15
	Sandiness	Yes	0.446	0.064	0.199	12
	Butter aroma	No	-0.326	0.186	0.107	0
	Sweetness	Yes	-0.202	0.421	0.041	0
	Chocolate aroma	No	0.151	0.549	0.023	0
	Time in mouth	Yes	-0.419	0.084	0.175	5
Fibre↑	Hardness in mouth	Yes	0.486	0.041*	0.236	25
	Crispness	Yes	0.395	0.104	0.156	15
	Sandiness	Yes	0.309	0.212	0.095	12
	Butter aroma	No	-0.660	0.003*	0.435	0
	Sweetness	No	0.202	0.422	0.041	0
	Time in mouth	No	-0.204	0.417	0.042	5

*TABLE 6 : Three influential pairs of compositional and sensory variables obtained from the multicriteria mapping of the 14 hard cookies and the resulting reformulation possibilities. The linear regression statistics (correlation coefficient, p-value, R^2), the presence of outliers, and the number of significant influences ($p < 0.05$) from the PLS regression are indicated. In italics is the final selected pair of variables. *significant linear regression with ($\alpha = 0.05$).*

Reformulation possibility and compositional characteristic	Sensory attribute	Outliers	Correlation coefficient	p-value	R^2	No. significant influences
Fat↓	*Hardness in mouth*	Yes	-0.489	0.076	0.239	1
	Crispness	No	-0.562	0.036*	0.316	2
	Sandiness	No	-0.133	0.651	0.018	0

4.2.3.4 Selection of promising reformulation possibilities

The most promising reformulation possibilities were selected based on five criteria (FIGURE 33). First, the linear regressions had to display a p-value of less than 0.2, which was the case for 26 of the 39 analyses. Second, outliers needed to be present, which was true for 14 of the 26 analyses. In general, we saw that the overall nutritional profile of the cookies could be enhanced by reducing levels of sugar, fat, chocolate chips, and salt and by increasing levels of fibre and protein (SUPPLEMENTARY FIGURE 5, SUPPLENETARY FIGURE 6, SUPPLEMENTARY FIGURE 7). In some cases, reformulation could take the form of reductions in sugar (3) and chocolate chips (3) and increases in protein (3).

However, there were fewer possibilities in which fat (2) and salt (1) could be reduced and fibre boosted (2). For most of the reformulation possibilities, there was a notably texture attribute, such as hardness in mouth (4), crispness (2), sandiness (2), and time in mouth (2). Consequently, we focused on the 10 linear regressions with most relevant nutrients and ingredients, notably sugar, fat, chocolate chips, and fibre (see the criteria-based selection process in SUPPLEMENTARY FIGURE 8).

Based on the PLS regression results for all the study cookies (n = 18; 95% confidence interval, components 1–2 = 46.09%), the texture-related sensory attribute hardness in mouth could be explained by 25 compositional and physicochemical variables. This complexity makes it difficult to identify a clear reformulation strategy, and we thus chose to exclude this sensory attribute. Similarly, crispness and sandiness could be explained by 15 and 12 compositional and physicochemical variables, respectively. They were thus also excluded. In contrast, the PLS regression results for the hard cookies (n = 14; 95% confidence interval, components 1–2 = 43.68%) found that a small number of significant variables (1–2) could explain the sensory attributes related to texture (hardness in mouth, crispness in mouth), highlighting some potential reformulation strategies.

Finally, when looking at reformulation possibilities exclusively involving sugar, fat, chocolate, and fibre, there were four linear regressions between compositional and sensory variables that displayed promise. They were those pairing sweetness and sugar content; perceived chocolate chip quantity and % chocolate chips in the recipe; hardness in mouth and fat content; and crispness in mouth and fibre content.

The four main reformulation possibilities were as follows (FIGURE 34): (A) a 13.3% reduction in sugar (from 36.9 to 32 g) while maintaining sweetness; (B) a 73.8% reduction in the percentage of chocolate chips (from 21% to 5.5%) while maintaining perceived chocolate chip quantities; (C) a 17.9% reduction in fat (from 28 to 23 g) while maintaining hardness in mouth in the hard cookies; and (D) a 53.8% increase in fibre (from 1.8 to 3.9 g). They are discussed in detail below.

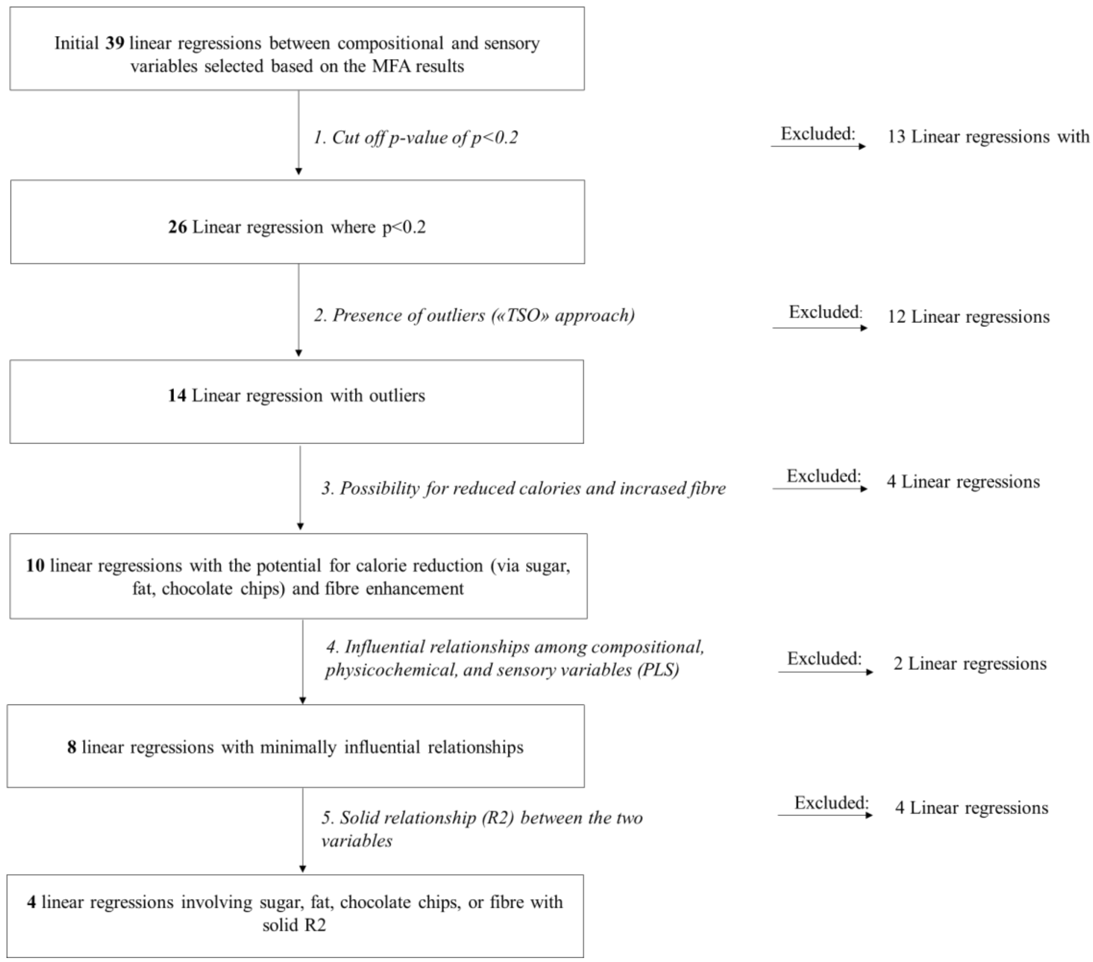


FIGURE 33 : Approach used to select reformulation possibilities from among the initial 39 linear regressions.

(A) Higher sugar content led to higher perceived sweetness (FIGURE 34A). This relationship displayed a stronger correlation than the other three relationships. For example, it can be seen that cookies C13, C16, and C6 were perceived as sweeter even though they have approximately the same sugar content as cookies C9, C10, C14, and C18. Interestingly, these three cookies have specific ingredients that differentiate them from all the other cookies: cookie C13 has chocolate aroma, cookie 16 has vanilla aroma, and cookie 6 has invert syrup. Additionally, cookie C3 was perceived as sweeter than cookie C2 despite its lower sugar content. The main difference between these two cookies is that cookie C3 has a dough made with chocolate powder. Cookies C4 and C11 were perceived as equivalently sweet, but cookie C4 contains less sugar. Cookie C11 contains both white crystal sugar and brown cane sugar. Furthermore, cookie C4 has a slightly higher fat content (26 g per 100 g) than cookie C11 (25.1 g per 100 g). In this regression, the outliers provided a more conservation reformulation strategy: a 13.3% reduction in sugar (from cookie 11 to 4).

(B) Higher percentages of chocolate chips were associated with greater perceived quantities of chocolate chips (FIGURE 34B). Some promising outliers were identified. For example, cookies C11, C13, and C6 had higher percentages of chocolate chips but, visually, were not perceived as having more chocolate chips on their surfaces. This result could be explained by a lack of visual contrast due to a browner cookie dough, resulting from the use of cacao and chocolate powder, or due to the use of brown cane sugar, which colours the dough more than white sugar. In contrast, cookie C17 was perceived as having a greater quantity of chocolate chips, but it does not have the highest percentage of chocolate chips. This result could be explained by the high density of small chocolate chips on the cookie's surface. In this regression, the greatest potential for chocolate chip reduction while maintaining perceived quantities was seen between cookies C6 and C1 (73.8%). The main difference between these two cookies is that cookie C6 has a chocolate dough, while cookie C1 has a plain dough. Other, less marked illustrations of this strategy can be seen in the differences between cookies C13 and C12 as well as cookies C11 and C7.

(C) Higher fat content led to lower perceived hardness in mouth (FIGURE 34C), although the correlation was weak. This finding underscores that, within hard cookies, there is a softening effect when fat is included in the cookie dough. Cookies C16 and C3 had the same perceived hardness in mouth, but cookie C3 had lower levels of fat. Thus, it is hypothetically possible to reduce fat content (by 17.9%) without modifying the perception of hardness in mouth. These two cookies mainly differ in their sugar content, protein content, and fat type (cookie C3 = sunflower oil vs. cookie C16 = butter).

(D) Although the correlation was relatively weak, higher levels of fibre resulted in greater crispness (FIGURE 34D) (Bonsmann et al., 2019). Cookies C6, C7, C10, and C12 are outliers because they were perceived as less crisp than their fibre contents might suggest. In contrast, cookies C5 and C11 have high fibre contents but were not experienced as intensely crispy. Cookie C8 highlights the potential for increasing fibre (53.8%) while maintaining perceived crispness. The main differences among these three cookies is that cookie C11 has a slightly higher sugar content and contains brown cane sugar. Another reformulation possibility is revealed by cookie C18 (2 g fibre). Increasing its similarity to cookie C2 (3.6 g fibre) would boost fibre content by 44.5%.

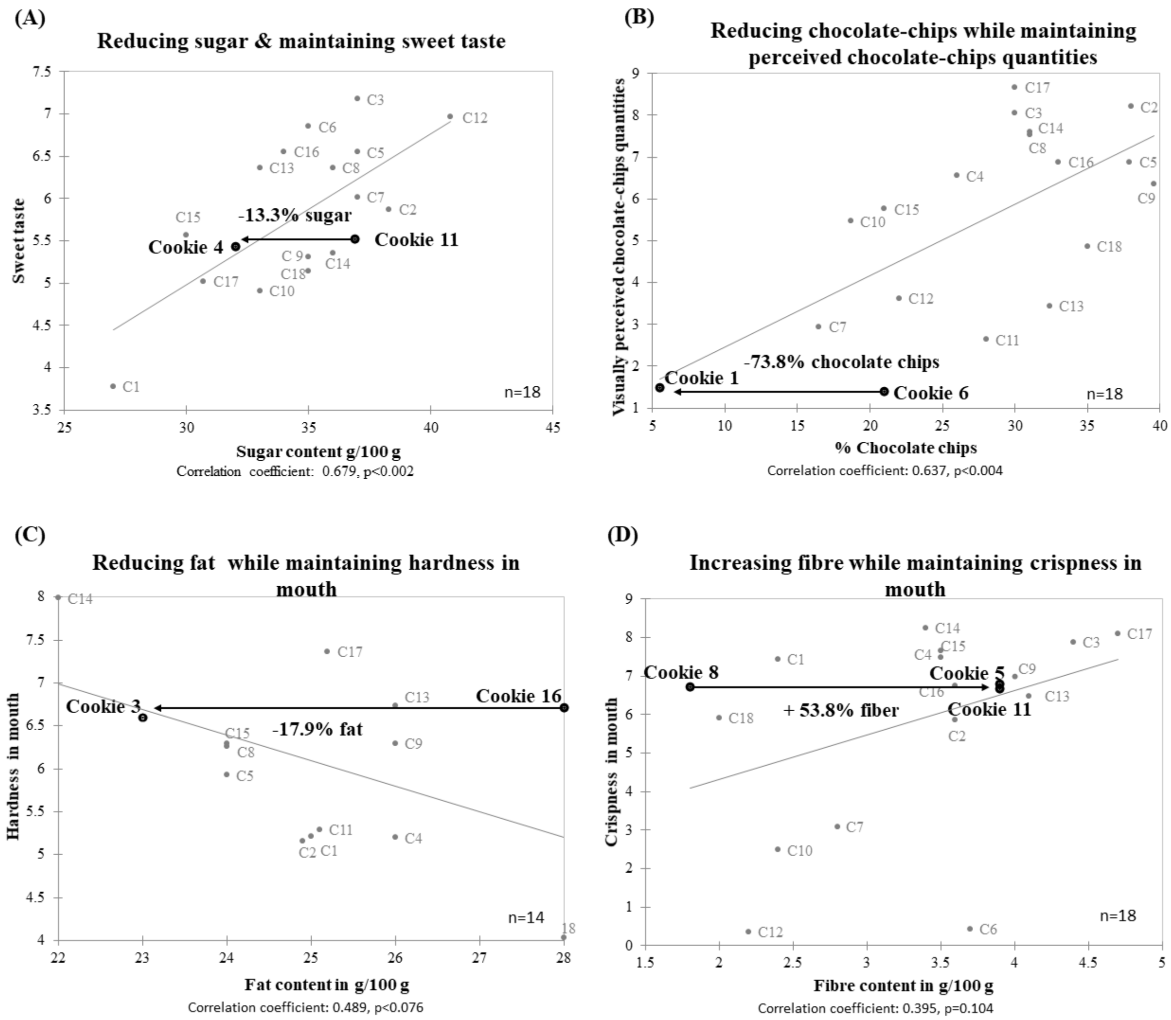


FIGURE 34 : Identifying outlier cookies and reformulation possibilities that maintain sensory attributes: (A) potential for sugar reduction, (B) potential for chocolate chip reduction, (C) potential for fat reduction in hard cookies, and (D) potential for fibre enhancement.

4.2.3.5 Reformulation effects on Rayner score, processing score, and calorie content

According to TABLE 7, reformulation would lead only to a weak reduction of the Rayner score. That said, cookie C16 obtained a better Nutri-Score, moving from E to D. With regards to calorie content, the greatest reduction was seen as a result of chocolate chip reduction in cookie C6 (-18 kcal, or 10.8% lower). Among the four target cookies, cookie C6 had the lowest Rayner score before and after reformulation. Thus, the largest reduction in calories did not impact the Rayner score. Instead, the largest reduction in the Rayner score (-3 points) arose from increasing fibre content (cookie C8); calorie content, however, did not change.

TABLE 7 : Rayner scores before and after potential reformulation of the four target cookies; with sfa = saturated fatty acids.

Cookie	Reformulation possibility	Nutritional impact per 100 g	Old vs. new Rayner score	Reduction in kcal per 100 g	Change per unit cookie
C11	Reduced sugar (13.3%) (36.9 to 32 g per 100 g)	Sugar (-4.9 g), kcal (-19.6)	21 vs. 20	-19.6 kcal	-2.7 kcal (-3.8%)
C16	Reduced fat (17.9%) (28 to 23 g per 100 g)	Fat (-5 g), sfa (-2.3), kcal (-45)	19 vs. 18	-45 kcal	-5.2 kcal (-8.8%)
C6	Reduced c. chips (73.8%) (21 to 5.5%)	Sugar (-3.1 g), fat (-4.3 g), sfa (-2.6 g), protein (-0.93), kcal (-51.6)	17 vs. 17	-52 kcal	-18 kcal (-10.8%)
C8	Increased fibre (1.8 to 3.9 g)	Fibre (+2.1 g)	24 vs. 21	-	+0.42g (+53.8%)

The four target cookies had very similar processing scores (SUPPLEMENTARY TABLE 8) that would not change much after reformulation. It is possible that the reduction in chocolate chips for cookie C6 could have an impact, but since the processing score is determined using a recipe, it is difficult to recalculate. However, when cookies with higher and lower processing scores were compared, some key differences in their ingredient lists were observed (TABLE 8). Cookie C5 had double the number of additives and contained more processed ingredients, such as wheat flour, concentrated butter, and wheat starch.

TABLE 8 : Ingredients of cookies with lower versus higher processing scores.

Cookie	Key contrasting ingredients	Additive number	Processing score
C16	• Cereal flour • Butter • Fewer chocolate chips (33%)	3	43.5
C5	• Wheat flour • Concentrated butter • More chocolate chips (37.9%) • Wheat starch • Caramel • Colouring agents	6	50.4

4.2.4 Discussion

Reformulation possibilities

We observed marked heterogeneity in the compositional, physicochemical, and sensory properties of commercial chocolate chip cookies, which generated potential for reformulation within this product category. Using a multicriteria approach, we identified several strategies for improving the nutritional profiles of cookies—by decreasing sugar (-13.3%), fat (-17.9%), and chocolate chips (-73.8%) and/or by increasing fibre (+53.8%)—while maintaining important sensory attributes, such as sweetness, perceived quantities of chocolate chips, hardness in mouth, and crispness in mouth.

Reducing sugar and chocolate chips

Past research has suggested that it might be impossible to reduce the sugar contents of baked goods by more than 10% if sensory attributes and textural properties are to be maintained (Luo et al., 2019). However, our results indicate that it might be feasible to lower sugar levels far more dramatically in commercial chocolate chip cookies. Panellists could not precisely gauge differences in sweetness among our 18 study cookies (range of sugar content: 27–40.8 g per 100 g). Past studies have proposed that sweetness can be maintained while reducing sugar content if sugar particle size is modified or the vanilla aroma congruency model is exploited (Bertelsen et al., 2021; Richardson et al., 2018). Indeed, here, we observed that cookies with increased vanilla or chocolate aroma were perceived as sweeter. We also discovered possible strategies for reducing the quantity of chocolate chips while maintaining their perceived amounts. For example, the contrast between the cookie dough and the chocolate chips can be decreased via the incorporation of cacao powder, which has a low impact on calorie content. Another possibility is reducing the size of the chocolate chips while increasing their density on the cookie surface.

Reducing fat

Producers of baked goods often utilise more saturated fats, such as butter and palm oil, because they result in particular textural and structural properties and underlie many sensory attributes (Atkinson, 2011). However, for both health and environmental reasons, highly saturated fats and oils should be replaced with alternatives such as rapeseed oil, for example. In this study, we found that the cookie made with butter was perceived as harder in mouth than the cookie made with sunflower oil. Indeed, another study found a similar result (Mamat & Hill, 2014).

Additionally, using a flour with a lower protein content could help prevent the cookie from becoming too hard (Singh et al., 2015). Further steps that could improve cookie softness include employing lower baking times, baking temperatures, or brown sugar with higher levels of molasses. The latter increases water content.

Increasing fibre

It has been well established that fibre positively affects health and weight management. Higher-fibre foods have longer oral processing times than do lower fibre foods, a trait that is associated with increased satiety (Zijlstra et al., 2008). We observed a positive relationship between cookie crispness and fibre content, a finding that has been seen before (Singh et al., 2015). In addition, fibre can act as a natural replacement in efforts to reduce fat (Erinc et al., 2018). Therefore, when increasing fibre content, strategies must be used to maintain crispness in mouth. Since this sensory attribute is strongly correlated with hardness in mouth, it should be possible to employ the same techniques as when reducing fat.

Modifying texture to increase oral processing time

We have demonstrated that cookie texture is an important consideration during product reformulation, as there were many differences in soft versus hard cookies in composition, sensory attributes, and physicochemical characteristics. Past research has found that texture modification does not just change nutritional profiles. It can also affect oral processing time, which has an influence on individual satiety and satiation (Fogel et al., 2017). We suggest that cookie texture could potentially impact oral processing, as denser cookies with higher water content were associated with a longer time in mouth. One explanation might be that such cookies are perceived as softer, chewier, and stickier. These properties might extend the time in mouth compared to harder, more brittle cookies. Furthermore, a recent study found that increased chewiness resulted in a diminished eating rate and lower levels of energy intake (Bolhuis & Forde, 2020). In summary, texture modifications could be useful tools for designing healthier products because they can increase oral processing and reduce energy intake.

Reformulation possibilities and limitations

We found that reducing chocolate chips had the greatest impact on calorie content (kcal: -10.8%), which makes sense given that chocolate chips are high in both sugar and fat (including saturated fat). However, greatly reducing calorie content did not impact the Rayner score, probably because the total reduction in sugar and fat did not go far enough. Our results indicate that, for energy-dense products, a small improvement in nutritional profiles might not affect the Rayner score. Consequently, the question arises as to whether the Rayner score is the optimal metric when reformulating calorically dense products with a view to reducing calorie content. Increasing fibre content is another useful option to consider when seeking to improve a product's overall nutritional profile. It is important to note that an 18-kcal reduction per cookie will do little to improve nutrition within a broader dietary context. To boost the effectiveness of food reformulation as a strategy, it is therefore important to focus on implementing reformulations in as many food categories as possible and to provide industries with incentives when they even slightly enhance their products' nutritional profiles.

In our methodological approach, we selected reformulation possibilities with the greatest potential for nutrient/ingredient reduction or enhancement. However, it might also be possible to aim for more moderate results, especially given that preferences must be accounted for. Since this approach will likely be used in the future to reformulate products for children, additional hurdles must be anticipated. Indeed, it is even more challenging to reformulate cookies for child consumers because sugar and fat strongly drive their preferences. Any modification can have huge consequences on children's preferences, positive sensory experiences, and food choices (Marty et al., 2018; Nguyen et al., 2015; Pareyt et al., 2009). This situation thus constitutes a real challenge for scientists and food manufacturers. Therefore, efforts at reformulation must consider preferences in addition to information about composition, physiochemical characteristics, and sensory attributes. Indeed, for products marketed to children, preference patterns will determine the extent to which sugar, fat, and chocolate chips can be reduced and fibre can be increased.

The multicriteria approach we describe here can be applied to any category of commercial products. However, the latter must be available in sufficient quantities over a period of several months for the necessary analyses to be conducted. Because food types differ in their food matrices, appropriate physicochemical characteristics will need to be selected for the category of interest. Not only can this approach be used to identify possibilities for improving nutritional quality while maintaining sensory attributes, but it can also serve as a tool for exploring options for reducing the degree of food processing; optimising oral processing via textural changes; selecting more natural and environmentally friendly ingredients; and predicting barriers to reformulation.

4.2.5 Conclusion

Our overall findings have highlighted that it should be feasible to reformulate commercial chocolate chip cookies while maintaining their sensory attributes. Using our linear-regression-based TSO approach, we identified specific strategies for doing so that reduced sugar (-13.3%), fat (-17.9%), and chocolate chips (-73.8%) as well as increasing fibre (+53.8%).

Furthermore, this study underscored the importance of considering more than just nutritional and compositional information during reformulation. It is also essential to look at the interactions between physicochemical characteristics and sensory attributes, which can point to the most promising options. We also found that cookie texture must be considered during reformulation and that the specific properties of cookie ingredients could help maintain sensory attributes.

In closing, this multicriteria approach should create a solid foundation for establishing preliminary recipes in the future. Notably, it should help reformulate products for children, improving the nutritional profiles of cookies while simultaneously maintaining their sensory attributes, which drive preference patterns. It is hoped that this approach can promote the use of food reformulation as a tool for increasing food choices and dietary quality.

4.3 ”Sensory preference patterns of French children aged 7-12 and their implications for the reformulation of commercial chocolate-chip cookies. ”

General Introduction

As any sugar and fat reduction among biscuits may impact the liking of consumers, it is crucial to include the liking information in the reformulation process. Therefore, this submitted study interested in the liking evaluation of eight commercial chocolate-chips cookies with children aged 7-12 years, as target population of this PhD work. The objective is to identify the sensory, composition and physicochemical drivers of liking and barriers to the acceptance of commercial chocolate chips cookies.

Moreover, possible inter-individual differences among children's age, gender, family, household income, city and liking patterns were investigated. In total, 151 French children aged 7-12 years old from Paris, Aix-en-Provence, Nantes and Toulouse were recruited by Eurofins Incorporated Company in France. The liking evaluation was conducted in 2020 via self-administered Home Used Test, using a five point hedonic (emoticon) scale including verbal anchors. In total 8 commercial chocolate-chip cookies selected from a representative subset of the market (18 cookies) with sensory, physicochemical and composition information were evaluated in this liking study. During eight days, children evaluated one cookie type per day in the afternoon snacking after school.

Different unidimensional (ANOVA) and multidimensional analyses (HCA, MFA) were performed to study the differences of liking between cookies and also the diversity of preference patterns. Based on the obtained clusters, children's drivers of preferences per cluster were investigated by external preference mapping via quadratic model. All the results are presented in the following part of result.

This study showed that the product category commercial chocolate-chips cookies were overall appreciated among children aged 7-12 years, despite a large composition, sensory and physicochemical diversity. This is promising for future reformulation work, as products with an enhanced nutritional profile were not disliked. Moreover, based on the identified three preference patterns, children do have preferences, and their preferences might be different based on the BMI. Further, the texture was identified as one of the key drivers of preferences (overall higher preferences for lower hardness and crispness) or disliking, where further composition (overall higher preferences for an increased salt and a reduced sugar and chocolate-chips content) and physicochemical (overall higher preferences for an increase density and water content) variables were of importance to better understand why a certain cookie is preferred or rejected.

Those obtained results will help in the next step of this PhD work, to develop preliminary recipes and a mixture design, in order to reformulate healthier cookies, while maintaining the liking and optimizing sensory perception. From now on, the study will switch from commercial to reformulated cookies. Indeed, following to the liking study, it seems now necessary to evaluate the impact of ingredients with their interactions on sensory perception and physicochemical parameters, by using the same ingredients and the same process of development. This approach will be developed in the next part of results.

"Sensory preference patterns of French children aged 7-12 and their implications for the reformulation of commercial chocolate-chip cookies. "

Research Paper, Manuscript submitted to Food Quality and Preferences

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Abstract

Food reformulation (such as sugar and fat reduction and fiber enhancement) is one possible leverage to improve children's food offer and diet. But food reformulation targeting on children seems to be challenging as sugar, fat and texture are strong drivers of preferences. Furthermore, preferences are different based on inter-individual variations and between different product categories.

Therefore, there is a need to investigate the frame in which it will be possible to reformulate a commercial products with a complex food matrix towards a healthier product, while maintaining the liking among children, considering as well their interindividual differences. In this context, the aim of this study was to better understand the drivers of preferences among school aged children for a range of commercial food products.

The focus in this study was set on commercial chocolate-chip cookies from a market inventory, which are energy dense from sugar and fat. Eight cookies were characterized with their sensory, composition and physicochemical properties in a previous study. Those cookies were then provided in the frame of a snacking situation in the afternoon at children's home. The liking was evaluated via home used test by 151 French children aged 7-12 years and having large difference in their BMI. Preference mapping were performed, based on sensory, composition and instrumental properties of cookies.

Results showed a large scope of action for a possible kcal (-6.8%), sugar (-26.8%), fat (-17.9%) and chocolate-chips (-83.4%) reduction and fiber enhancement (+59.1%) among commercial chocolate-chip cookies while maintaining the liking among children. Three identified clusters could be identified according their differences of cookies preferences. Among the cluster with the highest number of children, drivers of preferences of cookies were defined by texture and taste sensory properties (larger cookie size, lower sweet taste, lower crispness and hardness), by composition (increased salt and reduced sugar and chocolate-chip content) and by physicochemical properties (increased density and water content). Moreover, children with different BMI showed different preferences.

These results are promising to reformulate a healthier cookie while maintain the liking among children, taking into account that preferences among children 7-12 years are different. Sensory, composition and physicochemical information provide important information to better understand preferences or disliking, especially for complex food matrices such as sweet biscuits.

Keywords: Preference mapping, sensory, children, nutrition, health, biscuits

4.3.1 Introduction

Despite the current childhood obesity pandemic (NCD-RisC, 2017), packaged foods still have excessive high levels of sugar, fat and salt (Bonsmann et al., 2019). Especially, food product targeting children tend to have particularly high sugar content (Moore et al., 2020; Rito et al., 2019). This is of major concern for school-aged children.

Unfortunately, the food industry has made little progress so far. For example, between 2015 and 2018, most of the food companies in the UK couldn't reach the target sugar reduction set at -5% for the product categories that contribute the most to the high sugar intake (Bandy et al., 2021).

In this context, food reformulation is seen as a possible lever to enhance food nutritional quality and to improve consumers' diet and health (Gressier et al., 2021; Nijman et al., 2007; Spiteri & Soler, 2018). However, it seems necessary to rethink current reformulation strategies to improve the food offer.

The poor reformulation successes over recent decades might be explained by technological and sensory barriers. For example, the reformulation of high sugar and high fat foods – such as sweet biscuits – is a real challenge for the industry as those ingredients have multiple functional properties in the food matrix (Ghotra et al., 2002; Miller et al., 2017; Pareyt et al., 2009). Biscuit structure depends on both formulation (presence of sugar and fats) and processing conditions (temperature, moisture, time) (Hough et al., 2001). This means that any reduction of sugar or fat may change biscuit sensory properties and liking. Further, sugar and fat are known to be strong drivers of children's preferences and any reduction may alter sensory attributes and decrease liking (Cooper, 2017; Marty et al., 2018; Nguyen et al., 2015). Sugar and fat also play an important role in food texture, which is another important determinant of children's appreciation (Rose et al., 2004a, 2004b).

Moreover, studies conducted on various food categories found that children's' liking patterns may depend on their individual characteristics, like weight status, gender and age (Cox et al., 2016; Kubberød et al., 2002; Torri et al., 2021, Rose et al., 2004a, 2004b;).

Given the complex role played by each ingredient and their impacts on sensory attributes and preferences, it is important to take a holistic approach to food reformulation. Considering sensory perception and liking attributes in the early stages of reformulation would help avoiding usual hurdles.

Better understanding children's sensory drivers of preferences and relate them to their sociodemographic data would be a great asset for improving product nutritional quality.

Only if we understand the liking and disliking of specific product properties, we can adapt the reformulation work to specific target groups what may lead to a more successful reformulation. Including not only sensory drivers of liking or disliking, but as well composition and physicochemical information can provide and complete useful information for the product development. In sensory science, common methods to investigate consumers preferences is the cluster analysis, followed by an external preference mapping with a quadratic model (Masson et al., 2016; Saint-Eve et al., 2019).

The product category of interest in our study is the chocolate-chip cookies. Chocolate-chip cookies do have a high impact on childrens' diet due to its consumption frequency and poor nutritional properties (Alessandrini et al., 2019; European Food Safety Authority, 2011).

In this context, the aim of this study was to better understand children's sensory, composition and physicochemical drivers of preferences and possible disliking for commercial chocolate-chips cookies. The liking information will provide the frame of future reformulation and it allows to anticipate important cookie properties which are important to consider for future reformulation while maintaining the sensory perception and liking.

In total 8 commercial chocolate-chip cookies selected from a representative subset of the market (18 cookies) and 151 school aged children (7-12 years old) from four different cities in France (Paris, Nantes, Toulouse, Aix-en-Provence) were included. The hedonic test was conducted in 2020 at children's home with a collaboration work with Eurofins Incorporated Company in France, Paris. It was shown that home used tests including self-administered tasks for children aged 7-12 years is an appropriate methodology for hedonic evaluation (ASTM, 2021), as children must have a user friendly and safe environment during the test. Moreover, with the age of 7-12 years children might have peer interactions when conducting the test at school, what could lead to possible a bias (ebd.). Besides this, conducting a test in their natural environment reflects more properly their natural snacking behavior in the afternoon.

First, the overall appreciation among the product category commercial chocolate-chip cookie and the 151 children was investigated. Further, the link between children's liking pattern and their sociodemographic parameters such as age, gender, city, household income and BMI was analyzed. In a next step, the consumers with similar liking patterns were put together via cluster analysis.

Based on the obtained clusters, it was possible to investigate children's drivers of preferences per cluster with external preference mapping via quadratic model. To better understand the sensory drivers of liking or disliking, besides sensory variables - obtained from a trained panel - as well composition and physicochemical variables were included which were all obtained in a previous study.

4.3.2 Material and Methods

For this liking study, all participants provided written informed consent and the study was approved by University Paris-Saclay ethics committee (CER-Paris-Saclay-2020- 025).

4.3.2.1 Products

In total, 8 commercial chocolate-chip cookies (FIGURE 35) were evaluated in this study. The products were selected from a representative subset of cookies of a market inventory and based on composition, sensory and physicochemical properties performed on a previous selection of 18 cookies (Liechti et al., 2022 in section 4.1). The description on multicriteria variables of this 18 cookies was proposed in SUPPLEMENTARY FIGURE 9. In addition, supplementary criteria of cookies selection were their availability and to have similar storage conditions.

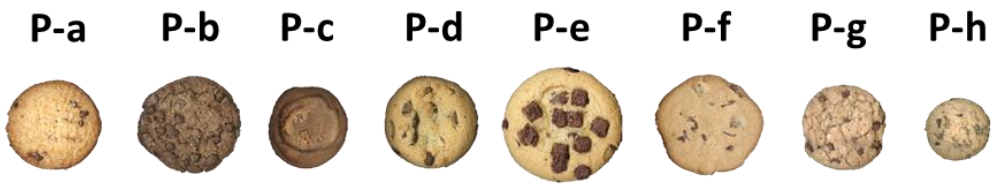


FIGURE 35 : Eight commercial chocolate-chip cookies P-a – P-h which were selected from a representative subset of the market, including sensory, composition and physicochemical information.

4.3.2.2 Composition, sensory and physicochemical variables from the chocolate-chip cookie sub-set

The 8 studied cookies were first characterized by 14 composition variables (TABLE 9). All composition variables were obtained directly from the packaging, or calculated from recipe information as the Rayner (Rayner, 2017) and the process scores (Maurice et al, submitted).

Besides the composition characterization, additional sensory and physicochemical analyses were conducted earlier. Sensory properties were carried out by quantitative descriptive analysis with 12 trained panelists. In total, 20 descriptors were generated. Anchors, definition and protocols of the attributes are detailed in SUPPLEMENARY TABLE 12. To obtain physicochemical properties of the products, measures such as density, spread ratio, texture (with strain and stress at rupture) and water content were conducted (TABLE 11).

TABLE 9 : Composition variables of all eight commercial chocolate-chip cookies included in this study. With kcal per 100g and fat, saturated fat, carbohydrates, sugar, fiber, protein and salt in g per 100g.

	P-a	P-b	P-c	P-d	P-e	P-f	P-g	P-h
Kcal	503	504	479	485	485	511	489	514
Fat	25	23	23	24	25	25.1	24	28
Saturated fat	12	6.6	14	12	14	16.1	5.9	13
Carbohydrates	62	66	61	61	60	62.2	59	57
Sugar	27	37	35	36	33	36.9	30	34
Fiber	2.4	4.4	3.7	1.8	2.4	3.9	3.5	3.6
Protein	6.5	6.1	5.6	5.2	4.7	7	7.6	7
Salt	1.5	1.3	0.2	0.8	0.8	0.6	0.4	0.4
% Chocolate chips	5.5	30	21	31	19	28	21	33
% Cacao & Chocolate powder	-	6.6	2.6	-	-	-	-	-
Number ingredients	9	11	10	13	17	8	12	11
Number additives	3	5	4	4	7	1	2	3
Rayner score	27	20	17	24	23	26	14	24
Process score	48.4	52.1	44.5	-	-	45.5	47.3	43.5

4.3.2.3 Participants

The liking study was performed by 165 school aged children, recruited by the Eurofins SAM company (France), but only 151 children finished the study and could be included in result part. The children lived in four locations in France (Paris, Aix-en Provence, Nantes, Toulouse). They were recruited about two weeks prior to the experiment using online and phone questionnaires, focused on their sociodemographic characteristics and consumption habits. Children included in this study had no ongoing adverse condition affecting vision, smell and taste, no temporarily assumed drugs that may influence taste and smell perception, no food allergies such as gluten, soy, lactose, legumes, nuts, seeds, not a specific diet and no restriction in diet.

Participants were selected using quotas for their gender, age (age in groups), household income and city (TABLE 10). The cut off for the subgroups 7-9 and 10-12 years old were selected in order to anticipate different liking patterns among younger and older children, as it was previously described (Rose et al., 2004a, 2004b). The subgroups for the total household income per months were created by Eurofins based on their database. Childrens' BMI was calculated as follows: $BMI = weight\ (kg)/\ height\ (m)^2$

To adapt childrens' BMI with their age und gender, the BMI tables "BMI for-age-boys" and "BMI for-age-girls" 5-19 years old with z-scores were used (WHO, 2007). With those tables it was possible to define childrens' BMI with the subgroups "thinness/severe thinness", "normal" and "overweight/obesity".

TABLE 10 : Sociodemographic and BMI information among all 151 children, in numbers and %.

Sociodemographic and BMI information	Subgroups	Numbers	%
Gender	Girls	75	49.7
	Boys	76	50.3
Age in years group	7-9 years	71	47
	10-12 years	80	53
Age in years	7	15	9.9
	8	27	17.9
	9	26	17.2
	10	30	19.9
	11	25	16.6
	12	28	18.5
Household income in €	0-1239 (very low)	27	17.9
	1240 -1911 (low)	29	19.2
	1912-2530 (middle)	34	22.5
	2531-3778 (high)	34	22.5
	Plus de 3779 (very high)	27	17.9
City	Paris	52	34.4
	Nantes	32	21.2
	Toulouse	20	13.2
	Aix-en-Provence	47	31.1
BMI for gender and age	Thinness/severe thinness	7	4.6
	Normal	111	73.5
	Overweight/obesity	33	21.9

4.3.2.4 Questionnaire

The questionnaire was first pre-tested on children, in order to ensure that children do well understand the questions and the tasks. After tasting the cookie, children were then asked if they like the cookie and to indicate their answer on the colored 5 point facial scale.

The type of questions was chosen in regard to literature and recommendation for children for the age 7-12 years old (ASTM, 2021; Popper & Kroll, 2007). Besides using verbal labels, it is also recommended to include a facial scale due to childrens' reading abilities, which might be very different even among the same age.

Therefore, for this study a colored 5 point facial scale with verbal labels was used, from the left side "1 = I don't like it at all" to the right side "5 = I like it very much" (ASTM, 2021, Laureati et al., 2015; Marty et al., 2018; Rannou et al., 2018) (SUPPLEMETARY FIGURE 10). The verbal labels were translated from French to English.

4.3.2.5 Study design

Liking evaluation of the 8 cookies by the children was done by a Home Use Test. All cookies in easy to open mylar bags were first distributed to the parents, in blind conditions (coded with 3 digit codes). Per bag and cookie variety, two cookies were provided. They were asked not to open the bags until to give the product to their child, in order to minimize the impact of moisture on the products. In the experiment, the order in which the eight cookies were consumed by children followed a Latin square design. The child evaluated the cookies according to a balanced experience plan. He/she was asked to eat and to evaluate one cookie variety per day. The test took therefore place during eight school days, respectively in the afternoon after school. The data was collected with the online sensory software RedJade.

4.3.2.6 Statistical analysis

All statistical analyses were conducted with XLSTAT version 2018.1.1 (Addinsoft, New York, USA) and R, including the SensoMineR package. The alpha level was set to 0.05.

Anovas were carried out to test the effect of the serving position (product x rank) and childrens' socio-demographic information and BMI (product x gender x age group x age in years x household income x city x BMI) on the liking scores for all the 151 children. When significant differences between products were revealed ($P < 0.05$), mean liking intensities were compared using the Newman–Keuls multiple comparison test between the different subgroups.

For the clustering, internal and external preference mapping, we excluded the results of 8 children due to their constant scoring for all 8 cookies. Therefore, for other analyses, the liking scores from total 143 children were included.

The diversity of preference patterns was explored using hierarchical cluster analysis (HCA) (Euclidean distance, Ward's criteria) on normalized liking scores. Differences among clusters and each cluster's specificity (in sociodemographic data and BMI) were analyzed further using a Fisher's exact Test. To first study and map the relationship of cookies sensory, composition and physicochemical properties, we performed a multicriteria mapping via multiple factor analyses (MFA) with a sensory (20 variables), a composition (9 variables) and a physicochemical (5 variables) table and one supplementary table (5 scores and composition variables). Parameters for the MFA were: centred by group; Pearson type; PCA type: correlation; coefficient: n; missing data: replace by mean). MFA is a useful tool for dealing with multidimensional data in the sensory sciences. Moreover, it makes it possible to visualise and interpret the relationships among different data types, such as compositional properties, physicochemical characteristics, and sensory attributes.

Then as a second step, the external preference mapping (with quadratic model formula = "~I(F1*F1)+I(F2*F2)+F1*F2") was conducted with SensoMineR using MFA as basis. Each consumer's liking scores were thus regressed on the first two dimensions of the global analysis of the MFA, using the coordinates of the centroids for each product as explanatory variables. As usual for quadratic model preference mapping, the scores were normalized for each consumer.

4.3.3 Results

4.3.3.1 Sensory and physicochemical diversity for chocolate-chips cookies

Based on the panellists' evaluations, the cookies differed significantly in all 20 sensory attributes ($p < 0.05$; TABLE 11). Overall, panellists scored most of the attributes in a consistent and repeatable way. The interaction effects were negligible compared to the product effects. In general, Fisher values were lower for sweetness, butter aroma, salty aftertaste, and time in mouth.

As well a broad physicochemical diversity was observed (TABLE 11). The cookies could primarily be differentiated based on spread ratio, water content, and stress at rupture. Most of the cookies tended to have higher stress at rupture, lower water content, and lower density; only a few cookies had greater water content and density.

FIGURE 39 is presenting the visualized diversity based on cookies sensory, composition and physicochemical diversity. In the correlation circle (FIGURE 39 A), on axe F1 cookies are mostly characterized by their hardness and crispness in mouth (sensory) and their density and water content (physicochemical). On axe F2, cookies were characterized by their sweet taste (sensory), their chocolate-chip quantity % (composition) and their cookie size (sensory).

TABLE 11 : Perceived mean intensities for the 20 sensory attributes evaluated by 12 trained panelists and for a total of 18 commercial cookies, by sensory quantitative descriptive analysis. Results of 8 out of the 18 cookies were presented on this table. Five physicochemical measures were further conducted on all 18 cookies in triplicates, where 8 cookies were presented in this table. Results of Anova and New-man Keuls with F and p-values, different letters represent significant differences (p ≤ 0.05) according to the Newman-Keuls test. Values that do not share letters were significantly different. With O=odor, H=texture in hand, T=taste, A=aroma, At=aroma after taste, M=texture in mouth, V=visual

	F	p-value	P-a	P-b	P-c	P-d	P-e	P-f	P-g	P-h
Chocolate O	26.3	**<0.01**	1.33 a	7.60 fg	8.53 g	2.10 ab	2.89 ab	3.71 bc	4.13 bcd	2.91 ab
Hardness H	64.9	**<0.01**	8.72 cd	8.54 cd	2.21 a	8.48 cd	1.47 a	8.83 cd	7.38 c	8.77 cd
Brittleness H	23.2	**<0.01**	2.94 abc	3.69 bc	1.17 a	6.54 de	1.52 a	3.05 abc	3.84 c	6.85 de
Sweet taste T	4.3	**<0.01**	3.75 a	7.07 b	6.80 b	6.32 ab	4.87 ab	5.47 ab	5.53 ab	6.50 b
Chocolate A	21.8	**<0.01**	0.62 a	7.29 ef	8.10 f	3.27 b	3.24 b	5.57 cde	3.94 bcd	3.81 bc
Butter A	7.5	**<0.01**	5.39 c	2.63 ab	4.32 abc	4.68 abc	4.82 abc	4.36 abc	2.53 ab	5.21 bc
Chocolate At	18.2	**<0.01**	0.71 a	7.38 fg	6.84 efg	2.10 ab	2.49 abc	5.13 def	2.64 abc	3.46 bcd
Salty At	2.1	**0.01**	4.37 a	3.48 a	3.16 a	2.75 a	2.71 a	2.90 a	2.55 a	3.25 a
Crispness M	38.2	**<0.01**	7.39 cd	7.74 cd	0.43 a	6.65 cd	2.47 b	6.68 cd	7.61 cd	6.71 cd
Sandiness M	25.1	**<0.01**	8.48 e	7.38 de	1.27 a	4.97 bc	1.42 a	4.63 b	7.05 cde	5.70 bcd
Hardness M	45.6	**<0.01**	5.17 de	6.48 efg	0.84 ab	6.25 efg	1.98 bc	5.25 de	6.22 efg	6.65 efg
Time in mouth M	5.4	**<0.01**	3.78 a	5.94 abc	6.66 c	6.49 bc	5.94 abc	4.75 abc	4.73 abc	3.98 ab
Color V	55.9	**<0.01**	3.62 bcd	8.15 f	9.13 f	2.08 ab	1.40 a	4.40 de	5.32 e	2.35 abc
Visibility chocolate chips V	39.8	**<0.01**	1.92 a	7.77 fgh	1.50 a	6.07 def	8.98 h	1.55 a	6.39 def	4.50 cd
Quantity chocolate chips V	41.1	**<0.01**	1.47 a	7.89 fgh	1.38 a	7.47 fgh	5.43 de	2.61 ab	5.72 de	6.82 efgh
Shape chocolate chips V	30	**<0.01**	1.82 a	3.76 bcd	3.98 bcd	4.81 cde	8.01 g	5.87 ef	3.65 abcd	2.67 ab
Contour regularity V	22.3	**<0.01**	7.18 de	6.63 cde	2.39 a	8.16 e	8.07 e	4.78 bc	6.65 cde	8.44 e
Cookie size V	29.1	**<0.01**	5.85 def	4.77 cd	4.08 c	2.64 b	7.18 f	6.41 ef	4.46 cd	1.38 a
Cookie height V	44.3	**<0.01**	2.88 bc	3.98 cd	8.70 j	7.23 i	4.95 def	1.43 a	4.86 def	6.57 ghi
Cracks surface V	49.3	**<0.01**	4.10 cd	7.46 f	1.72 ab	3.25 bcd	2.67 bc	0.37 a	7.24 f	3.25 bcd
Density in ρ	12.7	**<0.01**	0.64 ab	0.67 abc	0.97 g	0.66 abc	0.76 cdef	0.78 cdef	0.62 a	0.73 abcde
Spread ratio in mm	31	**<0.01**	7.23 fg	6.72 fg	3.45 ab	4.41 bc	7.62 g	4.33 bc	5.90 def	3.28 ab
Stress at rupture (σr) in kN/m2	20.7	**<0.01**	0.08 abc	0.17 cd	0.02 a	0.15 cd	0.08 abc	0.03 ab	0.13 cd	0.20 d
Strain at rupture (εr) in %	17.3	**<0.01**	0.01 a	0.01 a	0.12 a	0.74b	0.01 a	0.51 ab	0.55 ab	0.70 b

Water content in %	38.5	**<0.01**	3.63 abc	2.17 a	7.87 d	4.56 c	6.82 d	2.73 ab	3.65 abc	2.47 ab

4.3.3.2 Children liking scores of cookies

Mean liking scores ranged between 3.85 and 4.35 (on a scale from 1 = "I don't like it at all" to 5 = "I like it very much), indicating that children overall liked the 8 chocolate-chip cookies well. This said, significant differences among the products most were observed (DF 7; F: 5.1; p<0.001) (FIGURE 36). The cookie P-e was the best liked on average, whereas cookies P-g and P-c were less liked. In addition, there was a judge effect (DF 150; F: 2.8; p<0.001) and no significant impact of the evaluation order.

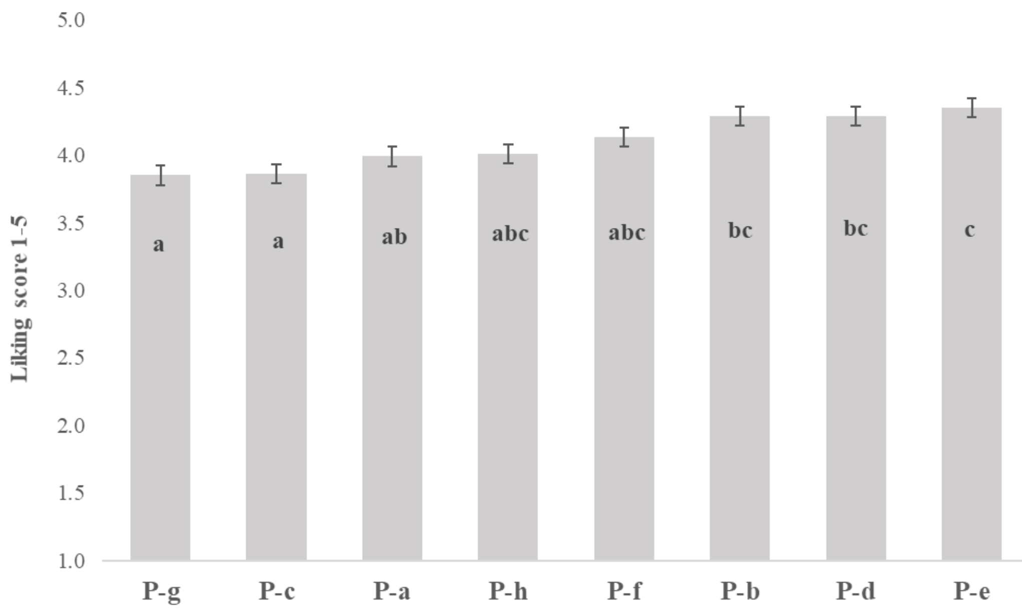


FIGURE 36 : Mean liking scores of eight (P-a – P-h) commercial chocolate-chips cookies evaluated by 151 French children aged 7-12 years old with standard error. Results of the ANOVA showed significant differences for the product effect among the liking score (DF 7; F: 5.1; p<0.001). Different letters represent significant differences (p < 0.05) according to the Newman-Keuls test. Values that do not share letters were significantly different.

Liking scores were also analyzed in the light of BMI and socio demographic data. On average, boys gave higher scores than girls (F:16.35; p<0.001). Different age groups also tended to give different scores (F: 3,51; p<0.001) (TABLE 12). Younger children aged 8, 9, 10 years gave higher scores than older children aged 11 years, whereas children with the age group 7-9 years tend to score higher than children aged 10-12 years (F: 1.02; p<0.31).

TABLE 12 : Effect of gender and age on liking scores, all products considered. Different letters represent significant differences (p ≤ 0.05) according to the Newman-Keuls test. Values that do not share letters were significantly different.

	F	P-value	Mean liking score
Gender	16.35	<0.001	
Girls			3.96 a
Boys			4.24 b
Age group	1.02	0.31	
7-9 years			4.17 b
10-12 years			4.03 a
Age in years	3.51	<0.001	
7 years			3.98 ab
8 years			4.26 b
9 years			4.25 b
10 years			4.19 b
11 years			3.86 a
12 years			3.98 ab

4.3.3.3 Liking patterns among children with different sociodemographic background and BMI groups

As a result of the AHC, we identified three different groups of children with similar liking patterns for commercial chocolate-chip cookies (FIGURE 37A). Within the clusters, most significant liking differences was found in cluster 2 (F: 19.1; p<0.0001), whereas lower liking differences were found in cluster 3 (F: 17.4; p<0.001) and cluster 1 (F: 3.17; p<0.003). The three clusters essentially differ on their appreciation of Product P-g (high liking score in cluster 3 (4.74) and the low liking score in cluster 2 (2.28), and for cluster 3 on the low liking score for product P-c (1.84) (FIGURE 37B). Moreover, the liking scores for product P-g in cluster 2 (2.28) and for product P-c in cluster 3 (1.84) were significantly lower than all other products and clusters (F: 14.8; <0.0001). The cookie P-e has the best score overall because it's well-liked on average and never disliked, but it's not a very liked product either.

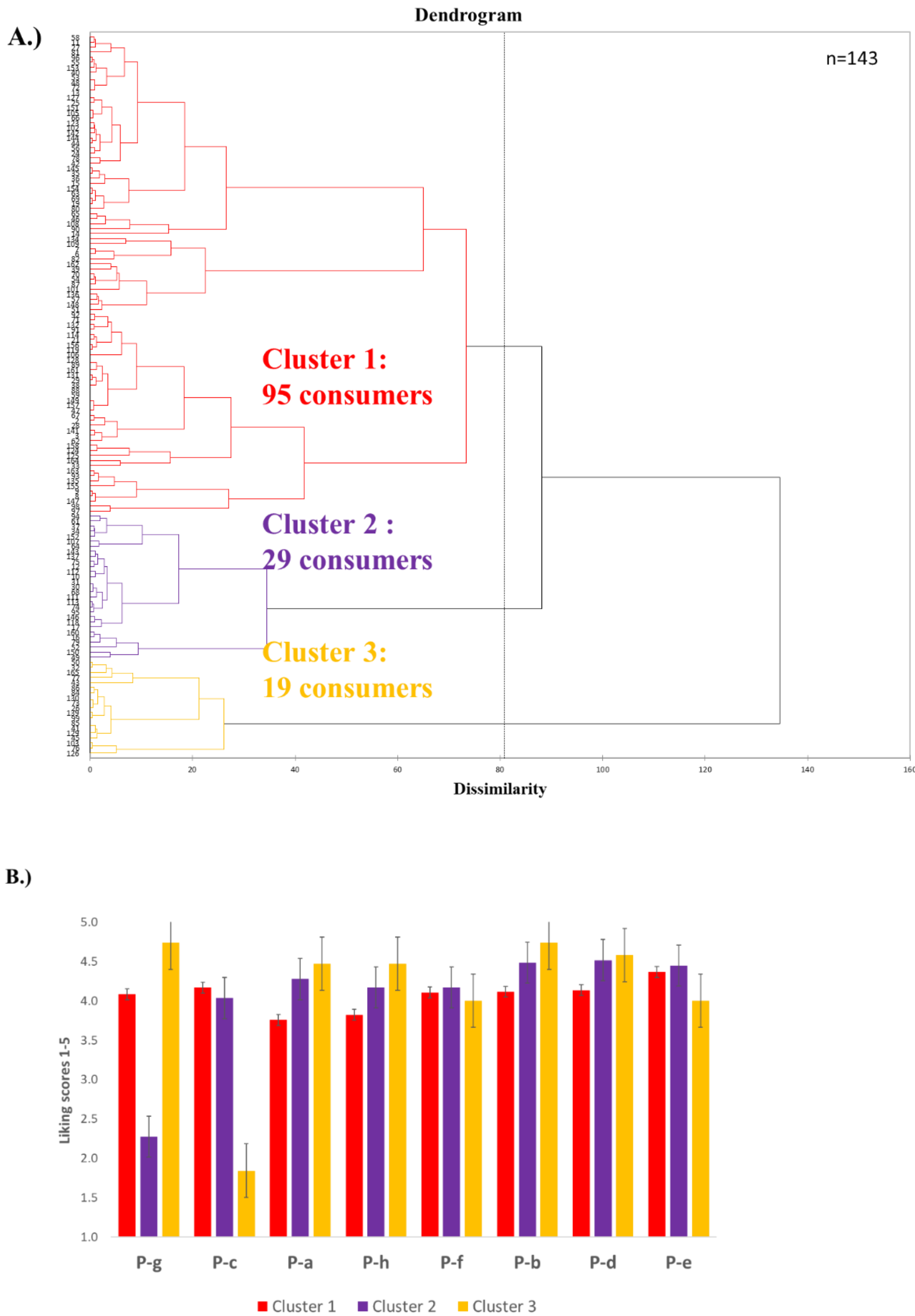


FIGURE 37 : A: Three obtained preferences clusters with 143 children and eight commercial chocolate-chip cookies, whereas cluster 3 (n=19) and 2 (n=29) contained a lower number of children than cluster 1 (n=95). B: Histogram with cluster 1, cluster 2 and cluster 3 and mean liking scores per cookie (P-a – P-h) and cluster with standard errors.

Most interestingly, these three clusters differed in their average BMI and sociodemographic values. The cluster 1 was characterized by a significant higher number of children with the BMI group "overweight/obesity" (Fisher's exact test, p<0.019) and a significant lower number of children with the BMI group "normal" (Fisher exact test, p<0.017) (FIGURE 38 A). On the other hand, the cluster 2 was characterized by less children with the BMI "overweight/obesity" (Fisher's exact test, p<0.025) and more children with the BMI group "normal" (Fisher's exact test, p<0.021). Furthermore, based on FIGURE 38 B cluster 1 showed a significant lower number of children coming from families with a middle household income of 1912-2530 € (Fisher's exact test, p<0.049). No significant link among the clusters and other children's sociodemographic data such as their gender, age group, age in years, city was observed (SUPPLEMENTARY FIGURE 11).

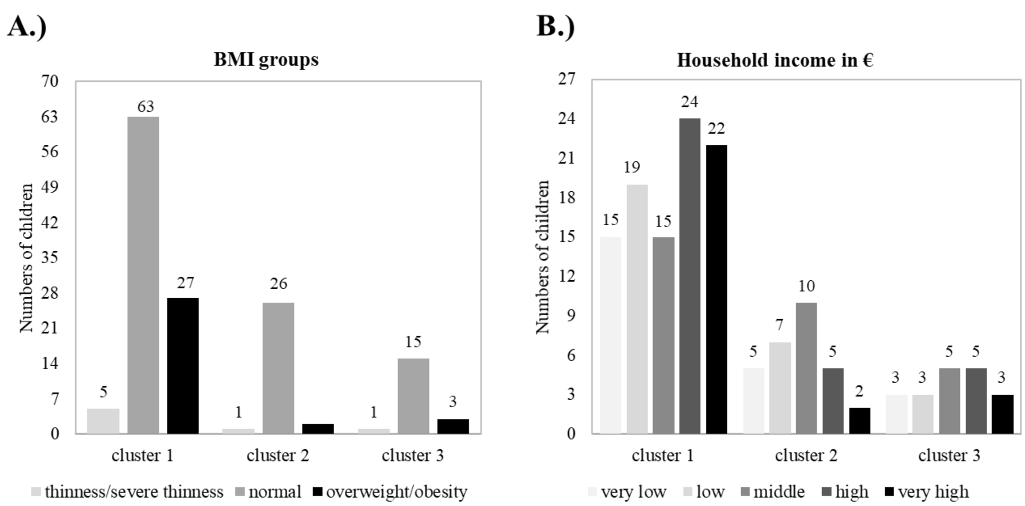


FIGURE 38 : Cluster 1 showed a significant higher number of overweight and obese children (Fisher's exact test, p<0.019) and a significant lower number of children with a normal BMI (Fisher exact test, p<0.017). The opposite was observed among the cluster 2, whereas significant less overweight and obese children (Fisher's exact test, p<0.025) were identified, but more children with a normal BMI (Fisher's exact test, p<0.021). B: A weak effect was found for the effect household income in cluster 1, whereas significant less children from families with a middle household income were observed (Fisher's exact test, p<0.049).

4.3.3.4 Drivers of liking

FIGURE 39 B.1 shows the global preference map for all 143 children. based on plotted 39 sensory, composition and physicochemical variables in FIGURE 39 A. Compared to other cookies in the figure, product P-e is positioned in the zone of maximum preference. This result is in line with the fact that cookie P-e was identified as having the highest mean liking score.

This zone of maximum preference is characterized by larger cookie size, higher salt content and higher spread ratio variable (axes F2 on the bottom) with a certain tendency for a higher density, water content and increased saturated fat content (axes F1 on the left side).

Areas of lesser preferences correspond to cookies with a more brittle, harder, crisper and sandier texture, and higher sweetness, sugar and chocolate-chips content and chocolate aroma.

FIGURE 39 B.2-4 shows the three different preference maps based for each of the three clusters obtained from the AHC.

Cluster 1

Like the overall preference pattern, as well cookie P-e is situated in the preference zone (FIGURE 39, B2). In comparison to the overall preference mapping, the preference zone is more situated towards the axes F1 on the left side (less hard and crisp, increased density and water content). Moreover, cookie P-c (axes F1 on the left side) and cookies P-b and P-g (axes F1 on the right side) tend to be less rejected than in the overall preference mapping. As well in this preference mapping, cookies on the axes F1 on the right side were more rejected (harder and crisper texture). Furthermore, the preferences of cluster 1 were strongly associated with a larger perceived chocolate-chip shape (r=0.888) and a longer time in mouth (r=0.792).

Cluster 2

Larger rejection zones were found on axes F1 on the right but as well on the left side (FIGURE 39, B3). The highest preference zone would be on axes F2 on the bottom (larger cookie size and higher salt content, lower sweet taste, reduced sugar and chocolate-chip content). Comparing cluster 1 with cluster 2 it is visible that cluster 1 demonstrated fewer cookies in the rejection zone, whereas cluster 2 showed more cookies in the rejection zone. Furthermore, the preference zone of cluster 1 tend to be more on axes F1 on the left side, while more children from cluster 2 would prefer cookies on axes F2 on the bottom. The preferences of cluster 2 were strongly associated with a higher Rayner score (r=0.713).

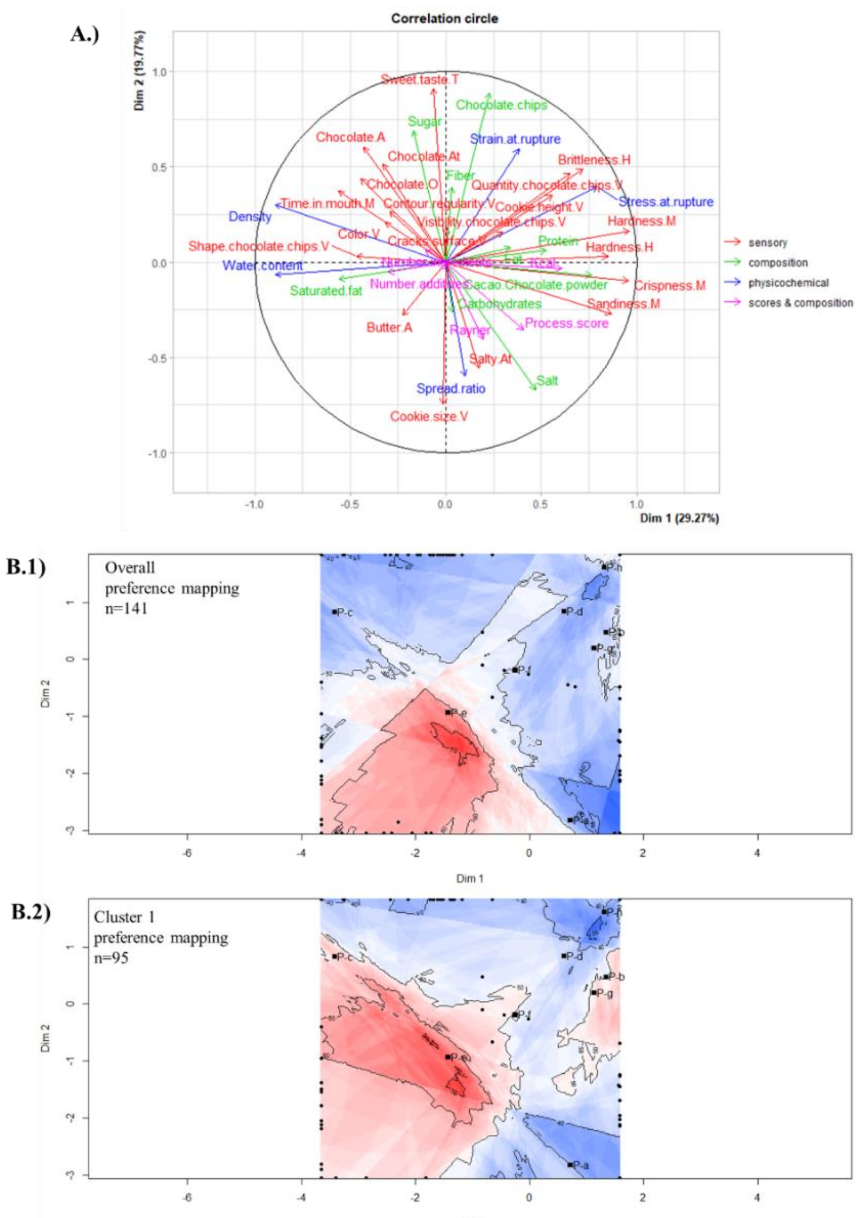
Cluster 3

Cluster 3 is the most homogeneous preference pattern, while around 95% of all children prefer the cookies P-b and P-g on axes F1 on the right side (hard and crisp texture) and on axes F2 more on the upper side (higher sweet taste, increased sugar and chocolate chip content) (FIGURE 39, B4). The highest rejection zone was found on axes F1 on the left side and more on the upper side on axes F2 (increased density and water content, higher sweet taste and increased sugar and chocolate chip content).

The preferences of cluster 3 were strongly associated with an increased crispness (r=0.880) and hardness (r=0.850) in mouth, an increased cacao and chocolate chip powder (r=0.806) and a reduced density (-0.953).

For most of the children was the zone of preference defined by cookies' sensory properties (larger cookie size, lower sweet taste, lower crispness and hardness), by cookies' composition properties (increased salt and reduced sugar and chocolate-chip content) and by cookies' physicochemical properties (increased density and water content). Most children rejected cookies with harder and crisper texture with either extreme sweet taste, sugar and chocolate content or extreme large cookie size with an increased salt content. The smallest cluster with 19 children showed the most different but most homogeneous preference pattern based on sensory, composition and physicochemical cookie properties. According to the model, children in this cluster would reject cookies with a low hardness, higher water content and increased density with an increased sweetness and time in mouth.

Moreover, cluster 1 FIGURE 39 B.2 which was characterized with more overweight and obese children, seem to rejected less cookies than cluster 2 in FIGURE 39 B.3 which was characterized with more children with a normal BMI. Furthermore, the overweight and obese children from cluster 1 tend to prefer more dense cookies with an increased water content and a higher sweetness, sugar and chocolate chip content than cluster 2 with more children with a normal BMI.



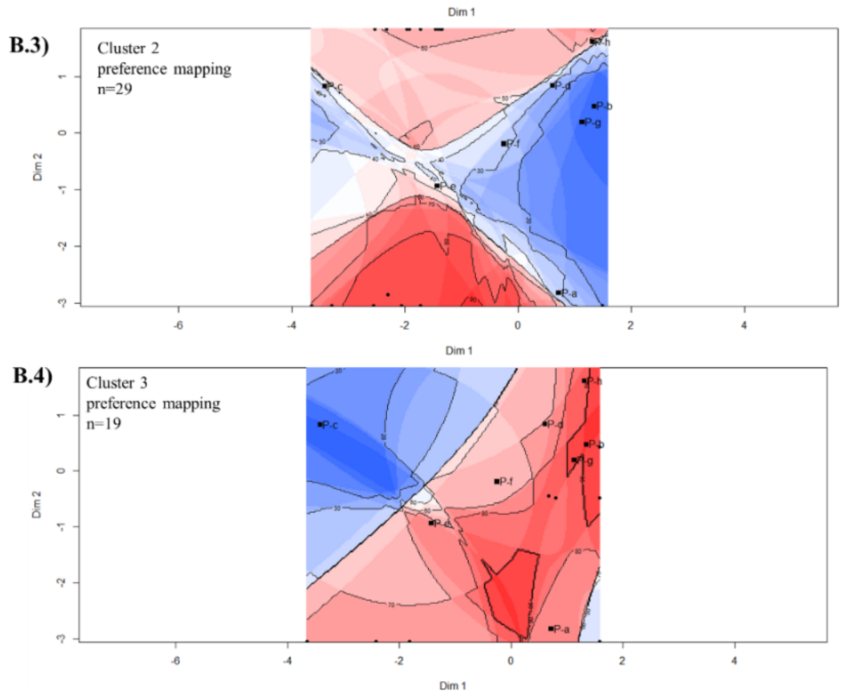


FIGURE 39 : Results of external preference mapping, based on MFA map of sensory profile, composition and physicochemical properties. A. Correlation circle with 39 sensory, composition and physicochemical variables. B1: Overall preference mapping with 143 children. B2: Preference mapping with 95 children, cluster 1. B3: Preference mapping with 29 children, cluster 2. B4: Preference mapping with 19 children, cluster 3.

4.3.4 Discussion

Overall liking and the association with the sweet taste

This study showed that all the tested chocolate-chip cookies were overall well liked. Products in this category are high in kcal, fat and sugar. However, the cookies selected for this study differed substantially in their sugar, fat, saturated fat and fiber content, as well as in their sensory and physicochemical characteristics. In spite of these differences, none of the cookies were particularly disliked on average. This gives way for a large scope of action for reformulation among this product category on the French market, while maintaining the liking among children aged 7-12 years old. Based on the different cookie composition, it might be possible to reduce the overall kcal (-6.8%), sugar (-26.8%), and fat (-17.9%) content and increase the fiber content (+59.1%) while maintaining the liking. Further, possible improvements to reduce the Rayner score (-48.2%), the process score (-16.5%) and the number of additives (-85.7%) might be possible.

These high liking scores are in line with earlier reports that children display high levels of liking for fatty and sweet food (Albataineh et al., 2019; Ambrosini et al., 2015; Marty et al., 2018; Moore & Fielding, 2016; Nguyen et al., 2015; van Buul et al., 2014). Accordingly, a fat and a sugar reduction in cookie dough may be expected to result in lower hedonic ratings (Biguzzi et al., 2015).

However, our results show that neither the cookie with the highest sugar content (37g per 100g, P-b) nor the cookie with the highest fat content (28g per 100g, P-h) were the most liked. This being said, the cookies with the lowest sugar content (27g per 100g, P-a) and the lowest fat content (23g per 100g, P-b and P-c) were the least liked. The preference mapping revealed that most of the children preferred cookies which tend to be less sweet, with a lower sugar, chocolate, and kcal content. This result is actually surprising since recent studies described children's' preferences for calorie dense and sugary food (Albataineh et al., 2019; Ambrosini et al., 2015; Marty et al., 2018; Moore & Fielding, 2016; Nguyen et al., 2015; van Buul et al., 2014). We may assume that for this specific product category the level of sugar and kcal is too high. This is an interesting finding for future reformulation work, as this shows a large frame of reformulation possibilities for a potential sugar and overall kcal reduction in chocolate-chip cookies, while maintaining the liking.

Other authors reported that a sugar reduction had no adverse effect on children's liking (Lima et al., 2019; Reed et al., 2019; Velázquez et al., 2020, 2021). Actually, some children even disliked the products with the highest sugar content (Velázquez et al., 2020). The author argued that it is probably not completely true that children always prefer the sweetest product. It might be more likely that more products are just perceived as too sweet instead of a lacking sweetness. Therefore, for these products, it might be possible to reduce the sugar content without affecting the liking as they are overall perceived as too sweet (Velazquez Mendoza et al., 2021a,b).

Texture as important indicator for preferences and food oral processing

Our study showed that the cookies texture was an important factor for the preference and limits for children. As mentioned in the literature, texture is a key perception for children, and their preferences for different textures are largely dependent on their age, with the growth of mouth muscles, jaw and teeth (Lukasewycz & Mennella, 2012; Rose et al., 2004a, 2004b; Szczesniak, 1972; Zeinstra et al., 2010). Those growth factors may largely affect children's chewing capacity (Narain, 2005). Furthermore, some textures can trigger children's neophobia and therefore induce rejection (Coulthard & Blissett, 2009).

In this study, based on the overall preference mapping with all 143 children, most of the children preferred cookie textures which tend to be less hard and softer. According to some authors, younger children with lower chewing efficiency preferred more simple and smooth textures with lower complexity and disliked crunchy or chewy textures (Urbick, 2002; Narain, 2005 and Ringel, 2005).

Further, it was shown that children preferred soft and uniform textures and dislike clumpy or granular food which is difficult to process in the mouth (Laureati et al., 2017; Szczesniak, 2002; Werthmann et al., 2015; Zeinstra et al., 2010). However, our study also identified a preference pattern for harder cookies (although this result was obtained from 19 children only). According to Laureati et al., (2019), children are both, soft and hard texture lovers.

Although previous studies found a link between texture preferences and children's age, we did not find any different preference pattern linked to children age. For instance, (Narain, 2005) found that younger children preferred a simple and smooth texture, what might be explained by a lower chewing effort. Furthermore it was found that texture and mouthfeel were more important among younger children aged 6.7 years, whereas taste and smell were more relevant for older children aged 10-11 years (Rose et al., 2004a, 2004b). Here, only a trend could be observed for the cluster 3, composed of younger children (7-9 years). The cookie which was rejected the most (P-c) showed specific physicochemical and sensory properties such as high density and water content and a longer time in mouth. Therefore, cookies' texture is more sticky and chewy, with larger particle size, what requires a longer time to masticate before swallowing. That in turn might be a possible explanation, why children in cluster 3 with slightly more younger children rejected product P-c, as it is more difficult to masticate and need more time, as explained by other authors above. On the other hand, cluster 3 was the only cluster with highest preferences for hard and crisp cookies. Also here, the preferences for "hard" texture for biscuits might be explained due to cookies structural and textural characteristics. The commercial hard cookies are very crisp and brittle (high sugar content) and they show very small particle sizes, what can explain the lower time in mouth needed before swallowing.

Eventually, our results show that structural and textural properties may impact the food oral process. Indeed, denser cookies with higher water content seem to be perceived as softer, but also more chewy and thus require longer time to masticate. This result is specially interesting in the light of a recent study that showed that an increased chewiness leads to a decreased eating rate and energy intake (Bolhuis & Forde, 2020). Texture could thus be an interesting lever to make products healthier by increasing food oral processing and reducing energy intake.

Differences for preferences among children with an increased and a normal BMI

We observed large inter-individual differences in preferences, some of which could be related to children's BMI. The preference pattern of cluster 1 was characterized with more children having a higher BMI (overweight/obesity), whereas the preference pattern 2 was characterized with more children with a normal BMI. Overall, it was found that the overweight/obese children rejected less cookies than children with a normal BMI, especially cookies which tend to have a higher sweet taste intensity, and a higher sugar and chocolate chip content (P-b, P-g).

The links between obesity and children’s preferences for high sweet and fat taste are controversial. Recent studies described a high relationships between fat hedonics and increased body weight (Cox et al., 2016), and increased liking for sweet and fat among obese children compared to non obese children (Bartoshuk et al., 2006). Likewise, Sobek et al., (2020) found an association between the preference for high sweet taste and obese children. However this was not the case for fat taste. Besides, no preferences for sweet taste was found between obese and non obese children in another study (Bobowski & Mennella, 2017). Moreover, a recent study showed no differences for soft or hard texture preferences among children when comparing their BMI among 6 European countries, except for one country (Austria), where children with an increased BMI preferred harder textures (Hörmann-Wallner et al., 2021).

According to a recent review, obese people may have a lower taste sensitivity and a higher preference and intake of fat and sweet foods, even though the latter was only to a lower extent (Spinelli & Monteleone, 2021). Furthermore, obese people may live in orosensory worlds different than non-obese individuals (ebd.). Authors stated however, that more research about the role of taste responsiveness and food preferences among obese individuals is needed, as in most of the studies the age and the gender was not balanced and studies were conducted on small samples only. A better understanding of taste alternation and food behaviors in obese people will help to develop more efficient reformulation strategies and to improve their diet and weight management.

4.3.5 Conclusion

To conclude, despite the large sensory, composition and physicochemical cookie diversity, an overall high appreciation among the product category "commercial chocolate-chip cookies" was observed. This is promising for future reformulation, as products with an enhanced nutritional profile were not disliked. Probably, it is needed to overthink the assumption that children prefer always products with highest sweetness levels. The texture was identified as an important driver of preferences, where further composition and physicochemical variables were of importance to better understand why a certain cookie is preferred or rejected. Especially among such a complex food matrix, as the sweet biscuits. Therefore, it is highly important to consider food reformulation as holistic approach, including sensory, composition, physicochemical and liking information.

Chapter 5

Results part with reformulated cookies

5 Chapter results part: Research with reformulated cookies

5.1 "Sensory-led reformulation of chocolate chip cookies using multifactor optimization."

General introduction

As food reformulation among a complex food matrix without any replacers and additives may induce reformulation barriers, it is highly important to better understand the roles and interactions between the ingredients participating to the recipe of cookies. This will make it possible to improve the recipe towards a healthier product, while maintaining the sensory perception and the liking.

This submitted article provided a sensory led reformulation approach with a mixture design and multicriteria optimization. This study aims therefore to better understand the interactions of ingredients within a complex food matrix and to identify key influential variables of sensory perception, physicochemical and nutrition parameters with a minimum of experimental runs. Another goal is to define optimal recipes while improving key sensory attributes, nutrition and physicochemical parameters.

This study builds upon previous researches of this PhD work, that showed reformulation opportunities for a fat, sugar, chocolate-chips reduction and fiber enhancement (section 4.2) and the overall liking (section 4.3) of commercial chocolate-chips cookies.

On this basis, 55 preliminary recipes with different levels and types of sugar, fat, flour and cereals, chocolate-chips and baking parameters were formulated, and characterized by sensory and physicochemical analyses. Based on the 55 preliminary recipes, five factors (ingredients) and levels were selected for the next step, which was the object of this result part. Four mixture factors were also selected, such as sugar 22.2-26.4%, fat 12.8-17%, chocolate-chips 13.2-16.5%, oat bran 3.3-6.5%, and a categorial process factor, the baking degree (150°C-180°C) was added for the development of a mixture design.

To study then the interactions among ingredients and their influence on sensory perception, physicochemical and nutrition parameters, a mixture design was thus carried out with the above mentioned five factors and levels. In total 28 different cookies were proposed from the design and produced in the plateau FRECE of the UMR SayFood. They were characterized by sensory (QDA with 10 panelists) and physicochemical (density, spread ratio, water holding capacity, texture, in vitro starch hydrolysis, viscosity) analyses.

To optimize recipes (factors sugar, fat, chocolate-chips, oat bran and baking degree), key sensory attributes (5 texture, 2 aroma, 1 taste), nutrition (kcal, Rayner score) and physicochemical (glycemic index, viscosity) parameters based on multiple linear regressions with desirability function was applied. All the results are presented in this result section.

This original approach showed that the use of a mixture design is a pertinent tool to better understand the role of ingredients and their interaction for a complex food matrix with the objective to reformulate a commercial product under multiple constraints : a) towards a healthier product (sugar -14.6%, fat -28.9%, chocolate-chip -8.5%, kcal -5.1%, Rayner score -11.4%, predicted glycemic index of -11.9%), b) while optimizing sensory perception and liking, c) without the use of additives or replacers.

Further, the fat was identified as important ingredient to soften the cookie texture, whereas oat bran was identified as a key ingredient helping to maintain sensory perception, to increase biscuits' viscosity and to reduce the kcal content.

This sensory-led reformulation approach showed further the possible chances for industries to adapt reformulation strategies based on consumer profiles. This approach might therefore increase the efficiency of reformulation and contribute to a healthier food environment among packed foods. As a next final step of this PhD and manuscript, a validation of the multicriteria approach (reformulated cookies) is needed to check to which extend the reformulated cookies are liked, based on different compositions. Then, a validation of the impact of reformulated cookies (and their ingredients) on children's eating behavior and adults' food oral processing behavior is needed. Therefore, in the next section we investigated the liking and the self-reported hunger levels among children and we measured the time in mouth among adults, for a selection of these reformulated cookies.

“Sensory-led reformulation of chocolate chip cookies using multifactor optimization.”

Research Paper, Manuscript submitted to Food Research International

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Abstract

Many factors contributed to the increasing rates of childhood overweight and obesity, including inactive lifestyle and food choices with a too high sugar and fat content food products. One of the possible levers to enhance the food offer could be food reformulation. However, this last one is faced with many hindrances due to multifunctional properties of ingredients in the food biscuit matrix, with impact on products’ structure, perception and liking.

Trying to limit those barriers, the aim of this study was first to propose a multicriteria approach based on multiple formulation constraints in order to identify the role of ingredients in a mixture on sensory, nutrition and physicochemical variables. Then we aimed to propose an approach to optimize cookies recipe while maintaining sensory properties and improving nutrition and physicochemical aspects.

First, a mixture design was implemented with four mixture factors (sugar 22.2-26.4%, fat 12.8-17%, chocolate-chips 13.2-16.5%, oat bran 3.3-6.5%) including a categorial process factor, the baking degree (150°C-180°C). A total of 30 cookie recipes were thus created. Sensory descriptive and physicochemical analysis including starch in vitro digestion or viscosity were conducted on all formulated cookies. The sensory analysis and the model performance with sensory, physicochemical and nutrition variables were assessed using analysis of variance.

Results of the sensory analysis showed that 11 of 20 sensory attributes were significant. Further, within the regression model of 12 sensory, physicochemical and nutrition variables were 9 significantly impacted by the formulation mixture. Fat was identified as mainly impacting the texture with softening effects.

Oat bran was identified as a key ingredient helping to maintain sensory perception, to increase biscuits' viscosity and to reduce the kcal content. It was possible to optimize cookie recipes with a sugar (-14.6%), fat (-28.9%) and chocolate-chip (-8.5%) reduction without impact sweet perception. This resulted in a kcal and Rayner score reduction of respectively -5.1% and -11.4% with a reduction of the predicted glycemic index of -11.9%.

With the use of a mixture design this multicriteria approach demonstrated that it was possible to reformulate a healthier commercial cookie without addition of additives or replacers. This approach might increase the efficiency of reformulation and contribute to a healthier food environment among packed foods.

Keywords: Food reformulation, Mixture design, Multicriteria, Nutrition, Sensory, Physicochemical, Cookies, Optimization

5.1.1 Introduction

Many processed foods such as sweet biscuits and drinks still contain a too high fat, sugar and a too low fiber content (Bonsmann et al., 2019). Food reformulation (reducing overconsumed nutrients such as sugar, fat and salt) is one of the interesting leverages to enhance the nutritional quality of the food offer, with the possibility to not largely changing consumers' behavior (Gressier et al., 2021; Raikos & Ranawana, 2019; Spiteri & Soler, 2018). Beside the several nutritional benefits of sugar and fat reduction, enhancing the fiber content also has positive effects on the glycemic index, lipid metabolism, satiety and satiation and body weight (Pentikäinen et al., 2014; Schuchardt et al., 2016; Regand et al., 2011; J. Slavin & Green, 2007; Slavin, 2005; Ye et al., 2012).

However, food reformulation faces many hindrances, especially when dealing with complex food products such as bakery foods. As consequence, any sugar and fat reduction is subject to technological-, sensory-, liking- and finally economical constraints. Moreover, when reformulating without replacers and additives, some interactions between ingredients in the food matrix are modified with some impact on structure, sensory properties and health relevant aspects. Therefore, it is crucial to consider food reformulation as a multi-dimensional approach, considering composition, physicochemical, sensory and liking information.

Indeed these information are first necessary to set a feasible cut off level for target nutrients and to provide key structural and textural characteristics and health relevant aspects. For example, in vitro starch hydrolysis can be used to calculate the predicted glycemic index, which can indicate how quickly the blood glucose level rises after the consumption of a food.

Food with a lower glycemic index might therefore delay the hunger feeling and reduce energy intake (Roberts, 2003). Concerning foods' texture and structure, these last are relevant to better understand food oral processing. Some rheological measures such as viscosity might explain the evolution of bolus during food oral processing. An increased viscosity led thus to an increased oral processing time, with consequence on an enhancement of satiety (Pentikäinen et al., 2014; Priyanka et al., 2019).

In addition, sugar, fat and foods' texture are known to be strong drivers of preferences, and modifying their amount or texture may likely alter sensory perception and decrease the potential liking (Marty et al., 2018; Nguyen et al., 2015, Cooper, 2017, Drewnowski, 1997; Scott & Downey, 2007). Therefore, for any successful reformulation, it is important to consider sensory and liking, in addition to composition and physicochemical data. Sensory quantitative descriptive analysis could also be used to describe a specific product category (Lawless & Heymann, 2010). The liking information helps to adapt the reformulation goals and provide important information about the possible range of reformulation while maintaining the liking. Taken altogether, this will then allow to reformulate products into a healthier version while optimizing sensory perception and liking by improving.

The reformulation is faced with many interactions of different ingredients. A supplementary challenge exists when food reformulation (reducing target macronutrients sugar and fat) is proposed without using fat or sugar replacers or additives. We expect reformulation of bakery products to be limited due to the complexity of food matrix. Further, to the best of authors' knowledge, there is limited research available by combining reformulation work by investigating multiple criteria at the same time and studying the impact on sensory, physicochemical and nutrition parameters.

Within this frame, this paper aims to conduct sensory led reformulation with multiple criteria. Therefore a mixture design was carried out to identify various reformulations of cookies in order to study the impact of the most relevant factors of formulation on sensory perception, physicochemical and nutrition parameters. Second, we proposed a multicriteria optimization via desirability function, to optimize recipes towards a healthier product while improving key sensory perceptions.

This study builds upon previous research that showed that large differences exist for this product category and therefore identified opportunities for reformulation (Liechti et al., 2022 in section 4.1). A subset of 18 cookies representative of the market was selected with multiple criteria (Liechti et al., submitted, in section 4.2) which allowed identifying reformulation opportunities thanks to the "TSO" (Trends, Scatters, Outliers) approach for a fat, sugar and chocolate-chip reduction and a fiber enhancement, all while targeting sensory perception.

As well, the liking scores of eight commercial cookies were evaluated by 143 children aged 7-12 years old in a previous study (to investigate the frame in which it is possible to reformulate while maintaining the liking) (Liechti et al., submitted, in section 4.3).

On this basis, 55 preliminary recipes with different levels and types of sugar, fat, flour and cereals, chocolate-chips and baking parameters were formulated. Sensory descriptive and physicochemical analysis such as the water content, the density, the texture (with stress and strain) and the spread ration were carried out. Those factors and levels were then selected: they did not largely affect sensory perception (via ANOVA), they were most close to a commercial cookie with high potential for reformulation and they were liked among children.

Following to this previous preliminary study, a D-optimal design was thus created with four independent mixture factors: sugar (22.2-26.4% with 2/3 white crystal sugar and 1/3 brown crystal cassonade sugar), fat (12.8-17% with 2/3 butter and 1/3 rapeseed oil), chocolate-chips (13.2-16.5%) and oat bran (3.3-6.5%). A baking degree with three levels (150°C, 165°C, 180°C) was added as fifth categorial factor. Sensory and physicochemical analysis were also conducted on all cookies to better understand the main drivers of perception by multivariate analysis. A desirability function was applied to optimize the recipes, while maintaining sensory perception and improving physicochemical and nutrition parameters, such as for example the predicted glycemic index, biscuits' viscosity, the kcal or the Rayner score.

5.1.2 Material and Methods

5.1.2.1 Cookie formulation

5.1.2.1.1 Ingredients

Formulated cookies were developed with different commercial available ingredients from the supermarket, whereas the flour "Fleuriane" was obtained from the French Moulin Soufflet mill (ville, France). The water and protein content was 13%, respectively 10.8%. Following ingredients with different brand where used: the sugars (2/3 white crystal sugar, 1/3 brown crystal cassonade sugar) (Saint Louis, USA), the fats (2/3 butter and 1/3 rapeseed oil) from Cora (Massy, France), the chocolate-chips from Vahiné (ville, France), the oat bran from Bjorg (ville, France), the eggs from Cora, the baking powder from Dr. Oetker (ville, France), the vanilla aroma from Déco Relief (ville, France) and the salt from Cora.

5.1.2.1.2 Dough formulation

All ingredients were stored and pre-weighted at room temperature in the pilot hall (~23 C°). For the ingredient preparation, the butter was first cut into small pieces, whereas the rapeseed oil was added. The egg white and yolk were first mixed together during 10 seconds before the weighing. The mixture of the cookie dough was performed with the Kitchen Aid (model 5KSM175PS, USA) and with a flat stirrer. At first, the sugars and the fats were mixed together during 5 minutes at level 3 to a creamy mass. Then, the liquid ingredients such as the egg and the vanilla aroma were added to the dough, followed by another 5 minutes of mixing at level 3. Then all dry ingredients such as the flour, the baking powder including the salt was added to the mixture and slowly mixed during 15 seconds at level 1 until no flour was visible anymore. As a last step, the chocolate-chips were added and stirred by hand for 15 seconds until all chips were equally distributed.

5.1.2.1.3 Forming, baking and storage

The cookies were then formed with the help of an ice scream portioner (Stöckel, size 24) and placed on a baking sheet covered with baking paper (~35 g per cookie). The baking sheet was then placed in the middle of the preheated oven, and the cookies were baked during 15 minutes with air circulation between 150-180°C degree (levels mixture design).

After the baking, the cookies were cooled (~25 minutes), and packed in sachets from the online mylar shop (non-transparent, aluminium, light-proof) together with an oxygen absorber (Oxyfree®). Both, the sachets and the oxygen absorber were approved and qualified for storage of dry biscuits for several months. The sachet and the oxygen absorber protect from oxygen, heat, pests, light and humidity. The sachets were heat sealed with low vacuum and stored at room temperature until analysis.

5.1.2.1.4 Experimental design

The implement of a Design of Experiments (DoE) were used to understand the impact of each ingredient on sensory perception and physicochemical properties and to identify optimize recipes (Galvan et al., 2021). Especially the mixture design is widely used and helps to select the level of specific target compound, in order to optimize a desired product characteristic or cost efficiency (Jain et al., 2019; Orives et al., 2014a; Orives et al., et al., 2014b; Sahin et al., 2016). Therefore, a D-optimal design (estimates the best possible model coefficients including interactions) seems to be a pertinent approach used in product development to optimize especially mixtures with various constraints including sensory evaluation (Franklin et al., 2019; Liu et al., 2010; Mancebo et al., 2015; Seo et al., 2010).

The desirability function can be used to maximize a response, nutritional or sensory information as examples, using a geometric mean (Derringer & Suich, 1980). According to a recent review about the use of mixture design in the bakery and confectionary domain, around 16 studies were identified (Galvan et al., 2021). Most of the studies focused on gluten free products or the incorporation of functional ingredients with different purpose. However, based on the review no study about biscuits was identified.

In order to define the factors and levels for this mixture design, a previous study with 55 preliminary studies was created. Thereby, recipes with different levels and types of sugars, fats/oils, flours/cereals including several process parameters were carried out. The selected factors and levels for the mixture design were sugar (22.2-26.4% with 2/3 white crystal sugar and 1/3 brown crystal cassonade sugar), fat (12.8-17% with 2/3 butter and 1/3 rapeseed oil), chocolate-chips (13.2-16.5%) and oat bran (3.3-6.5%). The total sum of the four mixture factors was always 62%. All other remaining cookie ingredients such as flour (27.7%), egg (9.5%), baking powder (0.3%), vanilla aroma (0.3%) and salt (0.2%) summed up to 38% and were constant during all formulations. Besides the ingredients in the food matrix, cookies structure and texture further depends on process parameters. Therefore, the baking degree with three levels (150°C, 165°C, 180°C) was added as fifth categorial factor. Thirty formulated cookies were thus produced and described in TABLE 13.

TABLE 13 : 30 Formulated cookies (Fc=formulated cookies) with their four mixture factors sugar, fat, oat bran and chocolate-chips and one categorial factor the baking degree. The sum of all mixture factors in this table is = 62%, whereas the sum of all other cookie ingredients was determined to be = 38%. 2/3 of the sugar was white sugar while 1/3 was brown sugar. 2/3 of the fat was butter while 1/3 was rapeseed oil.

	4 Mixture factors				1 Categorial process parameter
Recipe Nr°	Sugar (%)	Fat (%)	Oat bran (%)	Chocolate chips (%)	Baking degree
Fc-1	25.3	15.9	5.4	15.4	150
Fc-2	24.2	14.8	6.5	16.5	165
Fc-3	26.4	15.8	3.3	16.5	180
Fc-4	25.3	15.9	5.4	15.4	165
Fc-5	25.3	17	6.5	13.2	180
Fc-6	24.2	14.8	6.5	16.5	150
Fc-7	26.4	17	4.4	14.3	180
Fc-8	25.3	17	6.5	13.2	165
Fc-9	25.3	15.9	5.4	15.4	180
Fc-10	26.4	17	3.3	15.3	165
Fc-11	26.4	17	3.3	15.3	150
Fc-12	24	17	4.5	16.5	165
Fc-13	25.2	17	3.3	16.5	150
Fc-14	26.4	15.8	3.3	16.5	165
Fc-15	24.1	17	6.5	14.4	150
Fc-16	26.4	12.8	6.3	16.5	165
Fc-17[R2]	22.2	16.8	6.5	16.5	180
Fc-18	26.4	15.9	6.5	13.2	180
Fc-19	26.4	15.9	6.5	13.2	150
Fc-20	26.4	14.66	6.5	14.4	165

Fc-21[R1]	26.2	12.8	6.5	16.5	180
Fc-22	22.2	17	6.3	16.5	150
Fc-23[R1]	26.2	12.8	6.5	16.5	180
Fc-24	26.4	17	5.4	13.2	165
Fc-25	22.2	17	6.5	16.3	165
Fc-26	26.4	14.6	4.5	16.5	150
Fc-27	26.4	12.8	6.5	16.3	150
Fc-28[R2]	22.2	16.8	6.5	16.5	180
Fc-29	25.2	17	3.3	16.5	180
Fc-30	26.4	17	5.4	13.2	150

A mixture-process design was chosen to optimize the ingredient mixing ratios for the cookies. A D-optimal criterion was applied to minimize the numbers of runs (to facilitate sensory and physicochemical analyses). The ingredient mixing ratios for the experimental points are shown in TABLE 13. For the experimental design, 30 runs were planned (with 3 central points, first order interaction, efficiency D: 0.007747%, efficiency G: 75.21109%, efficiency A: 1.153%), whereas two runs were replications (Fc-21 and Fc-23; Fc-17 and Fc-28) (FIGURE 40).

The base of each recipe was composed of 339.8g flour (27.7%), 116.5g egg (9.5%), 3.7g baking powder (0.3%), 3.7g vanilla aroma (0.3%) and 2.5g salt (0.2%) while all other ingredients (sugar, fat, chocolate-chips, oat bran) were added based on the mixture design with different levels.

FIGURE 40 : This figure is presenting all 30 formulated cookies. Further, the nutritional values were calculated based on the weight differences before and after baking (water loss), including the Rayner score (Rayner et al., 2005) (SUPPLEMENTARY TABLE 15). Values for the kcal, the sugar and the fat ranges per 100g were 454-490 kcal, 18.9-23.6g fat and 34-39.3g sugar. The calculated Rayner score varied between 20 and 23 (Nutriscore E).

5.1.2.2 Sensory and physicochemical characterization

5.1.2.2.1 Sensory description of formulated cookies

A sensory quantitative descriptive analysis was conducted to investigate the sensory profile of the 30 formulated cookies and to evaluate the role of formulation on perception.

A panel of ten volunteers (6 women and 4 men, 21 - 55 years old) was recruited in 2021 at AgroParisTech (Grignon, France) and trained especially for this study. Before taking part in the study, panelists signed a consent form and received compensation for their participation.

In total, each panelists took part in 7 sessions. The first three sessions were dedicated to the generation and selection of attributes, followed by training in the use of these attributes for quantitative description of the products. During the first session, the 10 panelists generated a vocabulary of sensory attributes that covered the visual, odor, taste, after taste, texture in hand and texture in mouth. In total, 220 attributes were collected. A consensus phase was completed in order to reduce the vocabulary down to 20 sensory attributes with their definitions and evaluation protocols (TABLE 14).

Two sessions were then carried out to train the panel on these attributes. Finally, panelists were trained in the use of a 10-cm unstructured linear scale to evaluate the intensity of each attribute, using external reference products.

For the evaluation sessions, the chocolate chip cookies were presented according to a monadic sequential design. The sample evaluation order was balanced over the panel following a Williams Latin square design to account for potential order and carry-over effects. Panelists were asked to rinse their mouths with mineral water (Evian, Danone, France) between samples.

In total, four evaluation sessions were performed (8, 8, 8, 6 cookies per session). Chocolate-chip cookie samples were presented on a white cartoon plate and designed with randomly attributed three-digit numbers. The attributes were translated from French to English only for this article.

TABLE 14 : 20 sensory attributes generated with a sensory quantitative descriptive analysis with 10 panelists, including the attributes definitions and scale anchors. The attributes were presented in French and translated in English for the article.

Attribute family	**Attributes**	**Attributes in French**	**Definitions**	**Scale anchors**	
				minimal intensity (0)	Maximal intensity (10)
Aspect	*Color of the dough*	Couleur de la pâte	Color dough cookie surface	Clear	Dark
	Thickness	Epaisseur	Height cookie center	Thin	Thick
	Shiny	Brillance	Color reflection cookie surface	Mat	Shiny
	Roughness	Rugueux	Roughness cookie surface	Smooth	Rough
Texture in hand	*Hardness*	Dureté	Hardness cookie center	Soft	Hard
	Brittleness	Cassant	Resistance by breaking the cookie in two pieces	Easy to break	Hard to break
Texture in mouth	*Crispness*	Croustillant	Noise after a first bite	Little noise	Much noise
	Melting	Fondant	Time to get fluid in mouth	Little melting	Much melting
	Softness	Moëlleux	Elasticity and softness cookie dough	Low softness	High softness
	Sticky	Collant	Adhesion to the teeth	Low stickiness	High stickiness
	Pasty	Pâteux	Forming of dough pieces in the mouth	Low pastiness	High pastiness
	Quantity chocolate chips	Quantité pépites de chocolat	Presence chocolate-chips in the mouth	Low quantity	High quantity

Odor	*Chocolate*	Chocolat	Smelling the cookie surface by breathing in	Biscuit odor	Chocolate odor
	Vanilla	Vanille	Smelling the cookie surface by breathing in	Biscuit odor	Vanilla odor
Taste	*Sweet*	Sucré	Perceived sweetness during/after mastication	Low sweetness	High sweetness
Aroma	*Chocolate*	Chocolat	Perceived chocolate aroma during/after mastication	Biscuit aroma	Chocolate aroma
	Oat	Avoine	Perceived oat bran aroma during/after mastication	Biscuit aroma	Oat aroma
	Vanilla	Vanille	Perceived vanilla aroma during/after mastication	Biscuit aroma	Vanilla aroma
	Baked	Cuisson	Perceived baked aroma during/after mastication	Little baked	Much baked
	Nutty	Fruit à coque	Perceived nutty aroma during/after mastication	Biscuit aroma	Nutty aroma

5.1.2.3 Physicochemical characterization

Some measurements of physicochemical and structural measurements were performed on all formulated cookies in order to better understand the main drivers of products' perception and to be related to important nutrition and health relevant parameters. All physicochemical analyses were conducted on the 28 different reformulated cookies (without the two replications) in triplicate.

5.1.2.3.1 **Water content, texture, density, spread ratio**

All detailed methods for the water content, texture, density and spread ratio analyses were described in in previous studies, sections 4.1 and 4.2). The water content was determined by oven drying method adapted from (Upadhyay et al., 2017). The texture properties of the chocolate chip cookie subset were studied by a three points bending test, carried out with a TA.HDplusC Texture Analyser (StableMicrosystems, Surrey, UK). In order to compare products with each other, the stress (σr) and strain (εr) at rupture were calculated (Baltsavias et al., 1997).

Further, the density of the chocolate chip cookie subset was measured with VolScan Profiler (Stable Micro Systems, Surrey, UK) which was used in previous studies for baked products and baking ingredients (Mäkinen et al., 2013). The diameter of the cookie was measured with a vernier caliper and the spread ratio was calculated with the diameter divided by cookies height.

5.1.2.3.2 Water holding capacity (WHC)

The protocol for the WHC was adapted from those of Escobedo-García et al., (2020). Cookies were grinded with a mortar between 30 and 60 seconds to obtain visually same particle sizes. Then, 1.0 g of grinded cookies was filled into a dry empty centrifuge tube. Then 10ml of distilled water was added to the sample and was mixed with the vortex for one minute. The tube was then vertically standes at 37°C for one hour followed by a centrifugation at 3000g for 15 minutes. The supernatant was then poured off into a measuring cylinder to measure the volume.

The WHC was then expressed by the volume of water absorbed per gram of cookies [mL/g]:

$$\text{WHC (mL/g)} = \frac{Volume\ of\ water\ added - Volume\ of\ supernatent\ after\ equilibration}{Weight\ of\ cookies\ used\ (1g)}$$

5.1.2.3.3 In vitro starch hydrolysis and predicted glycemic index (pGI)

The starch hydrolysis protocol was adapted according to Englyst et al., 1992; Englyst et al., 2018; Englyst et al., 2000, Freitas & Le Feunteun, 2018; Schuchardt et al., 2015.

Different reagents and enzymes were used for the hydrolysis protocol. Reagents: sodium acetate tri-hydrate (CAS no: 6131-90-4 , Carlo Erba), guar gum (viscogum MP 41230, Cargill France), 37% HCl (Merk. Pcode: 101920213). Enzymes: pepsin from porcine gastric mucosa, powder, (≥250 units/mg solid, Product No: P7000, Sigma Aldrich), pancreatin from porcine pancreas (8×USP specifications, Product No :P7545, Sigma Aldrich), invertase from baker's yeast -Saccharomyces cerevisiae (Grade VII, ≥300 units/mg solid, Product No I4504, Sigma Aldrich), amyloglucosidase from Aspergillus niger, (≥260 U/mL, aqueous solution, Product No:A7095, Sigma Aldrich); D-glucose Test kits (GOPOD format). Pcode: K-GLUC04/20 (megazyme).

One to three grams of hand grinded cookies (see section WHC) was added to 10 ml enzyme solution (pepsin, guar gum, HCl) and incubated at 37˚C for 30 minutes in an orbital shaking waterbath (150±1 shaking/min) to simulate gastric digestion. Then, 10 ml of sodium acetate solution was added followed by a 5ml mixture of enzyme (pancreatin, amyloglucosidase, invertase, sodium acetate solution) was added. 1mL aliquots were taken at 20, 30, 60, 90, 120 minutes respectively and placed in a tube into a boiling water bath [99±1˚C] for 5 to 8 minutes to stop the enzyme action.

After centrifugation the supernatant was analyzed for their glucose content. A blank tube and the reference (1g bread) were also submitted to the same protocol. The glucose was measured using Megazyme D-Glucose Assay Kit according to the instructions of the manufacturer.

The curve of glucose release versus time of hydrolysis was plotted and the area under the curve was used to calculate the Glycemic index with the white bread as reference. The incremental area under the curve (AUC) was calculated using the trapezoidal rule (FAO, 1998; Freitas & Le Feunteun, 2018). The predicted glycemic index (pGI) was calculated as using equations 1 and 2 (Alongi et al., 2019; Giuberti et al., 2016; Granfeldt et al., 1992; Jenkins et al., 1981):

$$(1)\ Hydrolysis\ Index\ (HI) = \frac{\text{AUG of test food (i.e cookies)}}{\text{AUC of test food (i.e bread)}} \text{ x } 100$$

$$(2)\ Glycemic\ Index\ (GI) = 8.198 + 0.0862\ \text{HI}$$

Rapidly available glucose (RAG), slowly available glucose (SAG) and available glucose (AG) were estimated according to the method proposed by (Englyst & Hudson, 1996), with RAG = Glucose released after 20 minutes of digestion, AG = Glucose released after 120 minutes of digestion and SAG = Available glucose – RAG.

5.1.2.3.4 Viscosity

The sample preparation was identical as it was described in the section for the WHC. For the sample preparation, 20g of the grinded cookies was filled in a 250 ml tube. The amount of distilled water to add was adapted based on cookies total water (g) and dry mass (g) content to obtain always the ratio of 1 (water in g total): 1 (dry mass in g total). The total dry mass was then subtracted from the total water content:

$$1.\ Quantity\ of\ distilled\ water\ (g)\ to\ add = (\text{cookie sample(g)} * \text{dm}) - (cookie\ sample\ (g) * \text{WC})$$

With following parameters: Cookie sample (g) = Quantity of the cookie weighed (g); dm: cookies dry matter; WC %: Cookies water content on wet basis

The calculated quantity (g) of distilled water was then heated up to 37 degrees, before it was added to the weighed and grinded cookie sample. The total mass was slowly stirred until the grinded cookies were fully covered with distilled water.

The total mass (~37-40g) of grinded cookie and distilled water was then immediately added to the rheometers' couette geometry.

The viscosity (mPa·s) was measured with a Physican MCR 301 rheometer (Anton Paar Gmbh, Graz, Austria) equipped with a couette geometry (CC27-SS/S, 70271) and a vane (ST22-6V-16, serial number 35142) at 37C° (Pentikäinen et al., 2014) and with constant share rate at 60 1/s. The viscosity value was recorded 10 minutes (600 seconds).

5.1.3 Statistical analysis

All the statistical analyses were conducted using XLSTAT version 2018.1.1 (Addinsoft, New York, USA) and JMP (v. 16.1.0; SAS Institute Inc., Cary, SC, USA) to generate and analyze the optimal mixture design.

5.1.3.1 Statistical analysis sensory and physicochemical data

All physicochemical and sensory data were treated by ANOVA, to evaluate the significant differences between cookies. For sensory results, we carried out a three-way ANOVA on each attribute with product, panelists and order effects. For analyses of an inferential nature, $\alpha = 0.05$ was the threshold for statistical significance. To visually explore differences in the results, a principal component analysis (PCA) was carried out on a correlation matrix; the data were averaged across replicates and panelists.

5.1.3.2 Statistical analysis of the mixture design: modeling and optimization

5.1.3.2.1 Mixture design analysis and selection of variables

Multiple regression analysis was performed to evaluate the effects of all the variables from the mixture-process design on each response variable (i.e., via the regression coefficients with standard least square regression). A mixing response surface model was applied with first order interactions, except for the process parameter.

At first, a multiple regression analysis with total 16 separate regression models were calculated, one for each independent sensory (*visual:* V-color cookie dough, V-thickness cookie, V-shiny cookie surface, V-roughness cookie surface; *texture:* H-hardness, M-fondant, M-soft, M-crispy, M-perceived quantity chocolate-chips; *aroma:* A-chocolate, A-baked; *taste:* sweet taste), physicochemical (predicted glycemic index, viscosity) and composition (kcal, Rayner score) variable. Independent main factor variables were sugar, fat, chocolate-chips and oat bran, whereas the baking degree was only considered for the first order interaction.

In our study the focus was set on texture and taste perceptions, as those are most critical when it comes to reformulation, in particular when it comes to the liking among consumers.

Therefore, the four visual attributes were considered to be less relevant for this reformulation work and were thus excluded from further analyses. Then, the remaining 12 separate multiple regression models were then widened with a backward elimination ($p \leq 0.05$). The most influential independent variables were thus identified, while maintaining the main effects of the mixture factors. The regression coefficients were calculated for each final model. Model performances were assessed via ANOVAs (F-test for significance) and coefficients of determination (R2). To examine and visualize the impact of the four independent mixture- and categorial factors, the mixture profiler function was applied.

5.1.3.2.2 **Optimization along different reformulation goals**

In a previous study, children evaluated eight commercial chocolate-chip cookies at home, and indicated their liking on a five-point hedonic emoticon scale with verbal labels. The results showed mainly two different liking patterns, which were used to develop the reformulation goal 1 and 2 for this study (TABLE 15).

The optimization goal 1 (143 children) was characterized by a higher preference for fondant and soft cookies and with a lower preference for crisp, hard and sweet cookies with a lower perceived chocolate-chips quantity and chocolate aroma. The optimization goal 2 (19 children) tends to be the opposite of goal 1, therefore children preferred more crisp and hard cookies with a higher perceived chocolate-chips content, chocolate aroma and sweet taste. Fondant and soft cookies were less preferred.

To optimize the responses of the dependent sensory, physicochemical and composition variables and the ingredient mixture with these two mentioned different strategies, the desirability function "D" = $(d_1 \times d_2 \times \ldots x d_k)^{1/k}$ was applied (Harrington, 1965). This value represents the desirable ranges for each responses, which ranges from 0 (least desirable) to 1 (most desirable) (Harrington, 1965, Derringer & Suich, 1980). To simultaneous optimize several selected responses, each goal must have a minimum and/or a maximum value as response, to set a specific "target". If for a specific variable no goal is foreseen (="none"), the response will not be included for the desirability calculation.

Based on the preferences (mentioned optimization goals 1 and 2 above), specific sensory attributes were thus proposed to be minimized or maximized, in order to obtain an optimal recipe with the highest desirability value possible (0-1). Besides sensory optimization, the aim was as well to optimize nutritional composition (kcal, Rayner score) and physicochemical (predicted glycemic index pGI, viscosity) information. The sensory optimizations goals do change depending on optimization goals 1 and 2 (preferences), while the optimization goals for composition and physicochemical stay unchanged for the two goals (always minimize or maximize).

The baked aroma was included in the model as it was considered as interesting to investigate, however no liking information was available for this attribute and was therefore not included for the desirability (desirability = none). Strategies 1 and 2 with sensory, composition and physicochemical variables and their desirability options a*re* show in (TABLE 15).

TABLE 15 : Defined desirability goals 1 and 2 for reformulation based on liking information from children on commercial cookies. Sensory attributes where "maximized" when children preferred an increased intensity of a specific attribute, whereas they were "minimized" when children preferred a lower intensity of a specific attribute. The sensory attribute "baked aroma" was not included in the desirability function (="none"), due to insufficient liking information. Detailed information about children's preferences can be found in Liechti et al., submitted and section 4.3. To improve cookies profile, it was aimed to keep the pGI, the kcal and the Rayner score low, whereas those three variables had the desirability function "minimize". In order to increase biscuits viscosity due to possible health benefits, the desirability function was to "maximize".

	Responses	**Desirability goal 1 (n=143 children)**	**Desirability goal 2 (n=19 children)**
Sensory texture in mouth and hand	Crispness in mouth	Minimize	Maximize
	Fondant in mouth	Maximize	Minimize
	Softness in mouth	Maximize	Minimize
	Hardness in hand	Minimize	Maximize
	Perceived chocolate-chips quantity	Minimize	Maximize
Sensory taste	Sweet taste	Minimize	Maximize
Sensory aroma	Chocolate aroma	Minimize	Maximize
	Baked aroma	None	None
Physicochemical and nutrition parameters	pGI	Minimize	Minimize
	Viscosity	Maximize	Maximize
	Kcal per 100g	Minimize	Minimize
	Rayner score	Minimize	Minimize

5.1.4 Results

5.1.4.1 Sensory and physicochemical properties of the reformulated cookies

Based on the panellists' evaluations, the perceived intensities of the 30 formulated chocolate-chip cookies on 20 sensory attributes are given in TABLE 16*.* No order effect was observed. The cookies were significantly different with 11 of the 20 attributes ($p<0.05$). The highest F-values and also differences between cookies were found for the visual attributes, as well as for the hardness in hand and the baked aroma intensity. Besides, the sweet taste perceived intensity was not significantly different between cookies, allowing to answer the preliminary objective of maintaining of the sweet perception. Due to its high importance for reformulation, this attribute was nevertheless further included for the next step “sensory modeling” to develop reformulation strategies.

TABLE 16 : Assessment of 20 evaluated attributes by sensory quantitative descriptive analysis with 10 trained panelists and 30 commercial cookies. F and p-values for product and panelist, significant p-values (threshold of 0.05) are in bold. Abbreviations for attribute family: V=visual appearance, Te H=texture in hand, Te M=texture in mouth, O=odor, A=aroma, and T=taste

Sensory attributes	Product		Panelist	
	F	p-value	F	p-value
V-Color cookie dough	19.01	**<0.01**	6.43	**<0.01**
V-Thickness cookie	9.84	**<0.01**	21.06	**<0.01**
V-Shiny cookie surface	2.60	**<0.01**	41.52	**<0.01**
V-Rhoughness cookie surface	4.69	**<0.01**	17.82	**<0.01**
Te H-Hardness	5.88	**<0.01**	9.18	**<0.01**
Te H-Brittle	0.84	0.71	3.25	**<0.01**
Te M-Fondant	2.80	**<0.01**	13.24	**<0.01**
Te M-Soft	3.33	**<0.01**	19.22	**<0.01**
Te M-Crispy	2.72	**<0.01**	7.67	**<0.01**
Te M-Pasty	1.29	0.16	31.63	**<0.01**
Te M-Sticky	1.10	0.34	37.04	**<0.01**
Te M-Perceived quantity chocoalte chips	1.98	**0.003**	20.94	**<0.01**
O-Chocolate	1.16	0.27	7.76	**<0.01**
O-Vanilla	0.71	0.87	58.87	**<0.01**
A-Chocolate	1.61	**0.029**	19.47	**<0.01**
A-Oat	1.06	0.39	22.43	**<0.01**
A-Vanilla	1.28	0.16	47.97	**<0.01**
A-Baked	4.18	**<0.01**	21.75	**<0.01**
A-Nutty	1.39	0.09	85.71	**<0.01**
T-Sweet taste	1.10	0.34	33.00	**<0.01**

The observation plot on FIGURE 41 B shows a wide spread of the products along the axes F1 and F2. It’s not only the baking degree that differentiates the products. They are also clustered according to their fat level. The loading plot (FIGURE 41 A) shows that cookies are mostly differentiated on axis F1 by their «hardness in hand» and «thickness», and by their «softness» and «fondant». Axis F2 (on the top) is positively correlated to the «baked aroma» and «color cookie dough» and negatively correlated to «aroma chocolate». Therefore, cookies texture was mostly explained by axes F1 (hard and crispy vs. soft and fondant) whereas cookies aroma was mostly explained by axes F2 (chocolate aroma vs. baked aroma). The observation plot (FIGURE 41 B) presents that cookies with a higher baking degree are situated on axes F2 on the top, whereas cookies with an increased fat level are predominately on axes F1 on the left side.

Some significant correlations between sensory, recipe and nutrition value variables were observed between the percent of fat and «fondant» (r=0.642) and «soft» (r=0.572), between the percent of sugar and «crispy» (r=0.387) and «hardness» (r=0.376). Furthermore, cookies with a higher level of the baking degree tend to have a darker color dough (r=0.931) with an increased baked aroma (r=0.892). As well there was a positive correlation between the chocolate-chip quantity in the recipe and the perceived quantity in mouth (0.486). Further, the Rayner score was positive correlated with kcal (0.819), added the percent of fat in the recipe (r=0.729), total fat (calculated nutritional value) (0.778) and saturated fat (0.779) and negative correlated with percent of oat bran (-0.626), fiber (-0.596) and protein (-0.420)

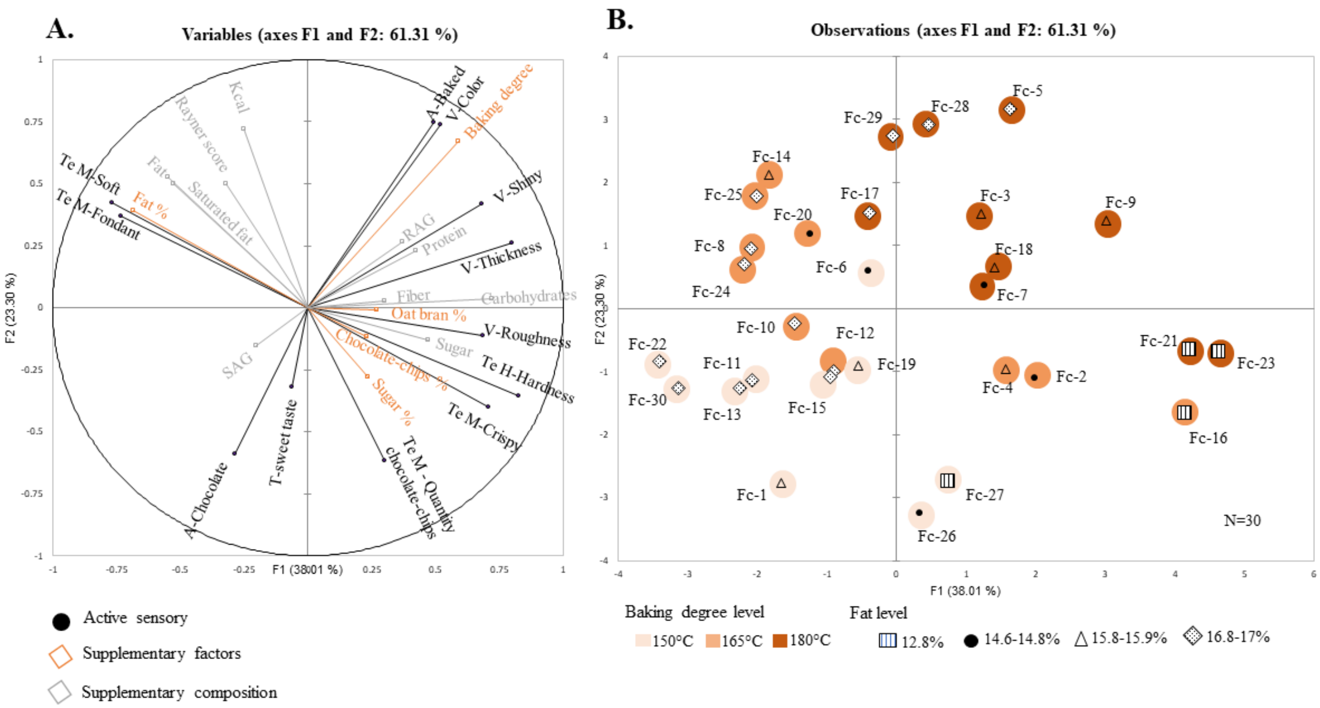

FIGURE 41 : PCA results for axes F1 and F2 (explaining 61.31% of the variation). (A) Variable correlation matrix with 12 active sensory (black), 4 supplementary factors (orange, added ingredients in % and baking degree) and 10 supplementary composition variables (calculated nutritional values, score, composition). With SAG=slowly available glucose and RAG=rapidly available glucose. Observation plot with 30 plotted formulated chocolate-chip cookies (Fc-1 – Fc-30), including two replicates Fc-21 - Fc-23 and Fc-17 - Fc-28. The cookies were colored and marked based on their mixture and categorial factors with highest factor loading on axes F1 and F2, whereas different colors indicate different levels of baking degrees and different symbols indicate different levels of fat.

Besides the sensory diversity, as well a broad physicochemical diversity was observed between cookies (TABLE 17, FIGURE 42). Especially the water content and the density demonstrated the highest F values.

TABLE 17 : Differences in physicochemical characteristics among the 28 different formulated cookies. (F values, p-values, means, SD, minimum and maximum values). Significance was determined using α = 0.05.

Physicochemical variables	F values	p-value	Mean	SD	Minimum	Maximum
Water content	30.86	**<0.01**	6.04	1.15	4.11	8.34
Water holding capacity	19.05	**<0.01**	0.54	0.15	0.29	0.90
Density	21.28	**<0.01**	0.69	0.05	0.6	0.85
Spread ratio	4.95	**<0.01**	4.04	0.58	2.68	5.75
Stress at rupture	9.77	**<0.01**	0.05	0.02	0.01	0.13
Strain at rupture	3.52	**<0.01**	0.07	0.03	0.03	0.20
Viscosity	12.10	**<0.01**	371.33	83.46	237.58	699.74
Glycemic index	5.66	**<0.01**	48.02	2.46	43.66	59.02
RAG	9.78	**<0.01**	46.05	3.03	40.28	56.00
SAG	11.86	**<0.01**	3.99	2.06	0.47	9.90

In Figure FIGURE 42 AB, the variable matrix shows that cookies were most differentiated based on axes F1 (left side) with “baking degree” (r=0.870), and F1 (right side) with “water content” (r=0.754), “density” (r=0.715) and water holding capacity (r=0.669). Furthermore, cookies on axes F2 were most differentiated by the stress at rupture (0.742).

In Figure FIGURE 42 CD, cookies among the axes F3 and F4 were mainly differentiated by their predicted calculated glycemic index and RAG (axis F3 on the right side) and their fat level in % (axis F4 on the bottom). Further, cookies on axes F5 on the top tend to have an increased oat bran and fiber content (FIGURE 42 EF).

Some correlations between physicochemical, recipe and nutrition value variables were determined between the percent of oat bran and viscosity (r=0.574), between the percent of oat bran and SAG (r=0.452), between the total sugar and strain at rupture (r=0.421) and between Glycemic index and RAG (r=0.864).

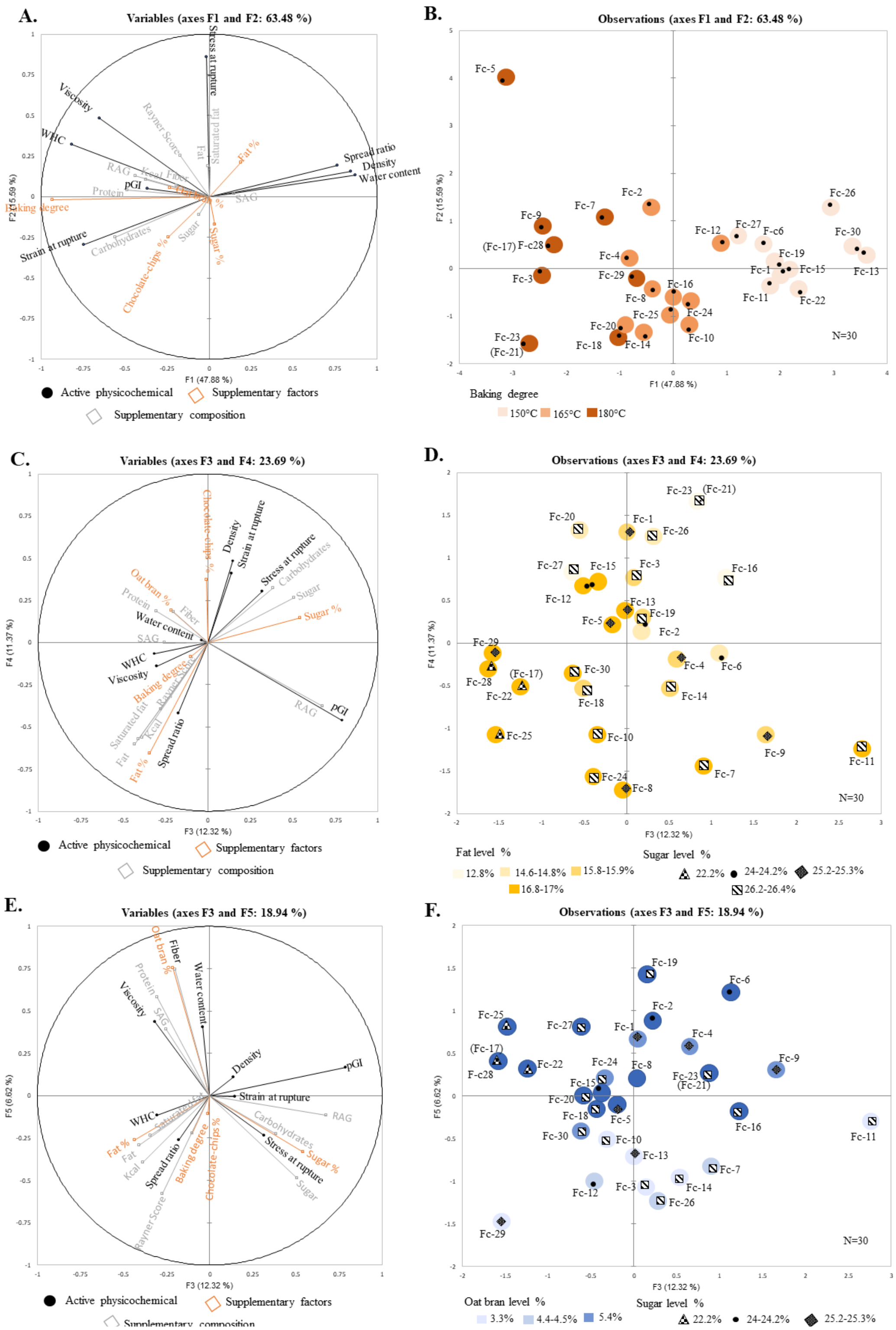

FIGURE 42 : 3 PCAs with active physicochemical and supplementary factors and composition variables and 30 re-formulated chocolate-chip cookies. A,B: PCA with axes F1 and F2 (explaining 63.48% of variance) and the colored levels of the baking degree. C,D: PCA with axes F3 and F4 (explaining 23.69% of variance) with colored levels for fat and symbols for sugar levels. E,F: PCA with axes F3 and F5 (explaining 18.94% of variance) with colored levels for oat bran and symbols for sugar levels.

5.1.4.2 Sensory modeling and impact on nutritional indicators

Optimal mixture models were obtained for the 16 variables with separate models with sensory, physicochemical and nutrition variables, before the backward elimination. The corresponding F ratios ranged between 1.22 (p=0.35) for the sweet taste and 60.85 (p<0.01) for the kcal content. In total, 9 variables showed significant results, mostly sensory visual and physicochemical variables. Most of the texture attributes were not significant, except the perceived crispness. The same goes for the two attributes related to chocolate perception ("Te-M-Perceived quantity of chocolate" and "A-chocolate") no significant results were observed. The R^2 values ranged between 50 and 98%. Best fits were found for the sensory attributes "A-Baked", "V-Color cookie dough", "V-roughness cookie surface", for the two nutritional indicators (Kcal, Rayner score) and for viscosity with ranges 80-98%. The lowest fit was found for sweet taste. All models with the profiler function are visualized in SUPPLEMENTARY FIGURE 12.

The next model focused only on total 12 variables, such as the 8 most relevant sensory texture, aroma and taste attributes and the same four selected physicochemical and composition variables, as described in section 5.1.3.2.1. After applying the backward elimination of 12 variables (12 separate models), the ANOVA showed for almost all models with sensory, physicochemical and composition variables significant results (9 out of 12, main effects and first order interactions) (TABLE 18). But no significant results were observed for the sensory models "sweet taste", "aroma chocolate" and the physicochemical model "predicted glycemic index". F ranges (with p-values) extended between 2.15 (p=0.12) for the sweet taste and 201.17 (p<0.01) for the kcal variables. For the same attributes, the R2 ranged between 20% and 98%.

TABLE 18 : Selected sensory (8) attributes with physicochemical and nutrition parameters such as pGI, viscosity, kcal and Rayner score. The performance of the optimal mixture models was analyzed via ANOVAs and the coefficients of determination (R2). F: Fisher statistic for the fixed effects. P: value: p-value for the Fisher test. Significant p-values (threshold of 0.05) are in bold.

		ANOVA		Fit
	Dependent variables	F	p-value	R^2
Sensory texture in hand & mouth	Te H-Hardness	7.63	**<0.01**	0.47
	Te M-Fondant	7.93	**<0.01**	0.48
	Te M-Soft	4.39	**0.01**	0.34
	Te M-Crispy	5.49	**<0.01**	0.53
	Te M-Perceived quantity chocoalte chips	4.67	**<0.01**	0.35
Sensory aroma & taste	A-Chocolate	2.70	0.05	0.30
	A-Baked	27.46	**<0.01**	0.85
	T-sweet taste	2.15	0.12	0.20
Physicochemical and nutrition parameters	Predicted cgylcemic index	2.53	0.06	0.34
	Viscosity	25.57	**<0.01**	0.85
	Kcal	201.71	**<0.01**	0.98
	Rayner Score	32.13	**<0.01**	0.84

As shown in TABLE 19 and TABLE 20, sensory attributes, physicochemical and nutrition parameters were affected by different factors and interactions between them. Among all sensory, physicochemical and composition variables, the highest F-values were found for kcal (sugar % * baking degree, fat %) and for the A-baked (sugar % * baking degree). Moreover, the highest F-values were identified for the texture M-Fondant (fat %) and for the measured viscosity (fat % * baking degree).

Among the sensory attributes (TABLE 19), the perceived crispness in mouth was the most impacted by the mixture factors compared with other attributes. Chocolate-chips were identified as a key ingredient to increase the perceived crispness. Further, it was shown that the fat content was a key (and only) significant indicator impacting for the perceived texture attributes “Fondant” and “Soft” in mouth. Regarding the aroma perception, the baking degree influenced the perceived chocolate and baked aroma. In this research, no significant influence of the oat bran on sensory perception was observed, except for the texture attribute “crispy”, whereas an increased oat bran content led to a reduced crispness.

TABLE 19 : Sensory models. All significant main effects with first order interactions (including the baking degree) identified using a backward elimination procedure while maintaining the main effects from the four mixture factors sugar%, fat%, chocolate-chips% and oat bran% (F = Fisher statistic for the fixed effects; p-value <0.05). Most significant p-values per factors and interactions were highlighted in bold for each variable. All models were significant, except for the attributes “sweet-taste” and “chocolate-aroma” as mentioned in TABLE 18.

	Sensory attributes	Factors and or first order interactions	F	p-value
Texture in hand and mouth	H-Hardness	Sugar %	16.13	<0.01
		Fat%	14.03	<0.01
	M-Fondant	Fat %	27.09	<0.01
	M-Soft	Fat %	18.5	<0.01
	M-Crispy	Chocolate-chips %	8.24	0.01
		Sugar %	7.86	0.01
		Fat%	7.29	0.01
		Oat bran %	6.81	0.02
		Fat % * Chocolate-chips %	6.42	0.02
		Sugar % * Oat bran%	5.42	0.03
	M-Perceived chocolate-chips quantity	Chocolate-chips %	18.72	<0.01
		Sugar %	4.89	0.04
Aroma & taste	A-Chocolate	Chocolate-chips %	10.67	<0.01
		Sugar % * Baking degree	7.31	0.01
		Sugar %	6.37	0.02
	A-Baked	Sugar % * Baking degree	132.05	<0.01
		Sugar %	7.43	0.01
		Chocolate-chips %	5.45	0.03
		Sugar % * Fat %	4.42	0.05
	T-Sweet	Sugar %	13.48	<0.01
		Chocolate-chips %	5.74	0.02

Concerning the physicochemical and composition variables, a high impact of mixture factors and interactions was observed (TABLE 20). The highest impact on the predicted calculated glycemic index was explained by chocolate-chips % and by the interaction sugar % and fat%, without significant impact of the oat bran %. All mixture factors showed significant impact on the viscosity, as the oat bran content showed the highest impact as main factor. As well for the composition variables kcal and Rayner score, all mixture factors showed significant impact, with exception of the oat bran % on the Rayner score.

TABLE 20 : Physicochemical and nutrition model. All significant main effects with first order interactions (including the baking degree) identified using a backward elimination procedure while maintaining the main effects from the four mixture factors sugar%, fat%, chocolate-chips% and oat bran% (F = Fisher statistic for the fixed effects; p-value <0.05). All models were significant, except the physicochemical factor "predicted glycemic index" (pGI).as indicated in Table 18.

	Physicochemcial & composition variables	Factors and first order interactions	F	p-value
Physicochemical	pGI	Chocolate-chips	7.96	0.01
		Sugar % * Fat %	6.48	0.02
		Fat %	5.91	0.02
		Sugar %	4.87	0.04
		Oat bran % * Baking degree	4.42	0.05
	Viscosity	Fat % * Baking degree	61.89	<0.01
		Oat bran %	13.48	<0.01
		Fat %	8.7	0.01
		Sugar %	7.63	0.01
		Sugar % * Fat %	7.49	0.01
		Chocolate-chips %	6.83	0.02
Nutrition	Kcal	Sugar % * Baking degree	324.07	<0.01
		Fat %	175.72	<0.01
		Chocolate-chips %	62.18	<0.01
		Sugar %	34.89	<0.01
		Oat bran %	13.62	<0.01
		Sugar % * Oat bran %	7.7	0.01
	Rayner score	Sugar %	58.95	<0.01
		Chocolate-chips %	39.14	<0.01
		Fat % * Baking degree	22.02	<0.01
		Fat %	20.64	<0.01

5.1.4.3 Recipe optimization with the desirability function

As can be seen in FIGURE 43AB, in general an increased fat content led to a less hard texture in hand, a reduced crispness and increased at the same time the softness and fondant perception. The sugar content on the opposite, showed a tendency for increasing the hardness in hand and the crispness. Furthermore, a higher chocolate-chips content contributed largely to an increased crispness. Moreover, the baking degree plays an important role for the aroma perception, whereas an increased baking degree led to an enhanced baked aroma and a reduced chocolate aroma.

Considering the physicochemical and nutrition parameters, it was shown that a higher content of chocolate-chips led to an increased predicted calculated glycemic index, whereas an increased oat bran content resulted in an increased viscosity. It was observed that an increased sugar content led to a reduced overall kcal content, as for those recipes the fat content is low. The opposite was observed for the fat content, as with an increased fat level the kcal increases as well due to the highest kcal density of the macronutrient fat with 9kcal per g. The oat bran on the other hand led overall to a reduced kcal content. Similar trends as for the kcal content were shown for the Rayner score.

Moreover, the FIGURE 43 AB demonstrated that depending on the optimized sensory, physicochemical and nutrition scores, it is possible to move the recipe towards a healthier product, such as a possible sugar, fat and chocolate-chips reduction, an oat bran enhancement, a reduction of the predicted calculated glycemic index, an increased viscosity and a reduction of the kcal and the Rayner score.

A. Optimization goal 1 **B. Optimization goal 2**

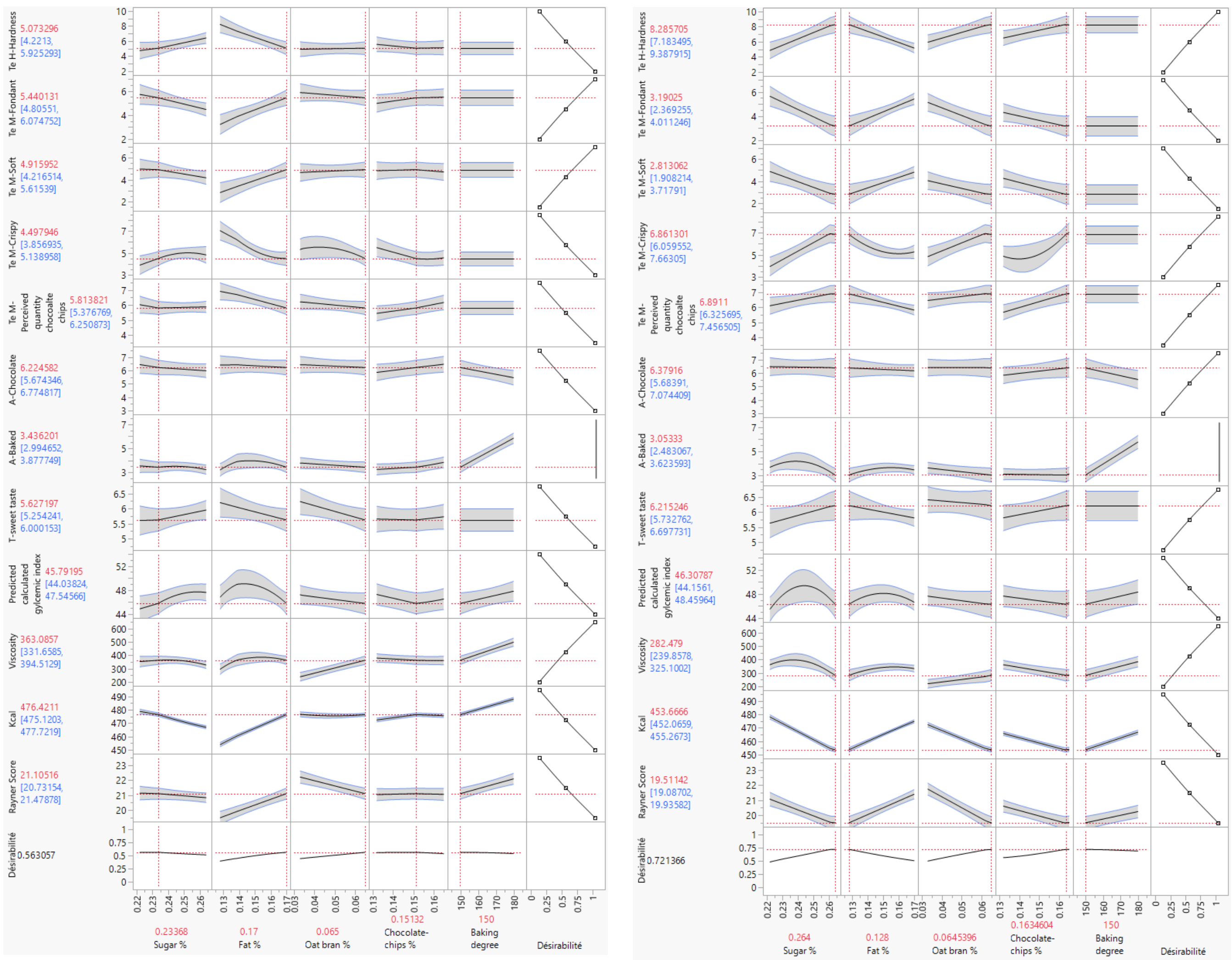

FIGURE 43 : A, B: Cross-sectional view of the predicted sensory, physicochemical and composition scores as a function of the four mixture factors sugar %, fat %, oat bran % and chocolate-chips % and the categorial factor baking degree for the optimization goals 1 and 2 (defined in M&M in section 2.3.2.2,Table 15), while the optimization only differ among the sensory optimization. The vertical red lines correspond to the current values of the factors (also indicated in red below the x-axes). The horizontal red lines correspond to the mean predicted scores based on the current factor values (also indicated to the left of the y-axes [95% confidence intervals in blue]). The confidence intervals are represented in gray on the plots. Overall recipe desirability is shown in the last plot row and column. It was defined as the geometric mean of the desirability functions for the individual responses.

With the optimization goal 1, an overall desirability of 0.56 was achieved. Thereby, an optimal recipe would be 23.4% sugar, 17% fat, 6.5% oat bran and 15.1% chocolate-chips baked at 150°C. Regarding the maximum values for the mixture factors, for this goal a sugar and chocolate-chips reduction up to 11.5%, respectively 8.3% is possible while optimizing sensory perception, physicochemical and nutrition parameters as much as possible.

For optimization goal 2, an overall desirability resulted in 0.72. An optimal composition would be composed of 26.4% sugar, 12.8% fat, 6.5% oat bran and 16.4% chocolate-chips baked at 150°C. Therefore, a fat reduction up to 24.7% is feasible while maintaining sensory perception and optimizing physicochemical and nutrition parameters.

A lower desirability was achieved with the optimization goal 1, while overall trying to reduce the hardness, the crispness, the sweet taste, the perceived quantity of chocolate-chips, the chocolate aroma and trying to enhance the softness and fondant. Further, this goal led to a higher viscosity (+25.5%) and lower predicted calculated glycemic index (-1.2%) than goal 2.

A higher desirability was achieved with the goal 2, with the aim to increase the hardness, the crispness, the sweet taste, the perceived quantity of chocolate-chips, the chocolate aroma while trying to reduce the softness and fondant. Compared to goal 1, goal 2 demonstrated a higher potential for an overall kcal (-4.8%) and Rayner score (-9.25%) reduction.

For both goals 1 and 2, a high oat bran content increased the desirability. When comparing the two reformulation goals with the target commercial cookie (TABLE 21), different reduction scenarios were possible.

TABLE 21 : Possible reformulation leverages for goal 1 and 2 in comparison with the initial target commercial chocolate-cookie.

	Sugar %	Fat %	Chocolate-chips %	Oat bran	Kcal	Rayner score	pGI
Optimization goal 1	23.4	17	15.1	6.5	476.4	21	45.8
Optimization goal 2	26.4	12.8	16.4	6.5	453.6	19.5	46.3
Commercial recipe	27.4	18	16.5	-	478	22	52
Leverages goal 1	**-14.6%**	-5.6%	**-8.5%**	+6.5%	-0.4%	-4.5%	**-11.9%**
Leverages goal 2	-3.6%	**-28.9%**	-0.6%	+6.5%	**-5.1%**	**-11.4%**	-11%

5.1.5 Discussion

Reformulation strategies and leverages to enhance a cookie recipe

This study shows that the use of a mixture design is a pertinent tool for a sensory led multicriteria reformulation approach. This study demonstrated a sugar, fat and chocolate-chips reduction and oat bran enhancement in cookies while optimizing sensory perception, physicochemical and nutrition parameters. Furthermore, sensory and physicochemical analyses showed a broad diversity of the formulated cookies. This underlines the difficulty of biscuit reformulation, where even a small sugar or fat change might impact products' structure and the sensory perception.

Furthermore, it was shown that process factors (such as baking degree) might be important to consider when it comes to aroma perception, but as well the final energy density of the biscuits.

Depending on the objective of reformulation and the sensory optimization goals, it was possible to improve the cookies' nutritional profile in different ways. The results of the optimization strategies 1 and 2 demonstrated the complexity of this food matrix, which is characterized by a high sugar and fat content. It is either possible to reduce the fat, the kcal and the Rayner score at once, or it is possible to reduce the overall sugar, chocolate-chips and glycemic index at one time. However, a simultaneous fat and sugar reduction could not be achieved and this underlines the difficulty when working without any fat and sugar replacers in bakery products. Reformulating biscuits with a complex food matrix high in sugar and fat is reportedly difficult, with many possible consequences of foods' structure and texture (Cooper, 2017).

Further, due to a higher desirability value of the goal 2 compared to goal 1, it might be more feasible to reduce the overall fat and kcal content including the Rayner score while optimizing sensory (more hard and crisp texture, increased sweetness and chocolate aroma, higher perceived chocolate-chips quantity) and physicochemical and nutrition parameters. In other words, a sugar reduction resulted in a lower desirability while a fat reduction showed a higher desirability. Indeed, sugar and fat do have multifunctional properties in the food matrix, and any modification may impact sensory perception and liking (Cooper, 2017; Ghotra et al., 2002; Marty et al., 2018; Miller et al., 2017; Nguyen et al., 2015; Pareyt et al., 2009). However, especially the sugar or sucrose is considered as the most important ingredient among baked products (Garvey et al., 2020). Sugars' role is going beyond providing sweetness, as this raw material is involved in creating and maintaining products' structure and reduce water activity what can result in an enhanced preservation. (Pareyt et al., 2009) had also shown that the level of sugar influenced to a higher extent cookies measured structure such as cookies' porosity, cell size, cell wall thickness and their relative distributions than the fat level did. Similar results were found for the sensory perception. For example, (Biguzzi et al., 2014, 2015) showed that fat reduction of commercial biscuits was less noticeable by consumers than a sugar reduction. Those results were as well confirmed in this study, where with the two goals a fat reduction was possible to a higher extent than a sugar reduction. However, caution is advised when reducing the fat content, as a fat reduction might induce a reduction of the sweet taste (Biguzzi et al., 2014).

In the case of sweet baked product, sugar reduction would thus be more difficult to achieve than a fat reduction.

However, several authors identified the excessive sugar intake as key dietary determinant of obesity among children and adolescents (Ambrosini et al., 2015; Te Morenga et al., 2012). Thus, in order to tackle childhood obesity, considering both, the total energy from fat and sugar seems to be important.

Besides the reduction of macronutrients and chocolate-chips, it was further possible to reduce the Rayner score and the predicted glycemic index (pGI). The incorporation of oat bran was identified as important ingredient to increase the overall desirability and to optimize sensory perception, and to reduce the overall kcal and to increase the viscosity.

Impact mixture factors on sensory perception, physicochemical and nutrition parameters

This study demonstrated the difficulty to reduce sugar and fat in a complex food matrix without the use of replacers or additives. As consequence, when manipulating one mixture factor, all factors change their ratios. Therefore, when we work with a higher sugar content, less fat is consequently needed and therefore the overall kcal content diminish. On the opposite, a sugar reduction will lead to an increased fat content and finally an increased kcal content and Rayner score. It is therefore questionable is the Rayner score is a suitable “global” nutrition tool for all product categories. Furthermore, comparing the Rayner scores among the two reformulation strategies and the commercial recipe, a sugar and a fat reduction did not largely impact the Rayner score. Although the sugar and fat reduction was around 15 almost up to 30%. In order to set incentives for industries to reformulate, the target goals and the measured success (like the reduction of a specific score) should be adapted on specific product categories.

This “mixture effect” highlights one of the limitations of reformulation, as confirmed elsewhere (Cooper, 2017). Further it is a plausible explanation why according to a recent review only limited data were available to support sugar reduction in bakery products without any substitution and additives (Luo et al., 2019). Moreover, an increased baking degree led as well to an increased kcal content, as an increased baking degree is associated with an increased water loss during baking. Therefore, a cookie will lose more water and the nutrients are more concentrated.

Further, our study identified a reformulation chance for the sugar- and the chocolate-chip reduction, as the models were not significant. Therefore, based on the sugar levels from the mixture design (22.2%-26.4%) our study showed that it is possible to reduce the sugar up to 15.9% without having a significant impact on the sweet taste perception.

As well another study found that consumers had difficulties in discriminating several sucrose levels among biscuits which are high in fat and sugar (Holt et al., 2000). Contrary, another study stated that it might be only possible to reduce the sugar content less than 10% among baked products to maintain sensory perception and textural properties (Luo et al., 2019). Sugar reduction might impact cookies' structure and texture more than the sweet taste per se. We might also hypothesize that the sugar and the fat levels in these products are just too high to be discriminated anyways.

Similarly, we found that it is possible to reduce the chocolate content by up to 19.5% without negative influence on the perception of chocolate-aroma. However, in our study, the perceived quantity of chocolate-chips in mouth increased the crispness. However, crispness was the most impacted sensory attribute from all factors, what means that not only the quantity of chocolate chips increased the crispness. This shows that the "crispness" perception is a complex and important attribute for cookies and needs high observation when reformulating biscuits. The importance of the attribute "crispness" was as well confirmed elsewhere, as this attribute can as well serve as shelf-life indicator (Piazza & Masi, 1997).

Besides, this study clearly shows that fat has a softening effect on the perceived cookie dough. This is inline with (Laguna et al., 2014) who showed that biscuits with a lower fat content were perceived as harder than those with a higher fat level. Besides the perception, as well physicochemical analysis showed that a reduction of the fat level in biscuits resulted in an increased breaking strength (Sudha et al., 2007). Further it was shown that fat is most important when it comes to aroma and flavor perception (Garvey et al., 2020). However, in our study, no significant effect of the fat content on any aroma or taste perceptions was observed.

However, this study showed that the addition of oat bran increased the measured viscosity, what might be explained by the increased beta-glucan content with swelling properties. As well in other studies it was shown that the high content of beta glucan content from soluble fibers such as oat and barley increased the viscosity due to its swelling properties (Anttila et al., 2004; Barsanti et al., 2011; Wanders et al., 2011).

In another study with biscuits it was shown that the addition of oat bran – rich in beta glucan - increased the measured viscosity including the post prandial satiety (Pentikäinen et al., 2014). Further, it was demonstrated that an increased bolus viscosity induced by fibers lead to an increased oral processing time (Priyanka et al., 2019). An increased food oral processing time was associated with an enhanced satiety and satiation (Fogel et al., 2017, 2018).

We found no direct impact of the oat bran on the predicted glycemic index, although it was reported that the viscosity of the beta glucan led to a reduced starch hydrolysis (Wang et al., 2020). However, as previous mentioned, as all mixture factors do change at once, it might be more difficult to make conclusions about the impact of one certain ingredient. Nevertheless, this study demonstrated that higher ratios of oat bran increased the slowly available glucose (SAG). This result was found elsewhere, where oat bran increased the SAG in frozen dough (Onipe et al., 2020). Moreover, the pGI ranges of 43.6-59.02 within the mixture design demonstrated that it is possible to reduce the pGI with different ratios of sugar, fat, chocolate-chips and oat bran. This is interesting, as the most important starch source of biscuits is the flour – and this ingredient was constant during all runs.

Therefore, the addition of oat bran is a further interesting leverage to impact the oral processing and the satiation and the satiety. Therefore, further behavior studies are needed to investigate the impact of the oat bran level on food oral processing, satiety and satiation.

5.1.6 Conclusion

This original approach showed that the use of a mixture design is a pertinent tool to better understand a complex food matrix and to reformulate a commercial product towards a healthier product. This sensory led multicriteria reformulation approach showed that it is possible to reduce target macronutrients and to enhance products' overall profile without replacers and additives, and while maintaining sensory perception.

Further studies are needed to investigate the impact of the reformulated cookies on perception and liking and the behavior related to food oral processing and satiation and satiety. This approach might increase the efficiency of reformulation and contribute to a healthier food environment among packed foods with positive impact on the diet and health.

5.2 "Measuring the impact of the reformulated cookies on children (liking, hunger level) and adults (time in mouth)."

General Introduction

To identify the best levers of reformulation towards a healthier product, an approach using a mixture design based on multiple criteria was proposed and described in the previous part of this manuscript. This sensory led reformulation approach showed that it was possible to reduce target macronutrients and to improve health relevant aspects without adding some replacers and additives, and while maintaining or targeting sensory perception. Some cookies were identified with a high potential to answer our objectives. This last section of the PhD and manuscript investigated the impact of the reformulated cookies on children's liking, self-reported hunger level and adults' measured time in mouth.

Therefore, 80 French children aged 10-13 years old (balanced for gender) from Paris and Aix-en-Provence were recruited by Eurofins Incorporated Company in France and included in this study. The liking and hunger level evaluation (before the snacking, immediately after snacking, two hours later) was conducted in 2021 via self-administered Home Used Test, using a five-point hedonic (emoticon) scale including verbal anchors. In total 4 different reformulated chocolate-chip cookies (with different levels of sugar, fat, chocolate-chips, oat bran and baking degrees) were selected from a mixture design with 30 cookies. Per day (mid-afternoon), the menu of snacking situation was customized to have 2 cookies, one apple puree and water, menu having similar nutritional characteristics.

To propose some mechanisms to explain the differences of liking, satiation and satiety (by comparison the differences of hunger levels) different properties were determined: food oral processing parameters and predicted glycemic index. The consumption times of these four cookies (T1 and T2) were indeed recorded just after the first bite before swallowing, and respectively when the cookie was entirely eaten among 10 adults.

"Measuring the impact of the reformulated cookies on children (liking, hunger level) and adults (time in mouth)."

To identify the best levers of reformulation towards a healthier product, an approach using a mixture design based on multiple criteria was proposed and described in the previous part of this manuscript.

This sensory led reformulation approach showed that it is possible to reduce target macronutrients and to improve health relevant aspects without adding some replacers and additives, and while maintaining or targeting sensory perception. Some cookies were identified with a high potential to answer to our objectives.

To go further and validate the approach, it was also necessary to investigate the impact of some of these reformulated cookies on children behavior, with impact on liking, food oral processing and satiation and satiety. For that, four cookies were selected and tasted during four different tea parties held at home by 80 children. We used a test design that allowed participants to engage in their usual cookies consumption habits as much as possible. For that purpose, we placed emphasis on a snacking context: children participants ate two cookies served with apple puree and water. We were in particular interested in finding out whether observed behaviors (in terms of liking, eaten quantity and satiation level) were linked to formulation of cookies, but also to body mass index (BMI) and to socio-demographic variables.

5.2.1 Materials and methods

5.2.1.1 Participants

This study was performed by 80 school aged children (10-13 years old), recruited by the Eurofins SAM company (France). They were recruited about two weeks prior to the experiment using online and phone questionnaires, focused on their sociodemographic characteristics and consumption habits. Children included in this study had no ongoing adverse health condition and were all cookies consumers. Participants were randomly selected using the quota method and their gender, age, sociodemographic characteristics and BMI were presented in SUPPLENETARY TABLE 16. Children's BMI (the subgroups “severe thinness”, “thinness” “normal”, “overweight” and “obesity”) was calculated as described in a previous study in section 4.3.2.3, whereas the BMI criteria was not a sampling criterion.

5.2.1.2 Products

Four formulated chocolate-chips cookies (named Fc-16, Fc-22, Fc-5, Fc-29) were selected from the 28 cookies developed from the experimental design described in section 5.1 (SUPPLEMENTARY FIGURE 13). The selection of these four cookies was based on their different multiple sensory (20), composition (18), and physicochemical (12) characteristics including their baking property (1).

Detailed recipe information, nutritional values, sensory (evaluated by adults) and physicochemical properties of the four selected cookies are presented in SUPPLEMENTARY TABLE 17, SUPPLEMENTARY TABLE 18, SUPPLEMENTARY TABLE 19, SUPPLEMENTARY TABLE 20.

The four cookies were produced in the laboratory manufacturing platform for cereal products (UMR Say-Food, Paris) (section 5.1.2.1). Microbiological analyses were conducted on all cookies in order to guarantee their food safety for children evaluation (evaluation with accredited external laboratory). Cookies were stored in heat sealed non-transparent mylar bags and stored at room temperature until children evaluation.

The tests were performed during a snacking situation in the afternoon. For each snacking situation, an commercial apple compote (Cora, France) and two formulated cookies were proposed to the children (with water as beverage). The total kcal of the snacks was between 324.4 to 341.8 (SUPPLEMENTARY FIGURE 13) and corresponded to the nutritional recommendation for a snack for children 10-12 years old child.

5.2.1.3 Contextualized test

The liking and self-reported hunger evaluation of the cookies by the children was done by a Home Use Test during the four school days monday, tuesday, thursday and Friday (in the same week). The test was then conducted in the afternoon, when children returned from school (16.30 – 17.30 pm).

The children were asked to eat one snacking package per day. All cookies in easy to open mylar bags and the compotes were first distributed to the parents. Cookies were distributed in blind conditions (coded with letters A, B, C and D). They were asked not to open the bags until to give the product to their child, in order to minimize the impact of moisture on the products. In the experiment, the order in which the four cookies were consumed by children followed a Latin square design. The data was collected with the online sensory software RedJade.

5.2.1.4 Self-administered questionnaires

The liking score was evaluated with a colored 5 point emoticon scale with verbal labels, from the left side “1 = I don’t like it at all” to the right side “5 = I like it very much” (ASTM, 2021, Laureati et al., 2015; Marty et al., 2018; Rannou et al., 2018). Besides the liking, further questions regarding their desire to eat a cookie, the quantity consumed and the possible quantity to re-consume were asked. Three questions were asked about children's self-reported hunger level at three different time points: before the snacking, immediately after the snacking and two hours later (SUPPLENETARY FIGURE 14) (Bennett & Blissett, 2014; Faith et al., 2002; Lange et al., 2019). To investigate then the impact of the formulated products on the self-reported hunger level, two deltas were calculated: Delta 1, “Hunger level immediately after snacking” – “hunger level before snacking” and Delta 2, “Hunger level immediately after snacking” – “hunger level after 2h”. Therefore, delta 1 provided information about the satiation, while delta 2 provided information about the satiety.

5.2.1.5 Food oral processing evaluation

To measure the time in mouth necessary to eat and swallow each cookie, a study with the same four cookies was conducted with 10 adult participants (students from AgroParisTech), in a controlled environment in the same period as children evaluation (same week in the afternoon).

For this evaluation, participants evaluated two cookies per test. The order in which the four cookies were evaluated followed a Latin square design. Between the consumption, participants were asked to rinse their mouth with mineral water. They were asked to eat the cookies and to signalize two different times: T1 was the time point just before swallowing of the first bite, whereas T2 indicated the whole time they needed for the entire cookie consumption. An instructor recorded the times in minutes needed for each participant and cookies.

5.2.1.6 Statistical analysis

All statistical analyses were conducted with XLSTAT version 2018.1.1 (Addinsoft, New York, USA). The alpha level was set to 0.05.

For children study, some anovas were carried out to test the effect of the serving position (product x rank) and children’s sociodemographic information and BMI (product x sex x age x city x BMI) on the liking scores, the desire to eat score, the quantity eaten score, the possible re-consumption score, the self-reported hunger level (3x) and the calculated delta 1 & 2 of the hunger level for all the 80 children. When significant differences between products were revealed ($P < 0.05$), mean liking and variable intensities were compared using the Newman–Keuls multiple comparison test. Although, only 80 children participated to the study, we investigated the diversity of preference patterns using hierarchical cluster analysis

(HCA) (Euclidean distance, Ward's criteria, clustering rows) on centered children-liking scores. For the clustering, we excluded the results of 20 children due to their constant scoring for all four cookies. Therefore, 60 children were included for the clustering.

For the study with adults and the recorded time in mouth, Anovas were carried out to test the effect of the serving position (product x rank) and the products and panelist on the recorded time in mouth.

5.2.2 Results

This part focused only on the main results, but all significant results of this study were presented in SUPPLEMENTARY TABLE 21.

5.2.2.1 Childrens liking among formulated cookies

All formulated cookies were globally appreciated by the 80 children, with high liking scores comprised between 3.8 and 4.1 on the 5 point scale (FIGURE 44). In addition, no significant differences were observed between the four cookies, although they presented different levels of sugar, fat, oat bran or chocolate-chips. By consequences, comparing the composition of these four reformulated products, this result showed that it is possible to maintain the liking whereas some reduction of the kcal (-5.9%), sugar (-15.9%), fat (-24.7%), and chocolate-chip (-20%) per cookie or increase in oat bran (+49.3%) were proposed. Those reduction levels refer to four different reformulated products, therefore these reformulation leverages were not carried out on one cookie.

In addition, the predicted glycemic index (-8.2%) and the Rayner score (-8.7%) were improved in these four cookies, showing the interest of the developed approach. Further, when comparing the four reformulated cookies with the commercial reference product (TABLE 21, commercial recipe), improvements are possible to an even higher extent such as a sugar (-19%), a fat (24.7%) and a predicted glycemic index (-13.5%) reduction and an oat bran enhancement (+100%).

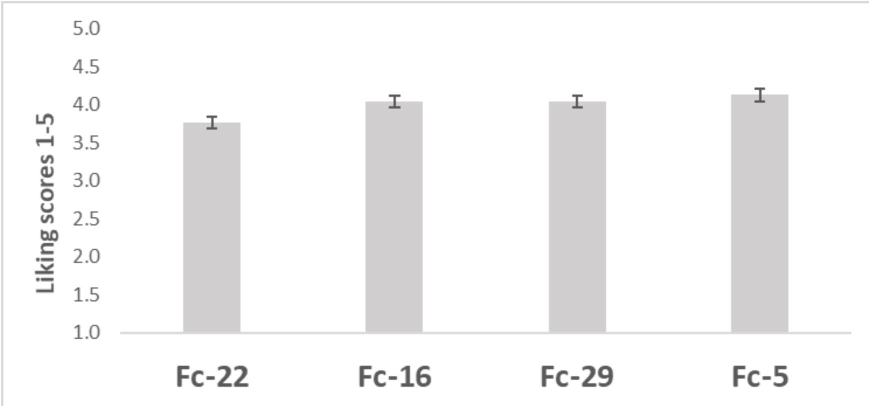

FIGURE 44 : Overall mean liking score for the four formulated cookies and the 80 children aged 10-13 years old, with standard errors The results of the ANOVA showed no significant impact of the products on the liking score (with $p \leq 0.05$).

Our results complement those of the literature, which showed the possibility to reduce the sugar content among foods and drinks with simple food matrices while maintaining the liking among children (Lima et al., 2019; Velazquez Mendoza et al., 2021a,b), but here, we confirmed as well the possibility to reduce the fat and the sugar content among a complex food matrix such as bakery products.

To go further with interpretation of trends (DF: 3; F: 1.85; p=0.14), the highest liking mean scores were observed for cookie Fc-5 (highest oat bran 6.5% and the lowest chocolate-chips 13.2% content and the highest baking degree 180°C). On the other hand, the lowest mean score was found for cookie Fc-22 (lowest sugar content 22.2% and the lowest baking degree 150°C). This trend confirms results of literature, with higher preferences of children for more sugary foods and sweet taste (Marty et al., 2018; Nguyen et al., 2015). However, the cookie with the highest sugar content (Fc-16) was not liked the most, suggesting the complexity of solid bakery products.

Furthermore, before the snacking, when only focusing on the visual appearance and the desire to eat, cookie Fc-5 and Fc-29 showed the highest mean score for “desire to eat” (browner color surface with a higher baking degree compared to cookies Fc-22 and Fc-16), whereas the cookie Fc-5 was significant more desired than cookie Fc-22 (F: 3.5; p<0.02). Those results underlined the obtained liking data, as cookies with the highest mean scores seem to be as well more visual appealing and provoke a higher “desire to eat” (Fc-29, Fc-5).

Although no significant results were observed for the liking among the four formulated cookies by all the children, we investigated possible liking differences between children. First, regarding children's socio-demographic data and BMI, it was shown that overweight children showed overall the highest liking score and which is higher than among thin children (F: 4.7; p<0.01) and girls consumed more cookies than boys (F: 8.7; p<0.01).

Then a clustering was performed to identify similar pattern of liking between children. The results of the clustering in FIGURE 45 showed three obtained clusters (cluster 1 n=29 children; cluster 2 n=12 children; cluster 3 n = 19 children) with different preferences and rejections for specific cookies. For example, children of the cluster 3 preferred cookie Fc-22, whereas at the same time cluster 1 showed the lowest preference for cookie Fc-22. The low sugar content and the low baking degree of cookie Fc-22 might impact children's sweet perception, but as well the texture and the visual perception on the cookie surface. The only cookie which was never the least preferred among the 3 clusters was the cookie Fc-5 (highest oat bran, lowest chocolate chip).

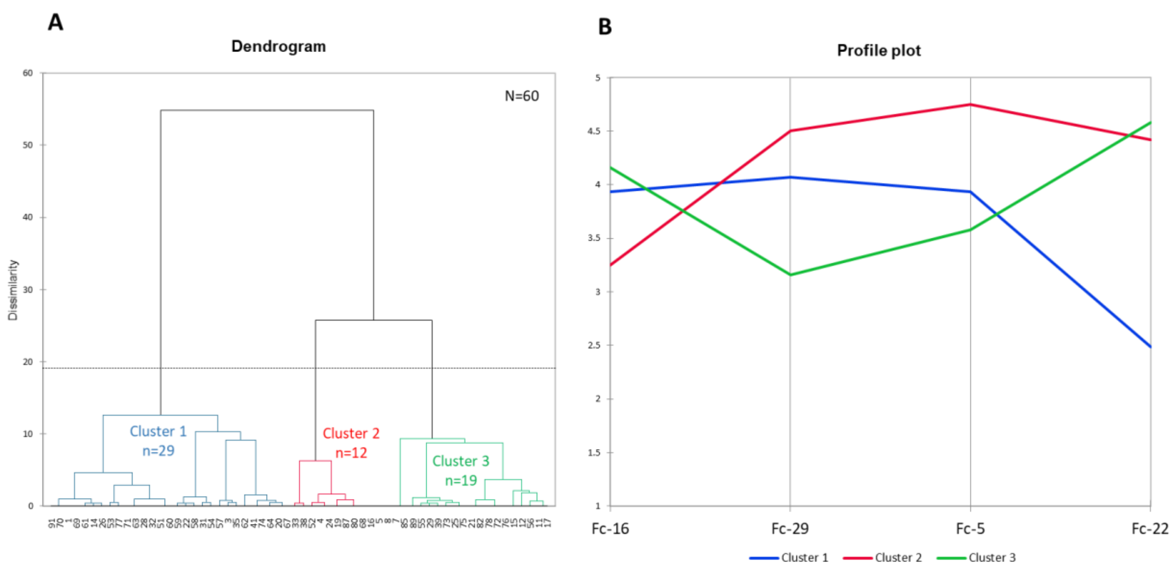

FIGURE 45 : Agglomerative Hierarchical Clustering among 60 children aged 10-13 years old with their liking scores of four cookies. A. Three obtained clusters of children. B. Different preferences and rejection zones among different clusters.

5.2.2.2 Childrens eaten behaviour among formulated cookies

Some trends could be observed which seemed interesting to discuss. A similar tendency as obtained from the liking and desire to eat was observed, as cookies most liked/desired (Fc-5, Fc-29) were also consumed in the highest quantities (F:1.25;p=0.29), with up to two cookies per variety of total ~60g (= the full amount provided). On the other hand, the cookie with the lowest mean liking score (Fc-22) tend to be consumed in a lower quantity, with an average of 1.5 cookies (~45g).

However, whatever the liking score, children ate overall more than one cookie, what might indicate the overall liking of this product category “chocolate-chips”. Interestingly, although cookie Fc-16 and Fc-29 do have the same mean liking score, cookie Fc-16 showed a slightly lower mean consumption quantity (1.5-2 cookies) than Fc-29 (2 cookies). It might be that the low baking degree, the higher oat bran content and the lower fat content of cookie Fc-16 could have influenced children’s consumption quantity.

Further trends were observed for the possible re-consumption, if they had the possibility. Overall, for any kind of cookies, children answered to re-consume at least one cookie more. Again, this might highlight the overall appreciation of this product category, or the snack provided showed a low satiation effect. Interestingly, the cookie with the highest liking score (Fc-5) was not the product which would be re-consumed the most. Instead, the highest mean for a re-consumption (1-2 cookies more) showed the two cookies with the same liking score (Fc-29, Fc-16) (F:0.83; p=0.47). It might be that the low chocolate-chips of the cookie with the highest mean liking score (Fc-5) might have influence children’s answer for a possible re-consumption.

5.2.2.3 Impact on satiation and satiety

Besides the liking, as well the impact of the four reformulated cookies on satiation and satiety were investigated by the self-reported hunger level before and after the snacking and after two hours later. As shown in FIGURE 46, no cookie significantly impacted any of the three reported hunger levels.

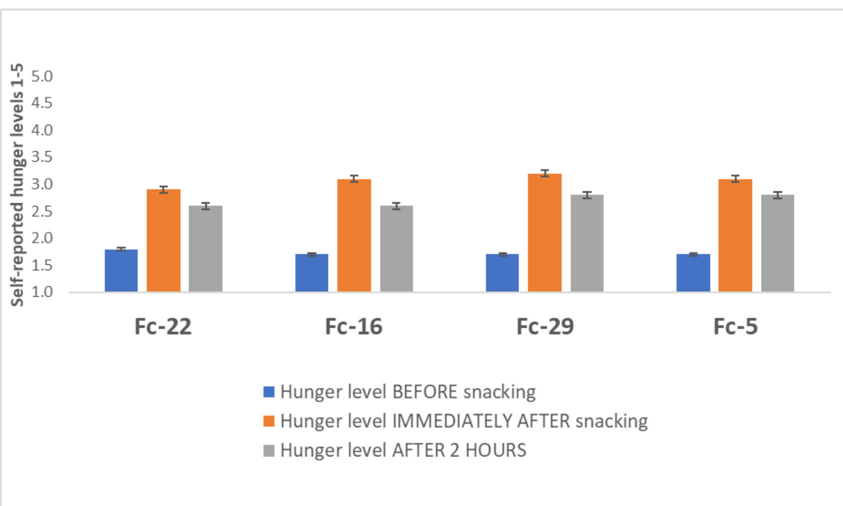

FIGURE 46 : Self-reported hunger levels among four formulated cookies and 80 children aged 10-13 years old at three different time points 1, 2 and 3 with standard errors. The results of the ANOVA showed no significant impact of the products on the self-reported hunger levels (with p ≤ 0.05).

Similar results were obtained when considering the calculated delta 1 (satiation: hunger level immediately after snacking – hunger level before snacking) and 2 (satiation: hunger level immediately after snacking – hunger level after 2h), whereas no significant impact of the four reformulated cookies on children's satiation and satiety level was observed (FIGURE 47).

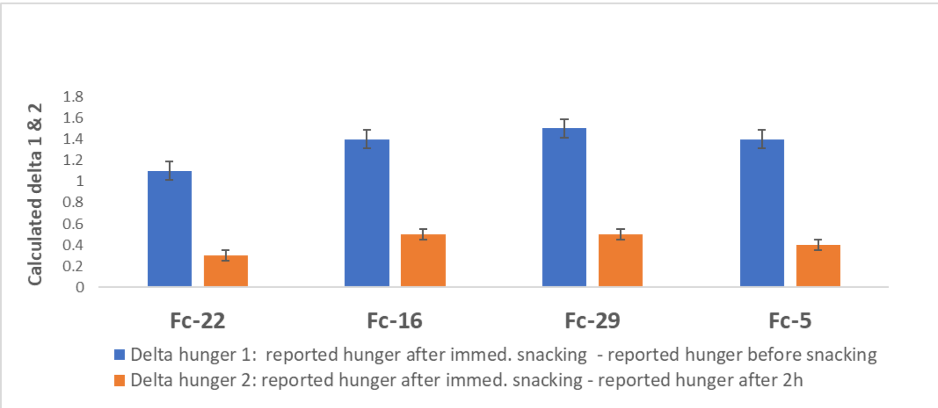

FIGURE 47 : Calculated delta 1 and 2 for the self-reported hunger levels among 80 children aged 10-13 years old and four formulated cookies with standard errors. The results of the ANOVA showed no significant impact of the products on the calculated delta 1 and 2 (with $p \leq 0.05$).

However, some observations for the satiation (F:1.28; p=0.28) and the satiety (F: 0.72; p=0.54) were noticed. When comparing satiation (delta 1) and satiety (delta 2) in FIGURE 47, cookie Fc-29 showed a tendency for a higher satiation effect (delta 1). On the other hand, cookie Fc-22 showed a trend for a higher satiety effect (delta 2). Interestingly, the lowest satiety effect was found for the cookie Fc-29 with the overall highest kcal (490) and lowest oat bran (3.3%) content, and for cookie Fc-16, with the highest overall sugar (26.4%) content. We conclude that adding oat bran into the cookie matrix might influence the perceived satiety.

Significant effect was found between children's BMI, the satiation and satiety levels (SUPPLEMENTARY TABLE 21). It was found that overweight and obese children showed the highest satiation levels immediately after snacking, where their satiation was higher compared to severe thin children (F: 4.2; p<0.01). Similar results were obtained for the satiety level after 2h, where overweight and obese children showed as well the highest satiety level, and which is higher than the satiety level of children with a normal, thin or severe thin BMI group (F. 7.4; p<0.01). This is an interesting finding, as the opposite was expected (children with higher BMI expected to have lower satiation and satiety effect).

5.2.2.4 Food oral processing: Time spend in mouth to swallow the cookies

One of the main hypothesis to induce a higher satiation and satiety was linked to the time spend in mouth and directly related to the texture and structure properties of cookies. Results showed that similar times in mouth were measured between cookies for T1 (time in minutes for the first bite before swallowing) and T2 (time in minutes after the consumption of the entire cookie), without having significant effects on the measured time in mouth (FIGURE 48) (T1 F:1.16; p=0.34; T2 F:1.88; p=0.15). However, significant interindividual differences for the measured time in mouth T1 (F: 6.12; p<0.001) and T2 (F: 3.77; p<0.001) were observed.

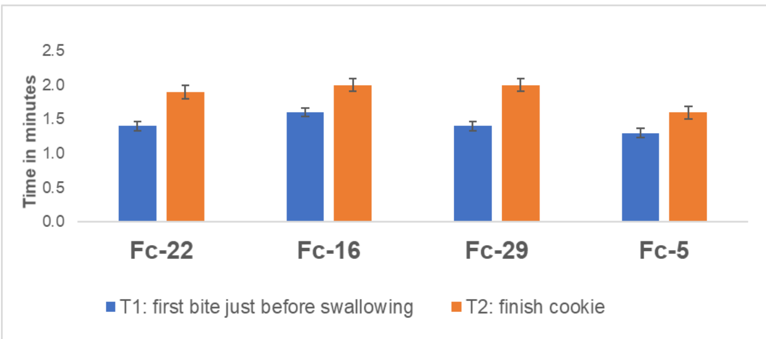

FIGURE 48 : Measured time in mouth among 10 adults and the four formulated cookies at two different time points, T1 and T2 in minutes. The results of the ANOVA showed no significant impact of the products on the time in mouth (with p ≤ 0.05).

5.2.3 Discussion

Overall, all reformulated cookies were liked although they had different composition, sensory and physicochemical characteristics. This is promising for future reformulation work within the product family sweet biscuits. Our study suggested that children do have preferences and that their liking evaluation might be influenced by their socio-demographic and BMI information. Different preference pattern among inter-individual differences was confirmed elsewhere (Cox et al., 2016; Kubberød et al., 2002; Rose et al., 2004a, 2004b; Torri et al., 2021).

Furthermore, we observed that liking scoring and self-reported hunger levels among overweight/obese and non overweight/obese children. Further studies with a higher number of children balanced for age, gender and BMI are thus needed to better understand the perception and behavior for children with an increased BMI. As children do have different chewing efficacy compared to adults due to their ongoing development of dentition (Lukasewycz & Mennella, 2012; Rose et al., 2004a, 2004b; Szczesniak, 1972; Zeinstra et al., 2010).

It seems important to test further food oral processing parameters (time in mouth, number of bites, bite sizes, saliva production etc.) on a large number of children, balanced for age and gender. Moreover, to have a better understanding of the impact of the reformulated cookies on oral processing behaviors, an investigation of the bolus properties (time measured to form a bolus, saliva incorporated etc.) is further recommended.

In our study, we used a home used test for children, to provide a safe, natural and real snacking environment. This kind of test is a suitable method for children (ASTM, 2021) However, this methodology might have limitations, as at children’s home it was not possible to provide help and to check their understanding of the questionnaire, even though the questionnaire was pre-tested on children. Furthermore, children might deviate from the test time in the afternoon or they could consume further foods after the snack, what will impact the self-reported hunger level after two hours. As well the fact that the study was conducted just before Christmas (with the assumption that children might have a higher intake of sweets such as biscuits) might have an impact on children’s perception, appreciation and desire to eat towards biscuits.

It might be that the textural differences among those four selected cookies is too small, to achieve a significant impact on food oral processing. Especially when considering the dosage of the oat bran, with the ranges between 3.3 – 6.5 %. Those four cookies were selected out of a mixture design with further 24 cookie recipes. Further hedonic evaluation among other recipes of the mixture design might be of interest. As well, it might be interesting to further increase the oat bran level above 6.5%. In addition, the number of participants for measuring the time in mouth should be increased, to obtain a better representation of inter-individual differences in oral process behaviors. Moreover, testing the target commercial reference product is of further interest.

5.2.4 Conclusion

To conclude, this multicriteria approach was a successful approach to reformulate a commercial product towards a healthier product, while maintaining sensory perception and the liking among 10-13 years old children. All four reformulated cookies were overall liked. Besides a reduction of target nutrients, as well an improvement of the predicted glycemic index and the Rayner score was possible. Trying to impact the satiation and satiety to a higher extend, further studies might be of interest to increase the oat bran or the source of beta glucan content, to test other cookies from the mixture design and to test as well a reference product, without any oat bran or beta glucan content. Further, sensory descriptive analysis and oral process behavior studies are needed to better understand children's perception and behavior in mouth. As well younger children should be considered. This study underlined further the importance to consider children's interindividual preferences for products, as there exists no product which is liked or rejected from everyone. Moreover, making a product visual more appealing might positively influence the desire to eat a product. In addition, further investigation is needed when it comes to children with an increased BMI, their liking and satiety.

Chapter 6

Overall discussion

Conclusions

Perspectives

6 Overall discussion and perspectives

The objectives of the present chapter are to integrate and discuss the results obtained during this PhD work, in particular to discuss the multicriteria approach used to propose some reformulation of food products as well as the different knowledge on products and methodologies. The main conclusions drawn in the previous chapters are presented in order to be afterwards discussed on following parts: i) the multicriteria reformulation approach under multiple constraints (including clean label, nutrition quality, process score, sensory perception), ii) impact of formulation on predicted glycemic index and children behavior, iii) role of food texture and food oral processing as key mechanisms in link with the perceived satiation and satiety.

6.1 Short summary about the achieved results including methodology

In order to improve the food offer, this PhD research was conducted in the frame of the European H2020 STOP project. Its aim was to develop an innovative food reformulation approach targeting at biscuits eaten by children 7-12 years old, following a multidimensional approach. Indeed, any modification in the food matrix might impact products structure, texture, consumers' perception and by consequences liking. Therefore, we proposed a multicriteria food reformulation approach that would simultaneously consider composition, nutrition, physicochemical, sensory and liking information. In this context, this PhD research project aimed to investigate the levers to improve the nutritional quality of the food offer for commercial products, while improving key sensory properties and the liking. Further, this work aims to understand the impact of the reformulated products on health relevant indicators, such as the biscuits' predicted glycemic index and the self-reported hunger level for children aged 10-13 years old. This study is the first step in thinking about the role of food oral processing parameter (time in mouth before swallowing) on perceived satiety.

As described in section 4.1 of the result, to study the recipe and composition diversity of the commercial cookies, a **comprehensive market inventory** was conducted on a total of 178 cookies. Due to the broadest market offer, the focus was then set on 62 chocolate-chip cookies. Among these, a broad composition diversity was identified and allowed to derive first possible pathways for reformulation for this product category. To conduct in depth-analyses and to obtain a better understanding of products' characteristics, the number of products must have been reduced.

To be able to make an informed subset selection and to complete the composition information, a water content analysis (link textural properties) and rapid sensory screenings were conducted on all chocolate-chip cookies. Thanks to a cluster analysis based on 11 nutrition, composition, and water content variables, a **representative subset of 18 cookies** could be derived from the obtained clusters.

On the subset of 18 chocolate-chip cookies, product properties were more thoroughly investigated via sensory and physicochemical analyses. At first, this allowed then to map all obtained composition (10), sensory (20) and physicochemical (5) variables on a multicriteria mapping. Second, with the applied "TSO" approach (trends, scatters, outliers) it was then possible **to identify potential opportunities for a sugar (-13.3%), fat (-17.9%), and chocolate-chip (-73.8%) reduction and a fiber (+53.8%) enhancement** on commercial chip cookies, **while maintaining key sensory properties**. These results were highlighted in the result part in section 4.2

According to FIGURE 49, it is important to emphasis here that indicated reductions and enhancement levels differ among different chapters, as the reformulation work was either based on commercial or reformulated cookies, with the aim to maintain or optimize sensory perception or to maintain the liking.

To investigate the range in which it will be possible to reformulate while maintaining children's liking, we conducted a hedonic study with 8 commercial chocolate-chip cookies (selected form the subset with the help of a multicriteria mapping with 10 composition, 5 physicochemical and 20 sensory variables) and 151 French children aged 7-12 years old. This study, described in the result section 4.3 of this manuscript, confirmed the **large potential to reformulate healthier commercial cookies**, while maintaining liking, as no disliking was observed on average. However, we highlighted **potential interindividual differences** for preferences. The preference mapping showed interindividual differences for the liking of children aged 7-12 years old and indicated possible strategies to follow for the next step.

Thanks to all this knowledge, we defined a base recipe for further reformulation work and selected the ingredients (factors) with their levels (%), which led us to bake a first round of 55 preliminary recipes. Based on the knowledge acquired from these trials, we created a **mixture design** with the following factors and levels: sugar (22.2-26.4%), fat (12.8-17%), chocolate-chips (13.2-16.5%), oat bran (3.3-6.5%) and a process factor "baking degree" (150-180°C). Thirty cookies were hence designed, including two repetitions. Sensory descriptive and physicochemical analyses like *in vitro* starch hydrolysis or viscosity measurements were conducted on all cookies. To identify the **role of ingredients in mixture on sensory, physicochemical, composition and health indicators** and to optimize cookies recipe, modeling with multiple regression analysis and desirability function was applied. Results showed the **possibility to optimize recipes** (sugar -14.6%, fat -28.9%, chocolate-chip -8.5%) **while improving key sensory properties and improving relevant nutrition and physicochemical aspects**, such as the total kcal (-5.1), the predicted glycemic index (-11.9%) or the Rayner score (-11.4%). These outcomes were described and discussed in the result section 5.1

As presented in the last result section 5.2, a final hedonic study with four selected reformulated cookies (selected form the subset with the help of a multicriteria mapping with 12 physicochemical, 20 sensory, 4 scores, 10 nutrition and 5 factors variables) and 80 French children aged 10-13 years was conducted in order to **study their liking and self-reported hunger level**. In addition to that, a study with the same four cookies and 10 adults was performed to study the food oral behavior (time in mouth before swallowing). Results indicated that all cookies were appreciated, and no decreased liking was observed on average. However, children do have preferences at an individual level. Therefore, this developed multi-criteria approach led to propose possible reduction of the kcal (-5.9%), sugar (-15.9%), fat (-24.7%), and chocolate-chip (-20%) per cookie and increase in oat bran (+49.3%), while maintaining the liking of children aged 10-13 years. Further, the calculated glycemic index (-8.2%) and the Rayner score (-8.7%) were improved. Among all four reformulated cookies no significant impact on the self-reported hunger levels for children nor on the measured time in mouth for adults was observed.

Thus, this PhD work provides some results which could be used to reformulate bakery products to improve their perception. In closing, the following FIGURE 49 presents a summary of the main results listed previously on knowledge developed in this multi-criteria formulation approach.

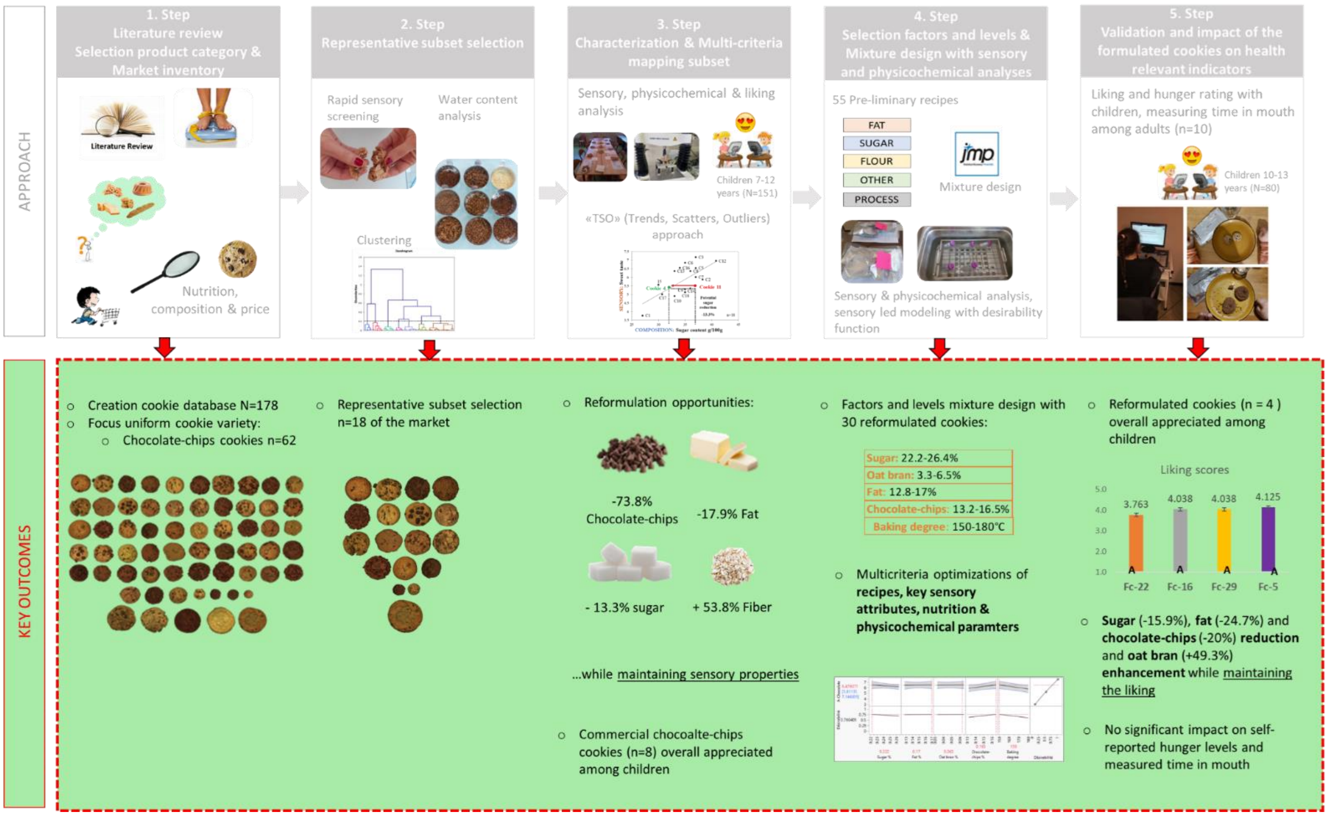

FIGURE 49 : Overview of the global approaches in grey and with the key outcomes in red, from step 1-5. As highlighted in red, per step reformulation approaches were either based on commercial or reformulated cookies with the objectives to maintain sensory perception and or liking.

To go further, all the results acquired during this thesis work lead us to different points of discussion, presented just below.

6.1.1 Is it possible to develop a sensory led-strategy including multi-criteria approach to answer to the challenge of reformulation?

a) Multicriteria approach

This multi-criteria reformulation approach demonstrated that a market inventory as a starting point contributes to the reformulation success for cookies, in order to improve products' nutritional quality, sensory properties and the liking. Furthermore this study confirmed the need to go beyond composition information, when improving the nutritional and sensory quality and the liking at once.

Inventorying the market for a single product category allows to obtain an actual view of their composition and recipe diversity from different manufacturers. Furthermore, it allows to set feasible cut offs for reformulation, as for example the nutritional values or portion sizes might differ less than when comparing different product categories with each other. Focusing then on a specific product variety (chocolate-chips cookies) - which showed the broadest market offer and diversity - was successful in our approach. Working with physical available products allows gaining further knowledge of products' characteristics such as texture and sensory perception. Nevertheless, conducting in depth sensory and physicochemical analyses implies to work on a reduced number of products. Ideally, this subset should be representative of the market. In our study, we suggested a way to make an informative and representative subset selection based on multiple criteria such as composition, sensory and water content analysis.

The market inventory for the product category commercial cookies was a solid base to orientate reformulation actions. However, the requirement is to work with physical available products in order to conduct analyses (in contrast to work with online data only) and this might not be always guaranteed for other product categories. Moreover, cookies have a low water content, and thus had good storage conditions, which made our study relatively easy from a logistical standpoint. Working with other product categories that are not shelf-stable (more vulnerable to microbiological growth for example, such as biscuits with fillings, coatings, or milk products), might be more complicated. Moreover, cookies are ready-to-eat products and thus did not require any preparation before sensory and physicochemical analysis.

Moreover, for other product categories than cookies, there is the possibility that the market offer might be either too broad or too narrow. For the first scenario, a too broad recipe diversity might imply that a direct comparison of their composition is not possible and it is therefore difficult to set a feasible cut off level for nutritional values. Therefore, the focus should be rather set on a sub category. If the market offer is too small to compare products' recipe and composition, it is more challenging to find pertinent scope of actions for reformulation due to a lack of products' diversity. It might be considered to include very similar product categories, in order to define possible scopes of actions.

Further, when working with other product categories, pertinent sensory and physicochemical analyses are to select which provide most relevant information about food properties. This is important as the selection of measurements depends on the type of food ingredient matrix. In our case, water content was found to be one of the most relevant analysis, as it can be linked to cookies texture, such as softness or hardness. This result confirmed also the main role of texture properties as a driver of preferences for food choices (Brown & Braxton, 2000; Jeltema et al., 2015).

b) Fat and sugar decrease while optimizing sensory properties

Based on the theoretical "TSO" approach, it was possible to identify reformulation opportunities among commercial cookies to reduce the sugar, the fat and the chocolate-chip content up to -13.3%, -17.9%, and -73.8%, respectively while increasing the fiber by +53%, all while maintaining sensory perception. These reformulation opportunities were confirmed by implementing a mixture design combined with multicriteria modeling of sensory responses and nutritional indicators. Among reformulated cookies, it was possible to reduce the sugar (without impacting the sweet taste), the fat and the chocolate chip (without impacting the chocolate aroma) content up to respectively -14.6%, -28.9%, and -8.5% while incorporating oat bran to the dough (6.4-6.5%) and optimizing key sensory properties. Besides that, the pGI, "biscuits bolus" viscosity, the Rayner score and the overall kcal were improved. The incorporation of oat bran was identified as a way to increase the overall desirability, to optimize sensory perception, and to reduce the overall kcal and to increase the viscosity.

Furthermore, this research showed that based on sensory preferences, specific ingredients properties might be useful to optimize sensory properties and recipes. For example, it was possible **to reduce the fat content** to a higher extent for those consumers who preferred harder textures. In our study, it was confirmed, that fat is having a softening effect. This is in line with the works of Laguna et al., (2014), who showed that biscuits with a lower fat content were perceived as harder than those with a higher fat level. In addition, the interindividual differences in sensory perception and preferences is also a chance for the industry to define different reformulation strategies.

The literature stated that it might be only possible **to reduce the sugar content** up to 10% for baked products to maintain sensory perception and textural properties (Luo et al., 2019). Our result suggests however that a sugar reduction in cookies might be even larger than assumed. This was found to be possible largely because the sugar content did not significantly influence the sweet perception at the considered levels of concentration. Furthermore, in the two conducted sensory descriptive analysis with adults, panelists showed difficulties to differentiate the sweet taste among commercial (27-40.8g sugar per 100g) and reformulated products (34-39.2 g sugar per 100g). Sugar reduction might thus impact cookies' structure and texture more than the sweet taste per se. We might also hypothesize that the sugar and the fat levels in these products are just too high to be clearly discriminated anyways.

Therefore, we suggest that a sugar reduction greater than 10% is possible for cookies, with up to 14.6% without impacting the adults' sweet taste perception. However, based on the literature, there might be **differences in sweet taste perception between adults and children** (Glanville et al., 1964; James et al., 1997; Yasaki et al., 1976). We may thus assume possible differences for the sweet taste perception between adults and children. Interestingly, for adults, the reformulated cookie with the lowest sugar content was perceived as sweeter than other cookies with an increased sugar level. However, this cookie showed the lowest liking score for children, although differences were not significant. We can therefore assume that the low sugar content had certainly an impact on children's liking.

In order to tackle childhood obesity, considering both, the total energy from fat and sugar seems to be important. But, in the case of sweet baked products, sugar reduction would thus be more difficult to achieve than a fat reduction. In our study, we demonstrated that a sugar reduction led to a lower desirability of sensory attributes, whereas a higher desirability was achieved with a fat reduction. Moreover, it was possible to reach a larger percentage of fat than of sugar reduction. According to the literature, sugar (especially sucrose) is considered as the most important ingredient for baked products (Garvey et al., 2020). Sugars' role is going beyond providing sweetness as this raw material is involved in creating and maintaining products' structure and reduce water activity what can result in an enhanced preservation. Pareyt et al., (2009) had also shown that the level of sugar influenced to a higher extent cookies measured structure such as cookies' porosity, cell size, cell wall thickness and their relative distributions than the fat level did. Similar results were found for the sensory perception. For example, (Biguzzi et al., 2014, 2015) showed that fat reduction of commercial biscuits was less noticeable by consumers than a sugar reduction. Those results were confirmed in this study, where a fat reduction was possible to a higher extent than a sugar reduction. However, caution is advised when reducing the fat content, as a fat reduction might also induce a reduction of the sweet taste (Biguzzi et al., 2014).

In our study, a simultaneous fat and sugar reduction could not be achieved. This underlines the difficulty when working without any fat and sugar replacers in bakery products, as already highlighted in literature (Cooper, 2017).

A negative effect of the use of a mixture design and the waiver of replacers or substitutes is that all recipe ratios do change when manipulating only one. This "mixture effect" was also noticed by (Cooper, 2017). It is a plausible explanation why according to a recent review only limited data were available to support sugar reduction in bakery products without any substitution and additives (Luo et al., 2019). However, this may lead to false interpretations, such as an increased sugar content can lead to a reduced kcal content, only because the fat content is decreasing. Trying to overcome this problem, it is recommended to incorporate other ingredients such as cereals with a high fiber content, to better balance possible changes in ratios. Furthermore, lowering the baking degree or even the baking time is another easy-to-implement lever- to reduce the overall kcal of a biscuits. In addition, in our study the level of the baking degree was identified an important indicator for the later aroma perception.

c) Rayner score (Nutriscore), Process score, Additives, Clean label

A supplementary challenge of the present study was to conduct a food reformulation with multiple constraints, linked to the absence of additives, to trend to clean label and a lowest process score and Nutriscore.

Most of the commercial cookies were graded with high Rayner scores (14-25, mean 20.5 ±2.9) and the highest Nutri-Score (E), which is associated with poor nutritional quality food. Nevertheless, the ranges demonstrated a certain scope of improvement for the Rayner score among commercial cookies. However, we reached only a weak improvement of the Rayner score of reformulated cookies (20-23, mean 21.5 ±1.0) compared with those of commercial cookies. Furthermore, comparing the Rayner scores for the two reformulation strategies and the commercial recipe, a sugar and a fat reduction did not affect much the Rayner score. Although the sugar and fat reduction was around 15 almost up to 30%. Further to consider is the "mixture effect" on the Rayner score, as a reduction of the fat content may lead to an increased sugar content.

This raises the question of whether the Rayner respectively the Nutri-Score is an optimal indicator to reformulate a product category, which is known to have very high sugar and fat contents, as the effect of the sugar and fat reduction on the Nutriscore itself might be low. In order to set incentives for industries to reformulate, the target goals and the measured success (like the reduction of a specific score) should be adapted on specific product categories. Furthermore, in the case of sweet bakery product reformulation, it might be clearly more realistic to lower the Rayner score by several points rather than changing the Nutriscore from one letter to another. This because the overall sugar and fat levels stay high compared to other product categories. Therefore, besides nutritional values, food reformulation should be considered in a more comprehensive way, including the level of processing, the number of additives and the type and source of ingredients.

As commercial cookies showed different levels of the process score (43-53, mean: 49.2 ±3.3), there might be as well a possibility to reduce as much as possible the overall process level of commercial cookies. Cookies with highest process scores tend to have more processed ingredients such as wheat starch, milk powder or whey powder. Additives such as emulsifiers, colorings and sweeteners also impact the process score, as well as the level of processing of each ingredient. Because in our mixture design, the type of ingredients was unchanged, the process score (47.3) was the same for all 28 reformulated cookies. Compared to the commercial cookies, a lower mean process score was achieved, mostly because in our mixture design the recipes were composed of natural, principle commercial cookie ingredients without artificial replacers or substitutes. Thereby, the type of ingredients might be therefore more impactful on the process score than different levels of the same ingredients, as shown for the reformulated cookies. Our study showed that it was as well possible to reduce the level of processing of cookies by using more natural and low processed ingredients, and trying to limit the number of ingredients. According to a recent study of reformulated baby food with yoghurt, it was shown that recipes with fewer processed and more natural ingredients were highly appreciated by parents and toddlers (Klerks et al., 2022). This highlights overall the demand and the chance to develop less processed food while maintaining the appreciation, what might be as well applicable for bakery goods.

Furthermore, the wide range of additives (between 1 and 8) among commercial cookies demonstrated the potential to produce cookies with a lower number of additives. This is of high relevancy, as it is known that additives may as well induce negative health and sensory side effects (Li et al., 2014, 2015; Suez et al., 2014). In addition, none of the currently available fat and sugar replacers can provide the full functional and sensory advantages of fat and sugar (Asioli et al., 2017). In our study, we demonstrated that it was possible to reformulate a healthier product, while improving key sensory perceptions and maintaining children's liking, with commercial ingredients and without additives (except the baking powder and the lecithin in the chocolate-chips). As consumers demand safer, healthier and more natural foods without artificial additives (Asioli et al., 2017), it is recommended to further set the focus on food reformulation with natural ingredients and avoiding as much as possible the use of additives.

In this study, the focus was set on most calorie dense macronutrients, sugar and fat. However, based on our data with large ranges for salt and saturated fat contents, there might be opportunities for a salt or saturated fat reduction as well. Palm oil or fat and butter which are high in saturated fats were identified as most common fat and oil source of commercial cookies. In bakery products saturated fat is highly important for textural and structural properties, but as well responsible for many sensory sensations (Atkinson, 2011). Due to the consumers demand for more environmental friendly, clean and healthy food, a partial or complete replacement of palm oil/fat and butter with another vegetable source (such as rapeseed oil) with lower saturated fats is highly recommended. Our study highlighted that using a mix of butter and rapeseed oil led to overall appreciated cookies. Further studies might be of interest to study other more environment-friendly oil or fat sources (for example shea butter) for bakery products, including their impact on sensory perception and physicochemical properties and liking.

6.1.2 What is the impact of the reformulated cookies on composition, oral processing (time in mouth before swallowing), children's liking and self-reported satiety?

a) Impact on predicted glycemic index and viscosity

Among the 28 formulated cookies of the mixture design, it was possible to obtain predicted glycemic indexes (pGI) between 45 and 53. Those ranges are classified as low glycemic foods (Augustin et al., 2015; Brouns et al., 2005). Furthermore, those ranges are lower than the measured pGI for the four commercial products with ranges between 52 and 57, which are classified as low and medium glycemic index foods (Augustin et al., 2015; Brouns et al., 2005). Among the four commercial products, the highest pGI was found for the cookie with the highest flour content (45%), the lowest sugar (17%) and chocolate-chips (5.5%) content. The flour content of the reformulated cookies stayed constant at 27.7% and the sugar and chocolate-chips levels were increased compared to the commercial cookie with the highest pGI. This showed clearly the high effect of the flour content on the pGI of cookies, as the flour is providing the largest carbohydrate source in the cookie dough. On the other hand, within the mixture design we showed that it is as well possible to reduce the pGI with different ratios of sugar, fat, chocolate-chips and oat bran. Therefore, further studies are needed to investigate the impact of single cookie ingredients and their interaction on the pGI, including different process parameters such as baking degree or baking time.

The relatively low pGI of the reformulated cookies might be partially explained by the constant flour level. Furthermore, the ranges of other glycemic relevant ingredients such as sugar, chocolate-chips or oat bran might have be too low to really impact the pGI. In addition, the effect of the mixture design makes it more difficult, to estimate a direct impact of a certain ingredient/level on the pGI, as all ratios do change. No direct impact of the oat bran on the glycemic index was observed, although this was reported elsewhere (Wang et al., 2020). However, it was shown that the slowly available glucose (SAG) was increased with an increased oat bran level. This result was found elsewhere, where oat bran increased the SAG in frozen dough (Onipe et al., 2020). Moreover, in our study an increased oat bran level was associated with a higher viscosity of a simulated bolus. Therefore, a positive effect of the oat bran and increased fiber was observed, although the effect was moderate. Furthermore, the starch digestion protocol was developed with the use of distilled water. As the flour content did not vary within the mixture design (same starch source for all cookies), we assume no large differences when conducting the starch hydrolysis with alpha amylase instead.

Therefore, when investigating the impact of a certain ingredient or level on the pGI, it might be recommended to manipulate only a target nutrient, in order to simplify the interpretations – although a certain mixture effect of other recipe ingredients will still exist. Moreover, to be impactful to lower the pGI, the focus should be set on the highest starch contributor in the cookie matrix, the flour. Thereby, the rapid digestible starch should be reduced or replaced as much as possible by slowly or non-digestible starch and high fiber sources. Possible alternatives with positive impact on the glycemic index of biscuits were defatted rice bran, apple pomace, pseudocereals (buckwheat or amaranth), legumes (soya and carob flour) or unripe banana flour (Agama-Acevedo et al., 2012; Alongi et al., 2019; Jia et al., 2020; Marangoni & Poli, 2008; Vujić et al., 2014). Furthermore, manipulating flour particle or using a flour with an increased particle size such as wholewheat flour is another interesting leverage to reduce the starch hydrolysis among bakery products (Lin et al., 2020).

Furthermore, the viscosity of beta glucan (in oat bran) depends on solubility, concentration and molecular weight (Anttila et al., 2004). This means, the effectiveness of the viscous fiber is dose and quality depending, including processing methods to avoid enzymatic or mechanical breakdown of the beta-glucan molecule. It might be that the beta glucan content in the oat bran was too low to cause a positive impact on the pGI. Other solutions trying to impact the pGI in a cookie matrix might be to further increase the oat bran level or adding only the concentrated beta glucan instead of the oat bran. Further studies are needed to study different levels of beta glucan solubility, concentrations and molecular weights in the cookie matrix.

Moreover, it should be stated that the developed in vitro starch hydrolysis protocol and the pGI are not specific adapted to children's physiological conditions, such as the first step of the mechanical destruction, enzymatic activity, saliva production etc. Moreover, it might be of interest to compare in vivo interindividual differences among children, especially when it comes to different BMI groups with different metabolism. Therefore, it might be of high interest to develop a starch hydrolysis protocol adapted for children and to measure the impact of reformulated biscuits with children, based on their blood glucose level and insulin response.

b) Impact on children's liking

The two hedonic studies with children performed during this study showed that commercial cookies and reformulated cookies were all well-appreciated on average. This confirms the feasibility to reformulate cookies towards a healthier cookie while maintaining the children's liking. Similarly, a recent study showed that it was possible to reduce the sugar content for baby food on a yoghurt basis, while maintaining toddlers' liking (Klerks et al., 2022). Our results suggest that further studies might even reduce the sugar and the fat content to a higher extent within the food matrix of sweet biscuits. Moreover, more research with children is needed to find thresholds of a possible sugar and fat reduction of bakery products before the liking turns into negative scores.

Children's high liking for a product category which is high in sugar and fat is not surprising. Our results underlined the findings from other authors who stated that children do have preferences for fatty and sweet food (Albataineh et al., 2019; Ambrosini et al., 2015; Marty et al., 2018; Moore & Fielding, 2016; Nguyen et al., 2015; van Buul et al., 2014). Moreover, the hedonic study with reformulated cookies demonstrated the lowest mean liking score for the cookie with the lowest sugar content (22.2%). But in opposition and surprisingly, nor in the hedonic study with commercial cookies nor in the hedonic study with reformulated cookies, cookies with the highest sugar content were not liked the most. Overall, children tend to prefer cookies that are less sweet, with a lower sugar, chocolate and kcal content. This was already observed in literature on vanilla milk dessert (Velázquez et al., 2020). Therefore, it might be assumed that children probably do not always prefer the highest sugar level among commercial products. But their liking response might become more drastic when the sugar level is too low.

It was shown in the literature that the cookies texture was key drivers of the preference and limits for children (Lukasewycz & Mennella, 2012; Rose et al., 2004a, 2004b; A. S. Szczesniak, 1972; Zeinstra et al., 2010). Furthermore, the perception of a certain texture can impact children's tactile sensation, what is known to impact neophobia (Coulthard & Blissett, 2009). Within the food matrix of cookies, the water content analysis was shown to be a pertinent measure to provide important information about cookies texture. Although cookies water content is low (2-10%), even a small change within this range had consequences on the perceived texture in hand and mouth. For commercial and formulated products, a higher water content was associated with a reduced hardness and an increased softness. The two hedonic studies with children showed that children can have both, preferences for soft- but as well harder and crisper textures. According to Laureati et al., (2019), children can be both, soft and hard texture lovers.

Based on the results from the final hedonic study, the cookie with the overall highest mean liking score had the highest oat bran content (6.5%) and the highest measured viscosity. This is interesting, as this showed that the increased viscosity of this cookie did no negatively impair the liking. Therefore, this study identified potential to further increase the level of oat bran in product. However, this conclusion is only valid for targeted children 10-13 years old. It is known that children's' preferences for textures depends on their age, which may relate to the growth of mouth muscles, jaw and teeth (Lukasewycz & Mennella, 2012; Rose et al., 2004a, 2004b; A. S. Szczesniak, 1972; Zeinstra et al., 2010). For example, based on the literature it was found that especially younger children preferred a simple and smooth texture, what might be explained by a lower chewing effort (Narain, 2005). Furthermore texture and mouthfeel were more important for younger children aged 6 - 7 years, whereas taste and smell were more relevant for older children aged 10-11 years (Rose et al., 2004a, 2004b). A similar trend could be observed in our results in section 4.3, whereas younger children (7-9 years) tend to reject a cookie with more sticky and chewy texture (higher measured water content and density) and larger particle sizes (resulted from observed grinding), what requires a longer time to masticate before swallowing.

Therefore, it is recommended to include as well younger children in the study when it comes to formulated products with different textures, as children aged below 10 years seem to be more sensitive towards texture perceptions.

Interestingly, both cookies (number 16 and 29) from the mixture design showed the same liking score, although they have very different composition (fat 12.8 vs. 17% and kcal per 100g 461 vs. 490) and texture profiles (hard and crisp vs. soft). Firstly, this showed clearly the potential for a fat reduction while maintaining the liking, although sensory perception is different. This was confirmed elsewhere, where it was possible to reduce the sugar content up to 40% of a vanilla milk dessert while maintaining the liking among school-aged children, even dough the sensory profile was slightly different (Velázquez et al., 2020). Secondly, this confirms the hypothesis that children might be both, hard- and soft-texture lovers (Laureati et al., 2019).

Besides the reduced sugar level for cookie 22 (lowest overall mean score for liking), there might also reveal a link between the baking degree, cookies texture and its impact on the food oral process behavior. In our study a lower baking degree was associated with an increased moisture content, therefore cookies' texture might be more chewy and needs more mastication efforts. It was shown that especially the texture is an important determinant for children's liking or disliking (Narain, 2005). However, results of the measured time in mouth with adults did not indicate a longer time in mouth for cookie 22. As children's' development of mouth muscles, jaw and teeth is not yet finished and differ therefore from adults', it is recommended to conduct further food oral processing measures with children.

Although all commercial and formulated cookies were in average liked, it was shown that children do have preferences and their liking scoring might differ based on their gender (boys scored higher than girls), their age (11 years old children scored lower than younger children aged 8,9 and 10 years old) and their BMI group (overweight children scored higher than thin children). Significant differences for preferences patterns were observed among children with normal and increased (overweight, obesity) BMI. Overall, it was found that the overweight/obese children rejected less cookies than children with a normal BMI, especially cookies which tend to have a higher sweet taste intensity, and a higher sugar and chocolate chip content. A recent study described a high relationships between fat hedonics and increased body weight (Cox et al., 2016), whereas another author found an increased liking for sweet and fat for obese children compared with non-obese children (Bartoshuk et al., 2006).

This underlines the importance of the liking information when it comes to food reformulation and especially to consider the interindividual differences, including sociodemographic parameters and BMI group of the specific consumers. Based on the results obtained, further research is needed to better explore possible differences between children and their appreciation with different BMI groups.

c) Impact on texture, self-reported hunger level and measured time in mouth to eat each cookies

This study demonstrated that cookies' texture is very important to consider when it comes to food reformulation, sensory perception, liking and food oral processing.

Studies have shown that texture modification can modify the food oral processing time with impact on satiety and satiation of individuals (Fogel et al., 2017). Likewise, our results with commercial products showed that textural properties may impact the food oral process, as more dense cookies with a high water content showed an increased time in mouth for adult panelists. An explanation for the longer time in mouth might be the perceived texture in mouth such as more soft, chewy and sticky including a larger particle size (grinding). This texture might extend the time in mouth compared to more hard and brittle cookies, which in our study showed smaller particle sizes and a shorter time in mouth. A recent study found that an increased chewiness lead to a decreased eating rate and energy intake (Bolhuis & Forde, 2020). Therefore, besides food reformulation strictly speaking, changing the texture is an interesting lever to make a healthier product by trying to increase the food oral process and reducing the energy intake.

However, the four cookies reformulated with different sugar, fat, chocolate-chips, oat bran and baking degree levels did not differ, neither for children's self-reported hunger levels nor on the measured time in mouth for adults. Our hypothesis could not be validated. Instead, our study showed several trends only. The quantity consumed of cookies in real snacking context (containing also apple puree) by children can maybe explain this result. Yet, in other studies, the addition of oat bran and beta glucan in biscuits increased the post prandial satiety, fullness and that an increased bolus viscosity induced by fibers led to an increased oral processing time (Pentikäinen et al., 2014; Priyanka et al., 2019; Vitaglione et al., 2010). In our results, trends are still interesting. For example, the cookie with the highest perceived hardness and the lowest measured viscosity (product) showed the longest time in mouth. This cookie had also the lowest predicted glycemic index (Fc-29) and an increased oral processing time when consuming the entire product, showed a tendency for a higher satiation effect. This results confirmed literature results, with an increasing of foods hardness which might help to reduce the energy intake, due to a longer oral processing time (Bolhuis et al., 2014). As reported from the literature, an increased oral processing time and a reduced glycemic index might impact the level of satiation (Chang et al., 2012; Fogel et al., 2017, 2018).

In our results, other interesting result was observed, showing that not only hardness could be implied in a longer time in mouth with possible consequences on satiation. Indeed, the cookie (Fc-22) presented the highest satiety effect and was characterized with the lowest baking degree and the lowest sugar content. The lower baking degree may induce a more chewy texture with an increased oral processing time (as observed among commercial cookies), what may lead to an increased satiety. However the measured time in mouth with adults did not confirm this hypothesis, what may underline cookies' lower viscosity, showing maybe too large difference in food oral processing between adults and children. It could be interesting to perform some evaluation of food oral processing with children to comfort or not the results observed with this particular cookies. As well the reduced sugar content might impact childrens' blood glucose and insulin response, with a positive impact on their satiety level. Indeed, this cookie showed a slightly reduced pGI.

In our study, one of the possible reasons for the low impact of the oat bran and the different levels of the measured viscosity on satiation, satiety and time in mouth might be again the mixture effect of other ingredients. For example, the cookie with the longest time in mouth (Fc-16) showed the lowest fat content.

This might as well impact the oral process, as a lower fat content might lead to a lower lubrication effect, therefore, more time is needed to prepare the food for swallowing. It was shown that increased lubrication increased the eating rate, induced by less chewing and faster bolus formation (Bolhuis & Forde, 2020). Further, the dosage of the oat bran in the cookie matrix was too low and the levels of oat bran (3.3-6.5%) were too close, in order to show significant impact on children's hunger rating and adults measured time in mouth. For future research, it is thus recommended to increase the level of oat bran and to test more extreme levels. Moreover, it might be interesting to use extracted beta glucan instead of the oat bran and to study the effect of different concentrations, solubilities and molecular weights. In addition, to measure biscuits' viscosity in a more close *in vivo* condition, instead distilled water it might be of interest to use alpha amylase instead, knowing that the level of starch will not change among the reformulated cookies. Therefore, it might be of further interest to test different levels of flour and flour types by using alpha amylase.

This study identified the potential to manipulate a cookies texture towards a more viscous, harder or chewier product, while maintaining the liking. This might potentially enhance children's food oral processing parameters. To manipulate cookies texture, including as well baking parameters in the reformulation process is highly important, as it contributes largely to cookies final texture (either hard and crispy or more soft and chewy). Therefore, further studies are needed to conduct oral processing studies with children on products with improved texture. Measuring the oral process behavior with children is highly important, as their growth of mouth muscles, jaw and teeth is not yet finished, therefore their oral processing behavior might be different than those from adults. Furthermore, different age classes should be considered, as there might be different oral processing behavior especially among younger (below 7 years old) and older children (older than 7 years old). Furthermore, to be able to measure the impact on a reformulated product over a period of time - such as changes in the weight status - a randomized controlled trial is recommended.

Moreover, based on significant different reported satiation and satiety levels between overweight/obese children and non overweight/obese children, further research is needed to better understand the perception and behavior of children with different BMI. This may help to improve food reformulation for a specific target group, such as obese children.

6.2 Reflexive analysis of the used approach

This study leads us to have a reflexive analysis on the potential limits related to this work.

First, working with commercial products implies that sometimes most wanted products (in terms of their composition, texture etc.) are not available in the desired quantity, or the products are only on the market during a limited time. But, working with physical available products is a requirement to conduct some sensory and physicochemical analysis.

Considering reformulation work, and due to the mixture effect of multiple ingredients, it might be more difficult to make conclusion about a single ingredient. Indeed, our work permits to better understand the interactions of ingredients within the cookie matrix with the most realistic approach as possible, but not to study the role of each ingredient. In addition, it could be interesting to continue the research work on the role of fibers on formulation. In this work, only a weak effect of the oat bran on the final fiber content was observed among the reformulated cookies. For further study, it could be interesting to add other types of cereals and fibers and to increase their level.

Considering sensory and liking study, the final liking validation included only children 10-13 years old. As the liking study was at children's home, older children are able to conduct tests alone without any additional help and supervision with external people. In addition, it might be difficult to measure and standardize the total daily kcal consumed, this influence not only the liking but as well the self-reported hunger level. However, conducting tests at children's home is most close to a normal snacking situation.

In addition, considering intra-individual variability, children's BMI was not included in the sampling and could be proposed for further studies.

6.3 Overall Conclusions

This multi-criteria reformulation approach demonstrated that a market inventory as a starting point contributes to the reformulation success for cookies, in order to improve products' nutritional quality, sensory properties and liking. Furthermore this study confirmed the need to go beyond composition information, when improving the nutritional and sensory quality and the liking at once. Further, the approaches such as to select a representative subset, the multi-criteria mapping, the theoretical "TSO" method and the creation of preliminary recipes based on the subset were useful tools to derive pertinent reformulation leverages while optimizing recipes sensory perception and liking among children.

This multi-criteria reformulation approach considering nutrition, composition, sensory and physicochemical variables demonstrated that it is possible to reduce the sugar, the fat and the chocolate-chips content and to increase the oat bran level while optimizing key sensory properties. Further, it was possible to improve the kcal content, the predicted glycemic index, the Rayner score and biscuits' viscosity. All while maintaining the liking. But our research showed as well the possibility to reduce the fat and the sugar content while maintaining the liking, even when sensory and physicochemical properties were different.

Beyond that, this multicriteria reformulation approach was as well a tool to identify possible pathways to decrease the process level, to decrease the number of additives and to use natural, environmental friendly ingredients which are moderate or low processed. Further, cookies texture was identified as interesting leverage to enhance children's oral processing behavior, as different textures of cookies such as hard, crisp, chewy or more viscous were all appreciated. This is promising for future research to improve food oral processing parameters among children, in order to positively impact their satiety and weight management.

This study showed that physicochemical and sensory information are highly important to better understand and anticipate children's drivers of preferences. Targeting the reformulation strategy on a specific consumer group is highly important, as consumers do have interindividual differences in their liking patterns, such as for example children with different ages or BMI groups. Also our study demonstrated that the interindividual differences in sensory perception and preferences can be as well a chance for the industry, in order to define different successful reformulation strategies targeting at specific consumers.

Our study further encouraged to overthink the confirmed but also "assumed" preference for high sweet taste among children. We suggest that among sweet bakery products with high fat and sugar, it is more difficult to differentiate key sensory perceptions such as sweet taste for example. Therefore, a reduction of the sugar content might be higher than assumed without impacting the sweet taste.

The findings of these multicriteria reformulation approach are important for the bakery industry, as our results suggest that industries might not lose market shares while reformulating sweet bakery products. Moreover, this approach might reinforce voluntary food reformulation among different product categories.

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H. List of Supplementary Tables

I. List of Supplementary Figures

J. Supplementary Tables

SUPPLEMENTARY TABLE 1 : Coding of the commercial chocolate-chips cookies in three different studies within this PhD.

COMMERCIAL COOKIES		
"How to Select a Representative Product Set From Market Inventory?" A Multicriteria Approach as a Base for Future Reformulation of Cookies	*"Multicriteria analysis of a product category to identify reformulation possibilities: a case study using commercial chocolate chip cookies."*	*"Children aged 7-12 years old do have different preference patterns for commercial chocolate-chip cookies."*
Chocolate-chips cookies coding: 1 - 62	**Subset coding: C1-C18**	**Eight commercial cookies coding: P-a - P-h**
1	C-1	P-a
2		
3	C-2	
4		
5	C-3	P-b
6		
7		
8	C-4	
9		
10		
11		
12		
13		
14		
15		
16		
17		
18		
19	C-5	
20		
21		
22	C-6	P-c
23		
24	C-7	
25		
26		
27		
28	C-8	P-d
29		
30		
31		
32		
33		
34		
35	C-9	
36	C-10	P-e
37		
38		
39		
40	C-11	P-f
41		
42	C-12	
43		
44		
45		
46		
47		
48	C-13	
49		
50		
51		
52		
53	C-14	
54	C-15	P-g
55		
56	C-16	P-h
57		
58		
59	C-17	
60		
61	C-18	
62		

SUPPLEMENTARY TABLE 2 : Coding of the reformulated chocolate-chips cookies in two different studies within this PhD.

REFORMULATED COOKIES	
"Sensory-led reformulation of chocolate chip cookies using multifactor optimization."	*"Measuring the impact of the reformulated cookies on children (liking, hunger level) and adults (time in mouth)."*
Reformulated cookies mixture desing coding: Fc-1 - Fc-30	**Four selected reformulated cookies coding: Fc-1 - Fc-30**
Fc-1	
Fc-2	
Fc-3	
Fc-4	
Fc-5	Fc-5
Fc-6	
Fc-7	
Fc-8	
Fc-9	
Fc-10	
Fc-11	
Fc-12	
Fc-13	
Fc-14	
Fc-15	
Fc-16	Fc-16
Fc-17	
Fc-18	
Fc-19	
Fc-20	
Fc-21	
Fc-22	Fc-22
Fc-23	
Fc-24	
Fc-25	
Fc-26	
Fc-27	
Fc-28	
Fc-29	Fc-29
Fc-30	

*SUPPLEMENTARY TABLE 3 : Nutrition (per 100g), composition and water content information among the chocolate chip cookie database. Eleven quantitative variables (fat, sfa, carbohydrates, sugar, protein, fiber, salt, ingredients, technological additives, sensory additives, water content) were included for the clustering, while 13 quantitative variables (kcal, fat, sfa, carbohydrates, sugar, protein, fiber, salt, Rayner score, ingredients, additives, water content) were included for the representativity check. With * for the selected cookie subset and with ** for the saturated fat content per 100g.*

Cookie N°	Kcal	Fat g	Sfa** g	Carbohydrates g	Sugar g	Protein g	Fiber g	Salt g	Rayner score	Ingredients	Technological additives	Sensory additives	Additives total	Water content %
1*	503	25	12	62	27	6.5	-	1.55	27	11	3	0	3	3.63
2	495	23	11.5	65.6	31.1	6.5	2.6	1.5	26	12	4	0	4	3.33
3*	509	24.9	13.3	64.3	38.3	5.2	3.6	1.5	25	12	5	1	6	3.87
4	508	26	11	61	34	6.4	4.6	1.4	24	12	3	0	3	3.04
5*	504	23	6.6	66	37	6.1	4.4	1.3	20	9	5	0	5	2.18
6	504	23	6.6	66	37	6.1	4.4	1.3	20	11	5	0	5	3.1
7	497	24.4	13.2	61	32.7	6.5	3.6	1.24	23	13	3	0	3	2.94
8*	495	26	13	58	32	5.5	3.5	1.2	24	10	5	0	5	2.65
9	504	26	15	59	34	6.5	-	1.18	24	6	4	0	4	3.29
10	498	26	13	58	32	6	4	1.17	23	11	4	0	4	3.08
11	499	23.9	12.2	64.9	28.3	5.3	-	1.15	27	12	4	0	4	3.53
12	490	24.6	11.6	61.8	37.2	5.4	-	1.1	28	13	5	1	6	2.81
13	499	24.6	11.6	61.8	37.2	5.4	4.5	1.1	23	11	5	1	6	2.69
14	494	24	8.9	62	37	5.2	3.2	1.1	22	13	4	1	5	3.54
15	484	24	15	62	34	4.8	2.7	1.1	24	12	6	0	6	7.38
16	504	26	14	61	36	4.5	2.9	1.05	23	10	5	0	5	3.68
17	504	24	13	64	31	5.8	3.5	1.04	22	11	4	0	4	2.56
18	498	23.2	14.7	62.2	33.3	7.6	-	1.03	27	10	1	0	1	3.68
19*	497	24	9.6	63	37	5.3	3.9	1	22	8	5	1	6	3.17
20	500	25	13	62	36	5.3	3.1	1	23	12	5	1	6	3
21	501	25	13	62	35	5.3	3.2	1	23	12	5	1	6	3.25
22*	479	23	14	61	35	5.6	3.7	0.18	17	11	3	1	4	7.88
23	498	24.2	10.1	63.4	36.6	5.3	3.3	0.92	23	13	4	1	5	3.09
24*	478	22	7.4	63	37	5.8	-	0.9	22	16	6	0	6	7.85
25	501	25	12	59	35	7.3	5.5	0.88	21	12	4	0	4	2.41
26	501	25	12	62	37	5.4	3.3	0.87	23	13	5	1	6	3.53
27	503	26	15	60	34	5.4	-	0.84	26	19	4	0	4	3.73

28*	485	24	12	61	36	5.2	1.8	0.83	24	13	4	0	4	4.56
29	516	24.4	13.6	62.7	31.8	7.4	3.6	0.82	21	12	4	0	4	3.15
30	511	25	15.9	63	38.7	6.9	-	0.8	27	13	2	0	2	2.55
31	452	21	12	60	36	5.1	3.3	0.71	21	16	6	0	6	9.36
32	492	23	8.7	61.2	27.2	7.2	5.2	0.7	18	12	3	0	3	3.46
33	494	24.1	16.6	61.4	32.6	6.7	-	0.7	26	11	5	0	5	3.46
34	511	26.9	13.7	61.1	34.1	4.5	-	0.7	26	10	3	0	3	3.3
35*	500	26	14	59	35	5.6	4	0.66	20	18	3	1	4	3.53
36*	485	25	14	60	33	4.7	2.4	0.75	23	17	6	1	7	6.83
37	506	26.3	17.4	62.5	31.5	6.8	-	0.65	25	13	3	0	3	3.47
38	493	23	6.6	63	37	6.5	3.8	0.65	17	11	5	0	5	2.88
39	488	23.1	14.8	61.9	32.4	6.4	-	0.65	25	11	4	0	4	3.54
40*	511	25.1	16.1	62.2	36.9	7	-	0.64	26	9	1	0	1	2.74
41	496	26	15	58	37	5.2	-	0.64	26	13	4	0	4	4.22
42*	458	17.1	9.5	70.8	40.8	4.8	2.2	0.6	22	23	5	0	5	7.93
43	465	19.2	10.6	67.3	41.8	5.3	5.7	0.5	21	15	5	0	5	7.56
44	498	26	14	59	38	6.2	3.4	0.59	22	20	3	1	4	4.29
45	493	25	16	61	37	6.1	-	0.56	26	10	3	0	3	5.79
46	486	23	14	61	31	6.6	-	0.55	24	12	1	0	1	3.6
47	486	23	14	61	31	6.6	-	0.53	24	12	1	0	1	3.36
48*	518	26	14	63	33	6.9	4.1	0.52	20	11	4	0	4	3.26
49	481	23	15	61	37	6.1	-	0.48	26	9	3	0	3	6.34
50	518	25.7	13.4	62.1	33.9	7.2	4.6	0.46	20	11	4	0	4	3.08
51	509	26.2	14.2	61.3	37.7	5.9	2.6	0.46	23	16	4	1	5	3.57
52	485	23	12	60	34	7	5	0.44	19	10	1	0	1	3.18
53*	488	22	9	64	36	6.7	3.4	0.44	18	13	2	0	2	3.32
54*	489	24	5.9	59	30	7.6	3.5	0.43	14	14	2	0	2	3.65
55	511	26.2	14.6	61.6	32.8	6	2.4	0.43	21	16	3	1	4	3.25
56*	514	28	13	57	34	7	-	0.42	24	15	3	0	3	2.47
57	493	24	13	60	33	6.9	4.6	0.41	19	11	1	0	1	3.65
58	433	18	10.3	59.9	37.4	6	3.1	0.4	19	13	3	0	3	8.33
59*	501	25.2	14.1	59.3	30.7	7	4.7	0.39	18	12	1	0	1	3.67
60	496	25	13	59	31	6.6	4.5	0.3	18	9	1	0	1	3.78

61*	511	28	18	57	35	5.8	-	0.3	24	7	2	0	2	3.49
62	496.8	26.2	14.6	59.6	35.9	5.7	2.6	0.89	23	15	3	0	3	3.68

SUPPLEMENTARY TABLE 4 : Eleven ranked criteria (1-11) with the 42 subgroups and the constraint "availability" among the 62 chocolate chip cookies.

		11 Criteria with subgroups**										
Cookie	**Con-staint**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
1*	ok	wheat	crystal	veg.	-	very l.	dark	soft	chips	cracks	low	low
2	ok	wheat	crystal	veg.	-	very l.	dark	hard	chips	cracks	low	very l.
3*	ok	wheat	crystal	veg.	-	very h.	dark	intermed.	chunks	cracks	mid.	low
4	not ok	wheat	crystal	mix.	-	very h.	dark	hard	chips & chunks	cracks	mid.	high
5*	ok	wheat	crystal	veg.	very h.	mid.	dark	hard	chips	cracks	low	very l.
6	ok	wheat	crystal	veg.	very h.	mid.	dark	hard	chips	cracks	mid.	very l.
7	ok	wheat	crystal	veg.	low	mid.	dark	intermed.	chips	cracks	low	very l.
8*	ok	wheat	crystal	veg.	high	Low	dark	soft	chips	cracks	low	very l.
9	ok	wheat	crystal	veg.	-	Low	dark	intermed.	chips	cracks	low	very l.
10	ok	wheat	crystal	veg.	high	Low	dark	intermed.	chips	cracks	low	low
11	not ok	wheat	crystal	veg.	-	very l.	dark	soft	chips	cracks	low	very l.
12	not ok	wheat	crystal	mix.	-	very h.	dark	intermed.	chunks	cracks	mid.	low
13	not ok	wheat	crystal	mix.	-	Low	dark	intermed.	chips & chunks	cracks	mid.	mid.
14	ok	wheat	crystal	mix.	-	very h.	dark	hard	chips & chunks	cracks	mid.	low
15	ok	wheat	mixed	ani.	-	very l.	dark	soft	chunks	cracks	very h.	high
16	ok	wheat	crystal	veg.	-	High	dark	intermed.	chunks	cracks	low	mid.
17	not ok	wheat	mixed	veg.	-	-	dark	hard	chips	cracks	very l.	high
18	not ok	mixed	crystal	ani.	-	Low	dark	intermed.	chips	no cracks	very l.	very h.
19*	ok	wheat	crystal	mix.	-	very h.	dark	soft	chips & chunks	cracks	mid.	very l.
20	ok	wheat	crystal	veg.	-	very h.	dark	intermed.	chips & chunks	cracks	mid.	low
21	ok	wheat	crystal	veg.	-	High	dark	intermed.	chips & chunks	cracks	mid.	low

22*	ok	wheat	mixed	ani.	low	very l.	dark	soft	chunks	other	very h.	high
23	ok	wheat	crystal	mix.	-	very h.	dark	hard	chips & chunks	cracks	mid.	low
24*	ok	wheat	crystal	veg.	-	very l.	dark	soft	chunks	cracks	very h.	very h.
25	not ok	wheat	crystal	veg.	low	mid.	dark	intermed.	chips	cracks	very l.	very l.
26	ok	wheat	crystal	mix.	-	High	dark	soft	chips & chunks	cracks	mid.	mid.
27	not ok	wheat	crystal	mix.	-	Low	dark	hard	chunks	cracks	very h.	high
28*	ok	wheat	mixed	veg.	-	High	milk	soft	chips	cracks	very l.	mid.
29	ok	wheat	crystal	veg.	low	Low	dark	intermed.	chips	cracks	low	very l.
30	not ok	wheat	crystal	ani.	-	Low	mix.	intermed.	chips	no cracks	very l.	very h.
31	not ok	wheat	mixed	mix.	very h.	-	dark	soft	chunks	cracks	very h.	high
32	not ok	wheat	mixed	veg.	mid.	Low	dark	hard	chips	cracks	mid.	very h.
33	ok	wheat	crystal	ani.	-	mid.	dark	intermed.	chips	cracks	mid.	very h.
34	not ok	wheat	syrop	veg.	-	-	dark	hard	chips	cracks	mid.	very l.
35*	ok	wheat	mixed	mix.	-	very h.	mix.	soft	chips & chunks	cracks	mid.	low
36*	ok	wheat	mixed	mix.	-	very l.	dark	soft	chunks	cracks	very h.	high
37	not ok	wheat	crystal	ani.	-	Low	mix.	soft	chips	cracks	very l.	very h.
38	not ok	wheat	crystal	veg.	-	High	dark	hard	chips	cracks	very l.	very l.
39	ok	wheat	crystal	ani.	very l.	Low	dark	intermed.	chips	cracks	mid.	very h.
40*	ok	wheat	crystal	ani.	-	Low	dark	intermed.	chips	no cracks	very l.	very h.
41	ok	wheat	crystal	mix.	-	very h.	dark	soft	chips	cracks	very h.	high
42*	ok	wheat	mixed	mix.	-	very l.	milk	soft	chunks	cracks	very h.	high
43	not ok	wheat	crystal	mix.	-	very l.	dark	soft	chunks	cracks	very h.	high
44	not ok	mixed	mixed	mix.	-	very h.	dark	hard	chips	cracks	high	low
45	ok	wheat	crystal	ani.	-	Low	dark	soft	chunks	cracks	very h.	very h.
46	ok	wheat	crystal	ani.	very l.	mid.	dark	hard	chips	cracks	very l.	mid.
47	ok	wheat	crystal	ani.	very l.	mid.	dark	hard	chips	cracks	low	mid.
48*	not ok	wheat	crystal	veg.	high	High	dark	hard	chips	cracks	very l.	mid.
49	ok	wheat	crystal	ani.	-	Low	dark	soft	chunks	cracks	very h.	very h.
50	ok	wheat	crystal	veg.	very h.	mid.	dark	hard	chips	cracks	very l.	mid.
51	ok	wheat	crystal	mix.	-	High	mix.	intermed.	chunks	cracks	high	mid.
52	ok	wheat	crystal	mix.	very l.	High	dark	hard	chips	cracks	mid.	mid.
53*	ok	wheat	crystal	veg.	-	High	dark	hard	chips	cracks	very l.	high
54*	ok	mixed	crystal	veg.	-	very l.	dark	intermed.	chips	cracks	very l.	high
55	ok	wheat	crystal	mix.	-	High	mix.	intermed.	chunks	cracks	high	mid.
56*	ok	mixed	crystal	ani.	-	High	milk	hard	chips	cracks	very l.	mid.
57	ok	wheat	crystal	veg.	very l.	mid.	dark	hard	chips	cracks	very l.	low
58	not ok	wheat	crystal	mix.	-	very l.	dark	soft	chips & chunks	cracks	very h.	very h.
59*	not ok	wheat	crystal	veg.	very l.	mid.	dark	intermed.	chips	cracks	high	low
60	ok	wheat	crystal	veg.	-	very l.	dark	soft	chips	cracks	low	very l.

61*	ok	wheat	crystal	ani.	-	High	dark	soft	chunks	cracks	mid.	very h.
62	ok	wheat	mixed	mix.	-	very h.	mix.	hard	chips	cracks	high	very h.

veg = vegetale, ani = animal, mix. = mixed, very l. = very low, very h. = very high, mid. = middle, intermed. = intermediate

* 18 selected cookies for the subset

**Criteria 1-11: 1 Type of flour, 2 Type of sugar, 3 Type of fat, 4 Cacao & chocolate powder %, 5 Chocolate inclusion %, 6 Type chocolate inclusion, 7 Texture in hand, 8 Shape chocolate inclusion, 9 Surface, 10 Weight cookie g/unit, 11 Price per kg

SUPPLEMENTARY TABLE 5 : All cookies which were not available in short time were excluded from the selection. The first criteria was then the type of flour. As it is visible in this SUPPLENETARY TABLE 5, the subgroup "mixed" was the only and unique subgroup within this criteria and cluster 1. Therefore, this cookie 56 was selected. Trying to maintain the cookie diversity, all cookies with the same type of sugar as the previous selected were then excluded (crystal sugar), until a subgroups was unique within a criteria (1-11) and until all number of cookies per cluster (1-7) were selected.

Cluster 1	**11 ranked criteria**											
	avai-la-bility	**1. type of flour**	**2. type of sugar**	**3. type of fat**	**4. % pow-der**	**5. % cho-co-late**	**6. type of cho-colate**	**7. sen-sory**	**8. shape chocolate chips**	**9. sur-face**	**10. g/unit**	**11. price**
~~27~~	~~not avai-lable~~	~~wheat~~	~~crystal sugar~~	~~mixed~~	-	~~low~~	~~dark~~	~~hard~~	~~chunks~~	~~cracks~~	~~very high~~	~~high~~
35	ok	wheat	mixed with sy-rop	mixed	-	very high	mixed	soft	chips and chunks	cracks	middle	low
36	ok	wheat	mixed with sy-rop	mixed	-	very low	dark	soft	chunks	cracks	very high	high
41	ok	wheat	crystal sugar	mixed	-	very high	dark	soft	chips	cracks	very high	high
~~44~~	~~not avai-lable~~	~~mixed~~	~~mixed with sy-rop~~	~~mixed~~	-	~~very high~~	~~dark~~	~~hard~~	~~chips~~	~~cracks~~	~~high~~	~~low~~
51	ok	wheat	crystal sugar	mixed	-	high	mixed	Inter-mediate	chunks	cracks	high	middle
55	ok	wheat	crystal sugar	mixed	-	high	mixed	Inter-mediate	chunks	cracks	high	middle
56	ok	**mixed**	crystal sugar	animal	-	high	milk	hard	chips	cracks	very low	middle

62	ok	wheat	mixed with syrop	mixed	-	very high	mixed	hard	chips	cracks	high	very high

SUPPLEMENTARY TABLE 6 : k-Means clustering with seven clusters among 62 cookies. Clusters with highest variances included the lowest cookie numbers and those cookies which were hardly available.

Results by k-Means clusters 1-7:	**1**	**2**	**3**	**4**	**5**	**6**	**7**
	44	22*		17	48*	19*	58
	55	40*	12	54*	50	38	43
	51	30	26	1*	18	6	31
	35*	9	23	2	57	5*	42*
	36*	45	14	11	52		24*
	56*	49	53*	32	29		
	62	34	28*		59*		
	27	61*	25		37		
	41	15	4		33		
		16	20		60		
			21		46		
			3*		47		
					7		
					39		
					10		
					8*		
Total cookies per cluster	9	10	12	6	16	4	5
Within cluster variance	15.428	21.577	9.925	21.260	11.698	17.406	54.409
Total selected cookies per cluster	3	3	3	2	3	2	2

* 18 selected cookies for the subset. Therefore, we selected three cookies per clusters containing higher cookie numbers and two cookies per clusters containing lower cookie numbers

SUPPLEMENTARY TABLE 7 : Representativeness of the selected subset based on 11 ranked criteria with subgroups.

Criterion/constraint	Total cookie numbers	Subgroups	Cookie numbers in subgroups and % from total cookie numbers	Selected cookies in numbers and % from cookie numbers in subgroups	Selected cookies per criterion
Constraint: availability	62	available	43 (69.4%)	18 (41.9%)	18

		not available	19 (30.6%)	-	
Type flour	62	wheat	58 (93.5%)	16 (27.6%)	2
		mixed	4 (6.5%)	2 (50%)	
Type sugar	62	crystal sugar	50 (80.6%)	13 (26%)	1
		mixed	11 (17.7%)	5 (45.5%)	
		syrup	1 (1.6%)	-	
Type fat	62	vegetale	28 (45.2%)	9 (32.1%)	2
		mixed	20 (32.3%)	4 (20%)	
		animal	14 (22.6%)	5 (35.7%)	
Amount chocolate & cacao powder	18	very low	6 (33.3%)	1 (16.6%)	1
		low	4 (22.2%)	1 (25%)	
		middle	1 (5.6%)	-	
		high	3 (16.7%)	2 (66.6%)	
		very high	4 (22.2%)	1 (25%)	
Amount chocolate inclusion	59	very low	12 (20.3%)	6 (50%)	2
		low	14 (23.7%)	2 (14.3%)	
		middle	10 (16.9%)	2 (20%)	
		high	12 (20.3%)	5 (41.6)	
		very high	11 (18.6%)	3 (27.3%)	
Type chocolate	62	dark	53 (85.5%)	14 (26.4%)	1
		mixed	6 (9.7%)	1 (16.6%)	
		milk	3 (4.8%)	3 (100%)	
Texture cookie	62	hard	21 (33.9%)	4 (19.1%)	1
		intermediate	20 (32.3%)	4 (20%)	
		soft	21 (33.9%)	10 (47.6%)	
Shape chocolate inclusion	62	chips	36 (58.1%)	10 (27.7%)	2
		chips & chunks	10 (16.1%)	2 (20%)	
		chunks	16 (25.8%)	6 (37.5%)	
Surface cookie	62	cracks	58 (93.5%)	16 (27.6%)	1
		no cracks	3 (4.8%)	1 (33.3%)	
		other	1 (1.7%)	1 (100%)	
Weight cookie	62	very low	15 (24.2%)	6 (40%)	3
		low	12 (19.4%)	4 (33.3%)	
		middle	18 (29%)	4 (22.2%)	
		high	5 (8.1%)	-	
		very high	12 (19.4%)	4 (33.3%)	
Price cookie	62	very low	13 (21%)	3 (23.1%)	2
		low	12 (19.4%)	3 (25%)	
		middle	12 (19.4%)	3 (25%)	
		high	12 (19.4%)	6 (50%)	
		very high	13 (21%)	3 (23.1%)	

*SUPPLEMENTARY TABLE 8 : : Nutritional values per 100 g and compositional information for the 18 study cookies. *cookies used in preference study*

Cookie	Kcal	Fat	Saturated fat	Carbo-hy-drates	Sugar	Protein	Fibre	Salt	% Choco-late chips	% Choco-late & ca-cao pow-der	Additive number	Rayner score	Processing score
C1*	503	25	12	62	27	6.5	2.4	1.55	5.5	-	3	27	48.4
C2	509	24.9	13.3	64.3	38.3	5.2	3.6	1.5	38	-	6	25	52.9
C3*	504	23	6.6	66	37	6.1	4.4	1.3	30	6.6	5	20	52.1
C4	495	26	13	58	32	5.5	3.5	1.2	26	4.8	5	24	53.3
C5	497	24	9.6	63	37	5.3	3.9	1	37.9	-	6	22	50.4
C6*	479	23	14	61	35	5.6	3.7	0.18	21	2.6	4	17	44.5
C7	478	22	7.4	63	37	5.8	2.8	0.9	16.5	-	6	22	49.9
C8*	485	24	12	61	36	5.2	1.8	0.83	31	-	4	24	
C9	500	26	14	59	35	5.6	4	0.66	39.6	-	4	20	51.9
C10*	485	25	14	60	33	4.7	2.4	0.75	18.7	-	8	23	
C11*	511	25.1	16.1	62.2	36.9	7	3.9	0.64	28	-	1	26	45.5
C12	458	17.1	9.5	70.8	40.8	4.8	2.2	0.6	22	-	5	22	46.2
C13	518	26	14	63	33	6.9	4.1	0.52	32.4	3.9	4	20	52.5
C14	488	22	9	64	36	6.7	3.4	0.44	31	-	2	18	52.1
C15*	489	24	5.9	59	30	7.6	3.5	0.43	21	-	2	14	47.3
C16*	514	28	13	57	34	7	3.6	0.42	33	-	3	24	43.5
C17	501	25.2	14.1	59.3	30.7	7	4.7	0.39	30	2.3	1	18	50.2
C18	511	28	18	57	35	5.8	2	0.3	35	-	2	24	46.2

SUPPLEMENTARY TABLE 9 : Type and source of the ingredients used in the 18 study cookies.

Cookie	Flour	Sugar	Fat	Chocolate	Cookie dough
C1	Wheat	White sugar	Palm oil	Dark	Plain
C2	Wheat	White sugar	Palm oil	Dark	Plain
C3	Wheat	White sugar	Sunflower oil	Dark	Chocolate
C4	Wheat	White sugar	Palm oil	Dark	Chocolate
C5	Wheat	White sugar	Rapeseed oil, butter	Dark	Plain
C6	Wheat	White sugar, brown cane sugar, crystallised invert sugar syrup	Butter	Dark	Chocolate
C7*	Wheat	White sugar, *vergeoise* sugar	Rapeseed oil, margarine	Dark	Plain
C8	Wheat	White sugar, glucose syrup	Palm oil	Milk	Plain
C9	Wheat	White sugar, glucose syrup, glucose-fructose syrup	Palm & sunflower oil, butter	Mixed	Plain
C10	Wheat	White sugar, glucose syrup, dextrose	Butter, palm oil, palm & shea butter	Dark	Plain
C11	Wheat	Brown cane sugar, white sugar	Butter	Dark	Plain
C12	Wheat	fructose, brown cane sugar, glucose syrup	Butter, palm oil	Milk	Plain
C13	Wheat	White sugar	Palm oil	Dark	Chocolate
C14	Wheat	Brown cane sugar	Margarine	Dark	Chocolate
C15	Wheat & quinoa	Brown cane sugar	Rapeseed oil	Dark	Plain
C16	Wheat & oat	White sugar	Butter	Milk	Plain
C17	Wheat	White sugar	Palm oil	Dark	Chocolate
C18	Wheat	White sugar	Butter	Dark	Plain

SUPPLEMENTARY TABLE 10 : Nutritional values (mean ± SD) of the hard cookies (n = 14) versus the soft cookies (n = 4).

	Kcal	Fat	Sugar	Protein	Fibre	Salt	% Chocolate chips	Additive number
Hard cookies	501.8 (±10.2)	25.1 (±1.7)	34.2 (±3.2)	6.2 (±0.8)	3.5 (±0.9)	0.8 (±0.4)	29.8 (±8.6)	3.4 (±1.7)
Soft cookies	475.0 (±11.8)	21.8 (±3.4)	36.5 (±3.3)	5.2 (±0.5)	2.7 (±0.7)	0.6 (±0.3)	19.5 (±2.5)	5.8 (±1.7)

SUPPLEMETNARY TABLE 11 : Rapid sensory screening results for the 18 study cookies—texture-in-hand scores (range: 0–10, where 0 = completely soft and 10 = completely hard) and water content. The values in bold and italics are the minima and maxima.

Cookie	Mean texture-in-hand score	Mean water content (%)
C1	4.9	3.6
C2	5.6	3.8
C3	8	***2.2***
C4	4.8	2.6
C5	4.1	3.2
C6	0.5	7.8
C7	0.2	7.8
C8	3.9	4.5
C9	4.9	3.5
C10	1.1	6.8
C11	6.8	2.7
C12	***0.1***	***7.9***
C13	8	3.3
C14	***9.4***	3.3
C15	5.1	3.7
C16	7.4	2.5
C17	5.6	3.7
C18	4.4	3.5
Overall mean	4.6	4.3
Overall SD	3.1	1.9

SUPPLEMENARY TABLE 12 : List of the 20 sensory attributes associated with the 18 study cookies defined by the 12 panellists using QDA. The definitions and scale anchors are also indicated.

Attribute family	Descriptor	Definition	Scale anchor	
			Min (0)	Max (10)
Visual appearance	◆ Dough colour	Dough colour at cookie surface	Light	Dark
	◆ Chocolate chip visibility	Visibility of chocolate chips on cookie surface	Hidden in dough	Apparent on dough
	◆ Chocolate chip quantity	Quantity of chocolate chips on cookie surface	Sparse	Abundant
	◆ Chocolate chip size	Size of chocolate chips on cookie surface	Small	Large
	◆ Contour regularity	Regularity of cookie surface	Irregular shape/ unmoulded	Regular shape/ Moulded
	◆ Cookie size	Diameter of cookie surface	Small	Large
	◆ Cookie height	Height at cookie centre	Short	Tall
	◆ Crackliness	Presence of cracks on cookie surface	Few cracks	Many cracks
Texture in hand	◆ Hardness	Hardness of cookie centre	Soft	Hard
	◆ Brittleness	Resistance when breaking cookie in half	Easy to break	Hard to break
Texture in mouth	◆ Crispness	Noise after first bite	Little noise	Lots of noise
	◆ Sandiness	Production of "sand" during mastication	Little "sand"	Lots of "sand"
	◆ Hardness	Resistance during initial mastication	Soft	Hard
	◆ Time in mouth	Time in mouth before swallowing	Short	Long
Odour	◆ Chocolate	Smell of cookie surface upon breathing in	Cookie odour	Chocolate odour
Taste	◆ Sweetness	Perceived sweetness during/after mastication	Low	High
Aftertaste	◆ Salty	Salty aftertaste in mouth after swallowing	Low intensity	High intensity
	◆ Chocolate	Chocolate aftertaste in the mouth after swallowing	Low intensity	High intensity
Aroma	◆ Chocolate	Perceived chocolate aroma during/after mastication	Cakelike	Chocolaty

◆ Butter	Perceived butter aroma during/after mastication	No butter	Butter

SUPPLEMENTARY TABLE 13 : Mean strain at rupture, stress at rupture, density, and spread ratio for the 18 study cookies. In bold and italics are the minima and maxima.

Cookie	**Strain at rupture (εr) (%)**	**Stress at rupture (σr) (kN/m²)**	**Density (ρ)**	**Spread ratio (mm)**
C1	0.011	0.089	0.640	7.238
C2	0.047	0.126	0.735	5.410
C3	0.018	0.169	0.673	6.745
C4	***0.010***	0.111	0.670	7.251
C5	0.034	0.130	0.749	5.064
C6	0.128	***0.022***	***0.975***	3.455
C7	0.029	0.062	0.853	9.137
C8	0.749	0.157	0.665	4.419
C9	0.038	0.204	0.716	4.453
C10	0.014	0.087	0.761	7.620
C11	0.512	0.036	0.781	***10.039***
C12	***1.983***	0.045	0.726	6.028
C13	0.280	0.272	0.789	***3.088***
C14	0.016	***0.316***	0.671	6.691
C15	0.554	0.138	***0.627***	5.900
C16	0.709	0.204	0.737	3.288
C17	0.027	0.294	0.678	7.284
C18	0.027	0.173	0.801	6.552
Overall mean	0.288	0.145	0.736	5.774
Overall SD	±0.515	±0.092	±0.090	±1.718

SUPPLEMENTARY TABLE 14 : Mean values of the 20 sensory attributes for the 18 study cookies. In bold and italics are the minima and maxima. Abbreviations for attribute family: O = odour, H = in hand, T = taste, A = aroma, At = aftertaste, M = in mouth, and V = visual appearance.

Cookie	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	Mean	SD
Chocolate (O)	***1.3***	5.3	***7.8***	6.8	6.0	8.6	2.2	2.1	5.9	2.9	3.7	2.9	7.7	7.5	4.2	2.9	7.7	5.9	5.0	±3.4
Hardness (H)	8.8	8.4	8.7	7.6	8.6	2.2	3.8	8.5	7.9	***1.5***	8.9	1.8	9.2	***9.4***	7.4	8.8	9.3	7.4	7.1	±3.2
Brittleness (H)	3.0	1.5	3.7	1.7	3.8	1.2	3.8	6.6	6.4	1.5	3.1	***1.0***	5.7	***7.8***	3.9	6.9	7.6	2.7	4.0	±3.3
Sweetness (T)	***3.8***	5.9	***7.2***	5.4	6.5	6.9	6.0	6.4	5.3	4.9	5.5	7.0	6.4	5.4	5.6	6.6	5.0	5.1	5.8	±2.8
Chocolate (A)	***0.6***	***6.0***	7.4	5.8	6.2	***8.2***	2.7	3.3	5.7	3.3	5.6	2.5	6.6	7.7	4.0	3.8	7.4	6.7	5.2	±3.2
Butter (A)	***5.4***	3.3	2.6	2.5	3.5	4.4	4.4	4.7	3.9	4.9	4.4	5.2	2.6	***2.4***	2.6	5.3	3.1	5.0	3.9	±3.0
Chocolate (Ar)	***0.6***	5.6	7.6	5.5	5.6	6.9	2.4	2.1	4.5	2.4	5.2	2.7	5.7	**7.7**	2.7	3.5	7.5	5.2	4.6	±3.4
Salty (At)	***4.4***	3.7	3.5	3.3	2.9	3.2	3.5	2.8	**2.1**	2.7	2.9	2.4	3.1	***2.1***	2.6	3.3	2.6	2.5	3.0	±2.6
Crispness (M)	7.4	5.9	**7.9**	7.5	6.7	0.4	3.1	6.7	7.0	2.5	6.8	***0.4***	6.5	8.2	7.7	6.8	8.1	5.9	5.8	±3.3
Sandiness (M)	***8.5***	6.3	7.5	7.5	6.1	***1.3***	2.7	5.0	6.1	1.4	4.7	1.2	6.3	5.2	7.1	5.8	4.6	5.0	5.1	±3.3
Hardness (M)	5.2	5.2	6.6	5.2	5.9	0.8	2.8	6.3	6.3	2.0	5.3	***0.4***	6.7	8.0	6.3	6.7	***7.4***	4.0	5.0	±3.0
Time in mouth (M)	***3.8***	5.0	6.0	3.6	5.5	***6.7***	6.9	6.5	5.9	6.0	4.8	6.1	4.9	5.1	4.8	4.0	6.2	6.5	5.4	±2.8
Colour dough (V)	3.6	3.9	8.3	8.1	4.9	9.2	3.8	2.1	4.2	***1.4***	4.4	2.3	8.5	***9.3***	5.4	2.4	9.4	2.5	5.2	±3.3
C. chip visibility (V)	1.9	7.7	7.9	6.9	6.1	***1.5***	2.8	6.1	6.3	**9.0**	1.6	5.2	3.7	8.4	6.4	4.5	8.7	4.7	5.5	±3.2
C. chip quantity (V)	1.5	8.2	8.1	6.6	6.9	***1.4***	2.9	7.5	6.4	5.5	2.6	3.6	3.4	7.6	5.8	6.9	***8.7***	4.9	5.4	±3.1
C. chip size (V)	***1.8***	6.5	3.8	4.0	6.0	4.0	5.4	4.8	4.9	***8.1***	5.9	7.7	2.3	3.0	3.7	2.7	2.8	7.4	4.7	±2.9
Contour regularity (V)	7.2	3.8	6.7	5.9	4.9	***2.4***	8.3	8.2	8.0	8.1	4.8	***8.5***	5.4	4.6	6.7	***8.5***	4.0	5.7	6.2	±3.0
Cookie size (V)	5.9	5.8	4.8	5.7	5.3	4.1	7.2	2.7	4.4	***7.2***	6.5	7.0	2.2	4.3	4.5	***1.4***	5.4	6.6	5.0	±2.4
Crackliness (V)	4.1	7.2	7.6	7.0	6.2	***1.7***	7.4	3.3	6.8	2.7	0.4	1.8	4.5	7.2	7.3	3.3	***7.7***	5.0	5.0	±3.2
Cookie height (V)	2.9	6.3	4.0	3.2	5.7	***8.8***	5.4	7.3	7.0	5.0	1.4	6.8	4.6	2.5	4.9	6.6	***3.1***	5.2	5.0	±2.5

SUPPLEMENTARY TABLE 15 : : Calculated nutritional values of all formulated cookies, including the Rayner score. Kcal per 100g, fat, saturated fat, carbohydrates, sugar, protein, fiber and salt in g per 100g.

Cookie Nr°	Kcal	Fat	Saturated fat	Carbohydrates	Sugar	Protein	Fiber	Salt	Rayner Score
Fc-1	468	21.5	10.2	61.8	36.4	6.3	1.8	0.4	21
Fc-2	471	21.2	10.1	62.8	36.3	6.6	2	0.4	21
Fc-3	484	22.2	10.6	64.4	39.2	6.2	1.5	0.4	23
Fc-4	478	21.9	10.4	63.1	37.1	6.4	1.8	0.4	21
Fc-5	485	22.7	10.6	63.1	36.4	6.6	2	0.4	23
Fc-6	467	21	10	62.2	36	6.6	2	0.4	20
Fc-7	488	22.9	10.8	64	38.2	6.3	1.7	0.4	23
Fc-8	480	22.4	10.5	62.5	36	6.5	2	0.4	21
Fc-9	477	21.9	10.4	63	37.1	6.4	1.8	0.4	21
Fc-10	484	22.8	10.8	63.2	38.3	6.1	1.5	0.4	23
Fc-11	476	22.4	10.7	62.2	37.6	6	1.5	0.4	22
Fc-12	482	23.1	11	61.6	36.1	6.3	1.7	0.4	23
Fc-13	477	22.8	10.9	61.5	37	6	1.5	0.4	22
Fc-14	480	22	10.5	63.9	38.9	6.1	1.5	0.4	22
Fc-15	474	22.5	10.6	60.9	34.8	6.5	2	0.4	21
Fc-16	461	19.2	9.2	64.8	38.6	6.6	2	0.4	20
Fc-17[R2]	490	23.6	11.2	61.9	34.9	6.8	2	0.4	22
Fc-18	479	21.6	10.1	64.2	37.5	6.5	2	0.4	21
Fc-19	463	20.9	9.8	62.1	36.3	6.3	2	0.4	21
Fc-20	469	20.5	9.6	64.1	37.7	6.5	2	0.4	21
Fc-21[R1]	467	19.5	9.3	65.6	38.9	6.7	2	0.4	20
Fc-22	478	23.1	11	60.1	34	6.6	1.9	0.4	21
Fc-23[R2]	467	19.5	9.3	65.6	38.9	6.7	2	0.4	20
Fc-24	480	22.3	10.5	63.1	37.2	6.3	1.8	0.4	22
Fc-25	484	23.4	11.1	60.9	34.3	6.7	2	0.4	22
Fc-26	465	20.5	9.8	63.2	38.2	6.2	1.6	0.4	21

Fc-27	454	18.9	9	63.9	37.9	6.5	2	0.4	20
Fc-28[R2]	490	23.6	11.2	61.9	34.9	6.8	2	0.4	22
Fc-29	490	23.4	11.2	63.2	38	6.2	1.5	0.4	23
Fc-30	474	22	10.3	62.2	36.7	6.2	1.8	0.4	21

SUPPLENETARY TABLE 16 : Sociodemographic and BMI group information among 80 children aged 10-13 years from France.

Sociodemographic and BMI information	Subgroups	Numbers	%
Gender	Girls	38	47.5
	Boys	42	52.5
Age in years	10	20	25
	11	24	30
	12	22	27.5
	13	14	17.5
City	Paris	39	48.8
	Aix-en-Provence	41	51.2
BMI groups	Severe thinness	2	2.5
	Thinness	4	5
	Normal	60	75
	Overweight	10	12.5
	Obesity	4	5

SUPPLEMENTARY TABLE 17 : Recipe composition of the four formulated cookies with different levels of sugar, fat, oat bran and chocolate-chips with different baking degrees. All other remaining ingredients such as flour (27.7%), egg (9.5%), baking powder (0.3%), vanilla aroma (0.3%) and salt 0.2%() stayed constant.

	4 Mixture factors				1 Categorial process parameter
Recipe Nr°	Sugar (%)	Fat (%)	Oat bran (%)	Chocolate chips (%)	Baking degree
Fc-5	25.3	17	6.5	13.2	180
Fc-16	26.4	12.8	6.3	16.5	165
Fc-22	22.2	17	6.3	16.5	150
Fc-29	25.2	17	3.3	16.5	180

SUPPLEMENTARY TABLE 18 : Calculated nutritional values per 100g including the Rayner score.

Cookie Nr°	Kcal	Fat	Saturated fat	Carbohydrates	Sugar	Protein	Fiber	Salt	Rayner Score
C5	485	22.7	10.6	63.1	36.4	6.6	2	0.4	23
C16	461	19.2	9.2	64.8	38.6	6.6	2	0.4	20
C22	478	23.1	11	60.1	34	6.6	1.9	0.4	21
C29	490	23.4	11.2	63.2	38	6.2	1.5	0.4	23

SUPPLEMENTARY TABLE 19 : Obtained 12 sensory attributes from a trained panel (10 panelists) among the four formulated cookies.

	Aspect				Texture hand	Texture mouth				Aroma		Taste
Products	Co-lor	Thick-ness	Shi-ny	Rough-ness	Hard-ness	Fon-dant	Soft	Cris-py	Quan-tity choco-late chips	Choco-late	Ba-ked	Sweet
Fc-5	6.3	7.7	4.1	4.5	8.1	4.6	4.3	5.9	4	3.4	5.8	5.6
Fc-16	4.2	9	3.8	7.2	8.3	2.7	1.9	7.6	7.2	5.5	4.5	5.4
Fc-22	1.7	4.7	2.5	4.6	4.4	6.7	6	3.7	6.5	6.3	3.3	6.6
Fc-29	6.6	7.2	4.7	5.1	4.5	6.4	5.5	5.1	5.6	5.7	6.6	6.1

SUPPLEMENTARY TABLE 20 : 8 physicochemical measures among the four formulated cookies.

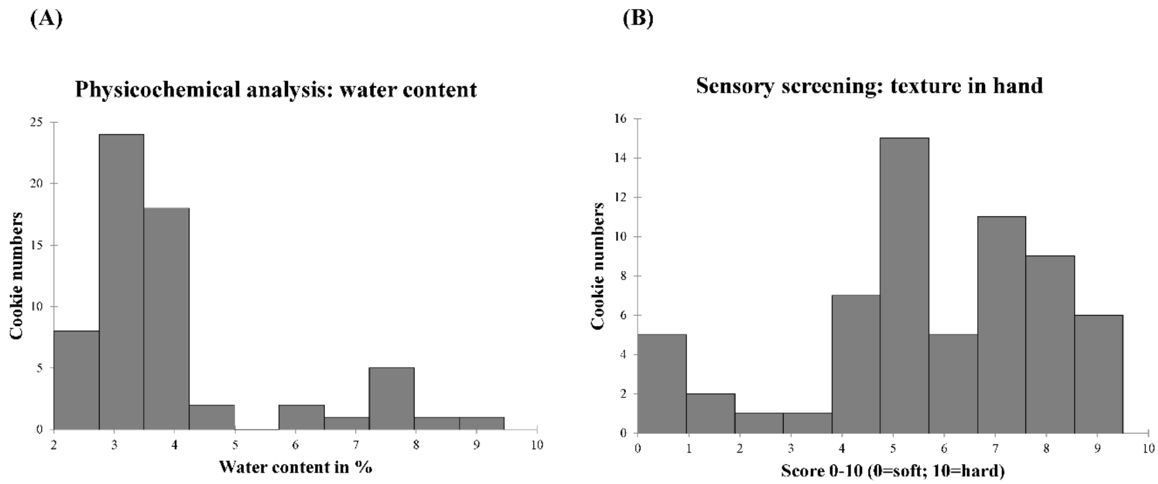
Products	Density	Spread ratio	Stress at rupture	Water content	Strain at rup-ture	Water holding capacity	Predicted gylcemic in-dex	Viscosity
Fc-5	0.64	4.02	0.12	4.44	0.09	0.83	49	616.29
Fc-16	0.71	3.46	0.06	5.22	0.07	0.45	49	312.62
Fc-22	0.73	4.68	0.03	6.92	0.04	0.49	46	342.38
Fc-29	0.64	4.2	0.05	4.3	0.07	0.63	45	373.43

SUPPLEMENTARY TABLE 21 : Significant ANOVA models with the liking score, the consumed quantity score, the desire to eat score, the hunger level immediately after the snacking and after 2 hours, including the calculated delta 2 hunger level and the four products including childrens' sociodemographic and BMI information evaluated by 80 children. Different letters represent significant differences (p ≤ 0.05) according to the Newman-Keuls test. Values that do not share letters were significantly different.

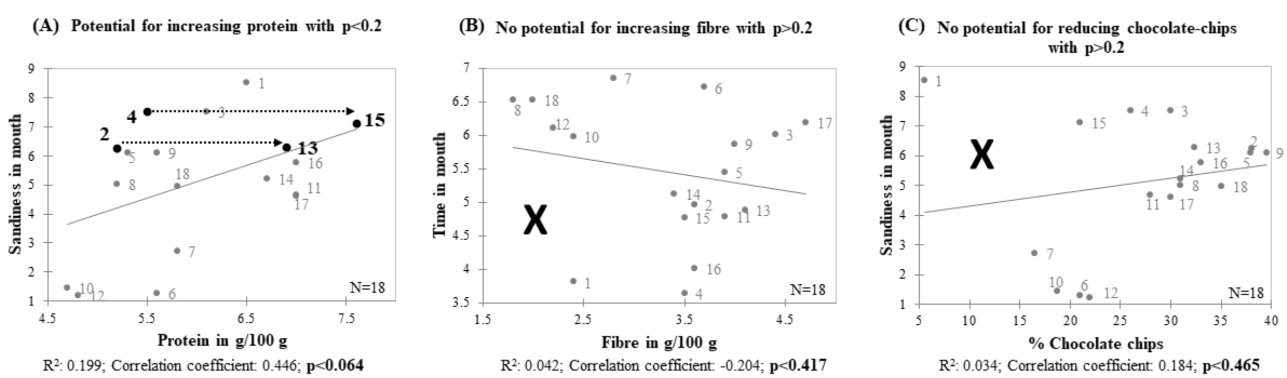
	F	P-value	**Liking**
BMI group	4.7	<0.01	
overweight			4.300 b
obesity			3.688 ab
normal			4.021 ab
severe thinness			3.750 ab
thinness			3.188 a
Sex	8.7	<0.01	**Consumed quantity**
Girls			3.530 b
Boys			3.204 a
Products	3.5	0.02	**Desire to eat (visual)**
Fc-5			4.300 b
Fc-29			4.200 ab
Fc-16			4.038 ab
Fc-22			3.875 a
Sex	2.5	0.11	**Hunger level immediately after snacking**
Girls			3.214 b
Boys			2.961 a
BMI group	4.2	<0.01	
overweight			3.675 b
obesity			3.625 b
normal			2.996 ab
thinness			2.813 ab
severe thinness			2.625 a
BMI group	7.4	<0.01	**Hunger level after 2h**
obesity			3.500 b
overweight			3.350 b
normal			2.529 a
severe thinness			2.500 a
thinness			2.313 a
Age in years	4.6	<0.01	
12			2.989 b
13			2.714 ab
10			2.688 ab
11			2.333 a
Age in years	0.9	0.3	**Delta Hunger 1**
10			1.588 b
12			1.386 ab
11			1.365 ab

13	1.000 a

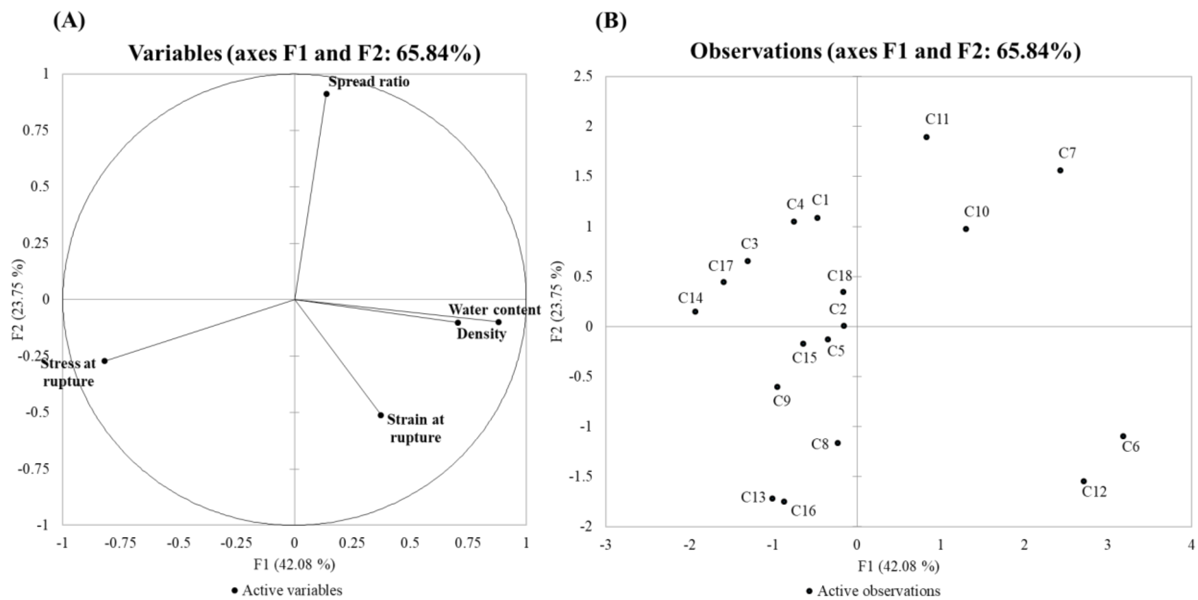
K. Supplementary Figures



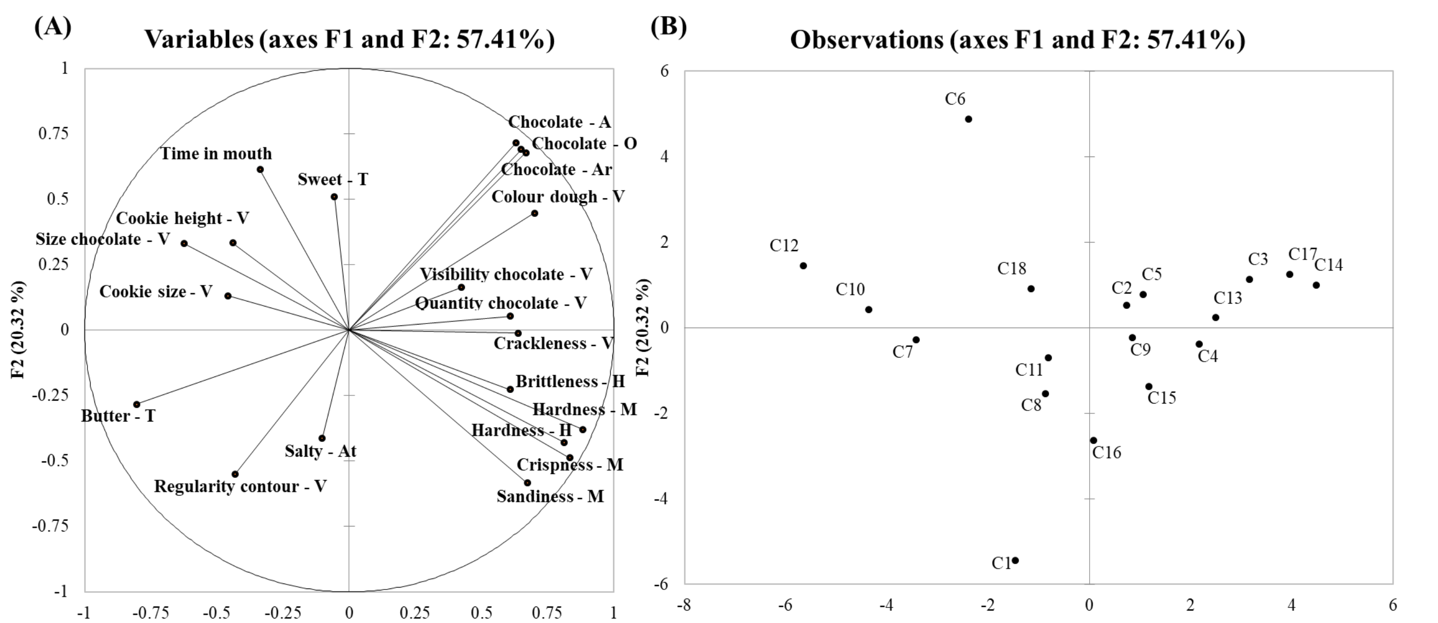
SUPPLEMENTARY FIGURE 1 : (A) the measured water content among 62 chocolate-chips cookies; (B) the sensory screening for the texture perception in hand among 62 chocolate-chips cookies.



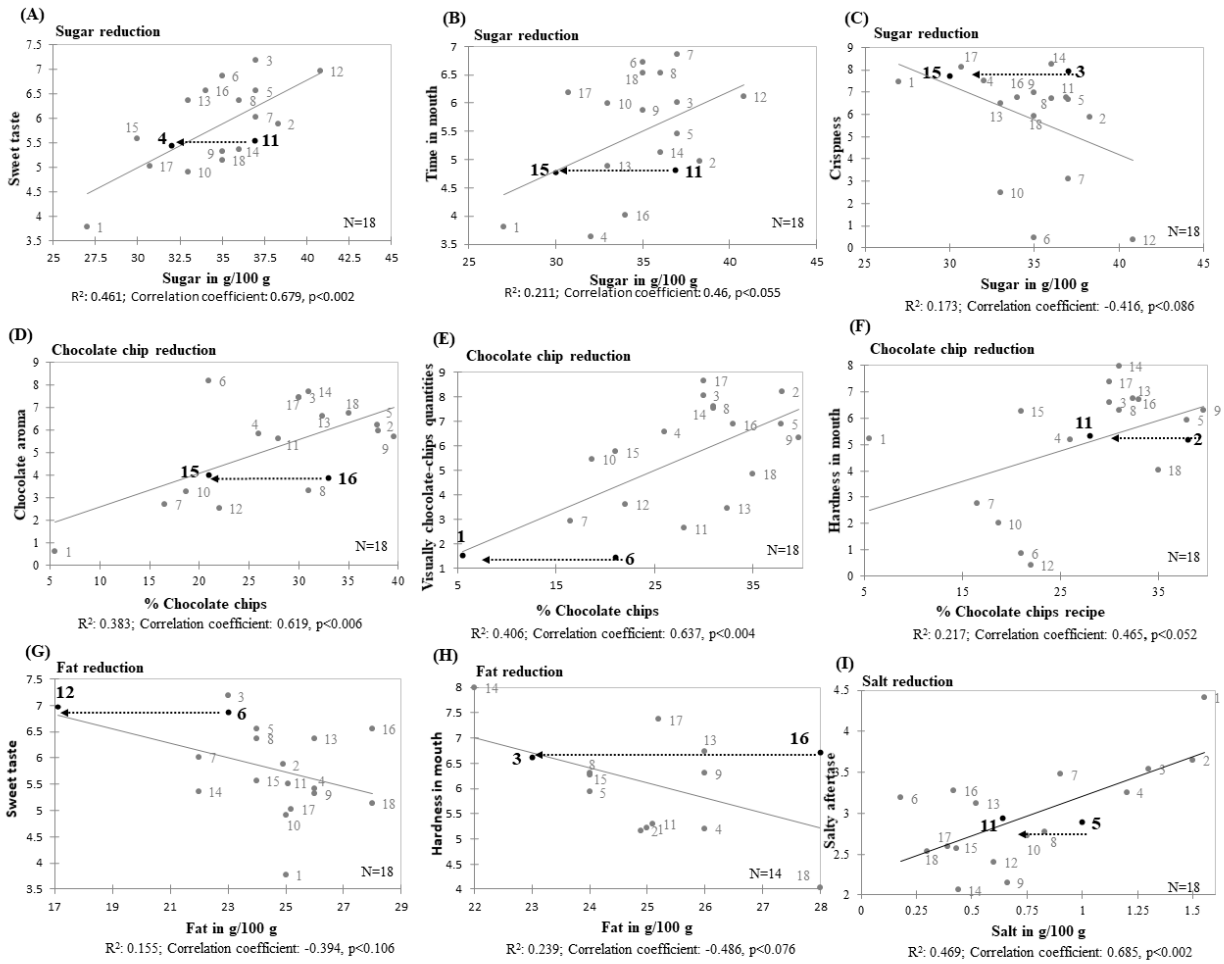
SUPPLEMENTARY FIGURE 2 : Ascertaining whether nutrition-oriented reformulation possibilities exist via linear regressions. (A) The relationship is moderately pronounced ($p < 0.2$) and contains cookies both near to and far from the regression line. There is potential for increasing protein content. (B) and (C) The relationships are less pronounced ($p > 0.2$) with either few cookies near the regression line or few clearly defined outliers. There is no potential for enhancing fibre (B) or reducing chocolate chips (C).



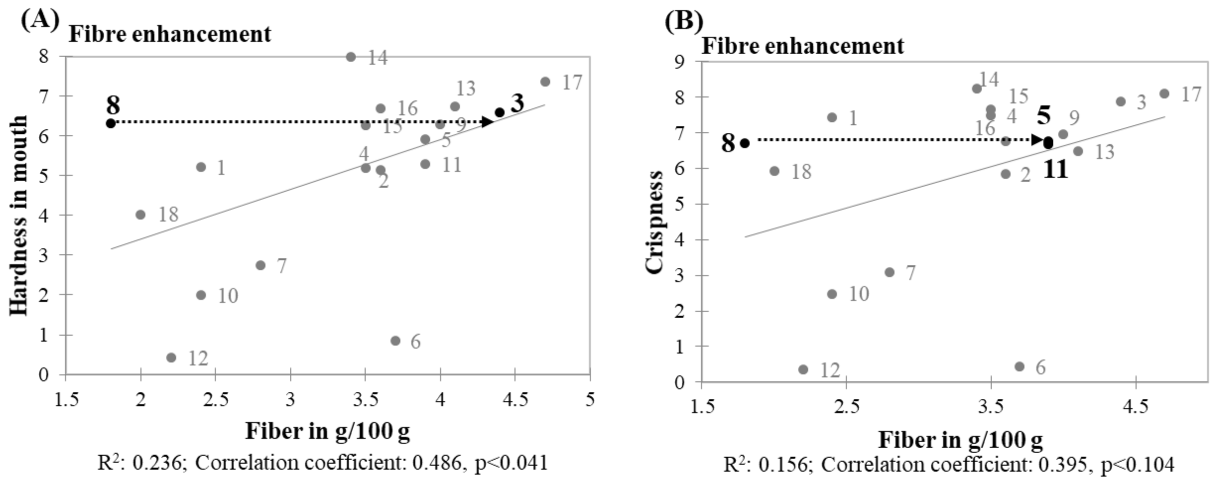
SUPPLEMENTARY FIGURE 3 : Results of the principle component analysis conducted on the five physicochemical characteristics of the 18 study cookies. Pronounced diversity can be seen along axes F1 and F2 (65.84% of variation explained). (A) Variable correlation circle with the five physicochemical characteristics: stress at rupture, strain at rupture, water content, density, and spread ratio. (B) Observation plot showing the 18 study cookies (C1 through C18).



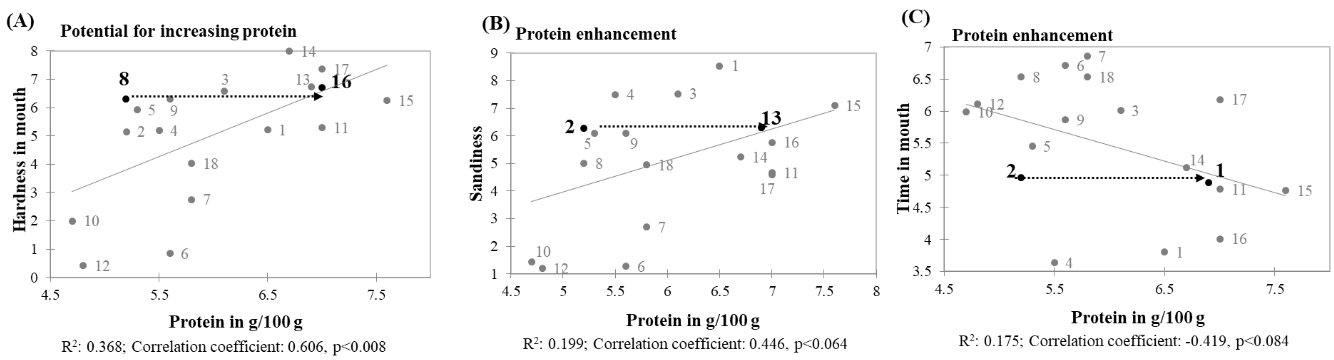
SUPPLEMENTARY FIGURE 4 : Results of the principle component analysis conducted on the 20 sensory attributes of the 18 study cookies. Pronounced diversity can be seen along axes F1 and F2 (57.41%). (A) Variable correlation circle with the 20 sensory attributes. (B) Observation plot showing the 18 study cookies (C1 through C18).



SUPPLEMENTARY FIGURE 5 : Linear regressions for all 18 study cookies (A–G, I) and for the 14 hard cookies (H) where p < 0.2 and there were identifiable outliers. These relationships reveal opportunities for improving nutritional profiles by reducing sugar (A–C), chocolate chips (D–G), fat (G–H), and salt (I) while nonetheless maintaining sensory attributes.



SUPPLENETARY FIGURE 6 : Linear regressions for all 18 study cookies (A–B) where p < 0.2, outliers were present, and opportunities existed for enhancing fibre content while maintaining sensory attributes.



SUPPLEMENTARY FIGURE 7 : : Linear regressions for all 18 study cookies (A–C) where p < 0.2, outliers were present, and opportunities existed for enhancing protein content while maintaining sensory attributes.

Initial 39 linear regressions between compositional properties (C) and sensory attributes (S)

1. Cut-off p-value of < 0.2

- Sugar (C) - Sweet taste/Time in mouth/Crispness/Sandiness (S)
- % Chocolate chips (C) - Chocolate aroma/Chocolate aftertasteVisibility chocolate chips/Quantitity chocolate chips/Sweet taste/Hardness in mouth/Crispness (S)
- Fat (C) - Sweet taste/Time in mouth/Hardness in mouth/Crispness (S)
- Saturated fat (C) - Butter aroma/Sweet taste (S)
- Salt (C) - Salty aftertaste (S)
- Protein (C) - Hardness in mouth/Crispness/Sandiness/Butter aroma/Time in mouth (S)
- Fibre (C) - Hardness in mouth/Crispness/Butter aroma (S)

Excluded: →

- Sugar (C) - Hardness in mouth (S)
- % Chocolate chips (C) – Sandiness (S)
- Fat (C) - Butter aroma/Sandiness (S)
- Saturated fat (C) - Time in mouth/Hardness in mouth/ Crispness/Sandiness (S)
- Protein (C) - Sweet taste/Chocolate aroma (S)
- Fibre (C) – Sandiness/Sweet taste/Time in mouth (S)

2. Presence of outliers

- Sugar (C) - Sweet taste/Time in mouth/Crispness (S)
- % Chocolate chips (C) - Chocolate aroma/Quantitity chocolate chips/Hardness in mouth (S)
- Fat (C) - Sweet taste/Hardness in mouth (S)
- Salt (C) - Salty aftertaste (S)
- Protein (C) - Hardness in mouth/Sandiness/Time in mouth (S)
- Fibre (C) - Hardness in mouth/Crispness (S)

Excluded: →

- Sugar (C) – Sandiness (S)
- % Chocolate chips (C) - Visibility chocolate chips/Sweet taste/Crispness/Chocolate aftertaste (S)
- Fat (C) - Time in mouth/Crispness (S)
- Saturated fat (C)- Butter aroma/Sweet taste (S)
- Protein (C) – Crispness/Butter aroma (S)
- Fibre (C) - Butter aroma (S)

3. Possibility of reduced calorie content and increased fibre

- Sugar (C) - Sweet taste/Time in mouth/Crispness (S)
- % Chocolate chips (C) - Chocolate aroma/Quantitity chocolate chips/Hardness in mouth (S)
- Fat (C) - Sweet taste/Hardness in mouth (S)
- Fibre (C) - Hardness in mouth/Crispness (S)

Excluded: →

- Salt (C) - Salty aftertaste (S)
- Protein (C) - Hardness in mouth/Sandiness/Time in mouth (S)

4. Minimal influential relationships among compositional, physicochemical, and sensory variables (PLS)

- Sugar (C) - Sweet taste/Time in mouth/Crispness (S)
- % Chocolate chips (C) - Chocolate aroma/Quantitity chocolate chips (S)
- Fat (C) - Sweet taste/Hardness in mouth (S)
- Fibre (C) – Crispness (S)

Excluded: →

- % Chocolate chips (C) - Hardness in mouth (S)
- Fibre (C) - Hardness in mouth (S)

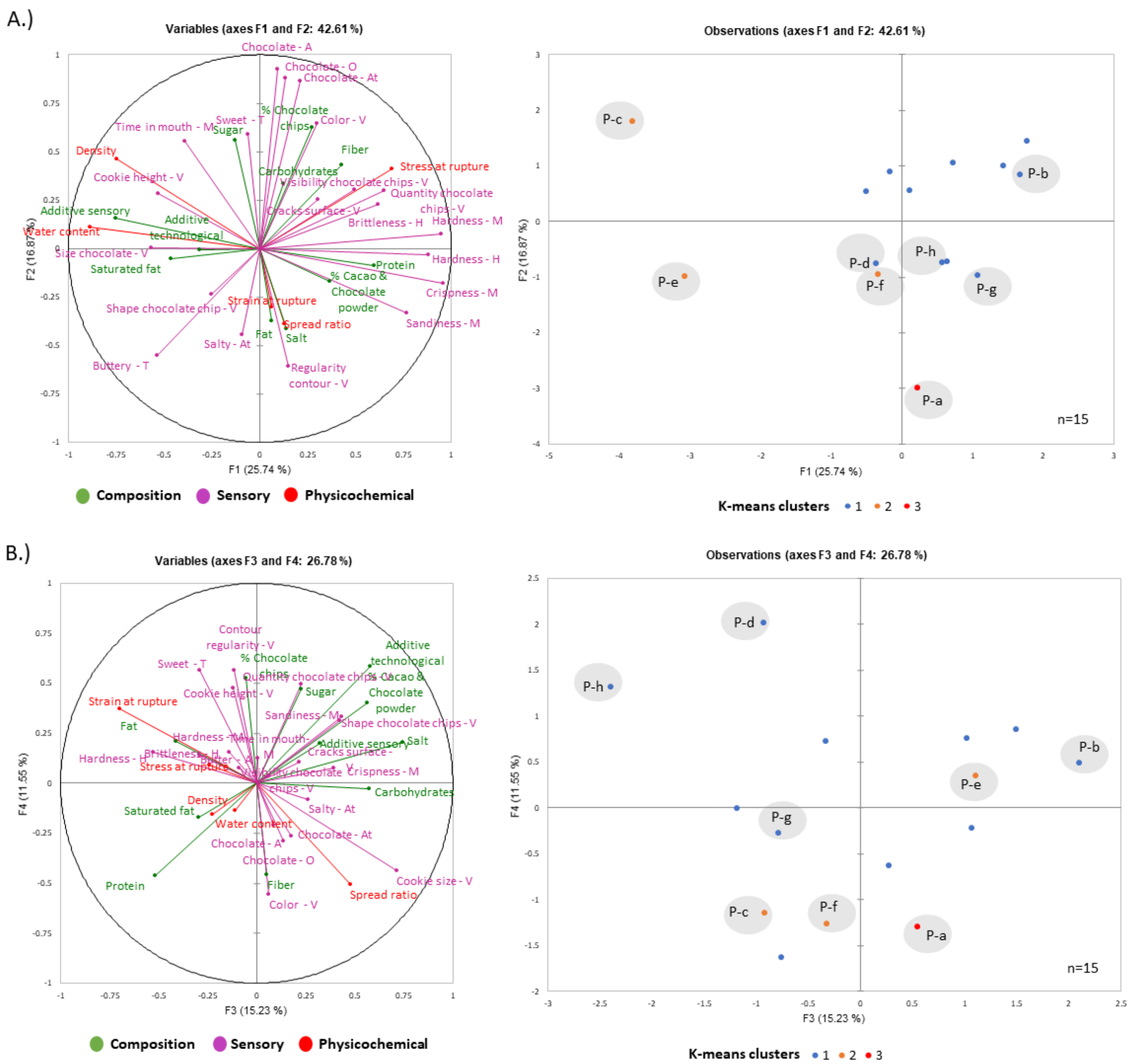
5. Solid relationship (R2) between the two variables

- Sugar (C) - Sweet taste (S)
- % Chocolate chips (C) - Quantitity chocolate chips (S)
- Fat (C) - Hardness in mouth (S)
- Fibre (C) - Crispness (S)

Excluded: →

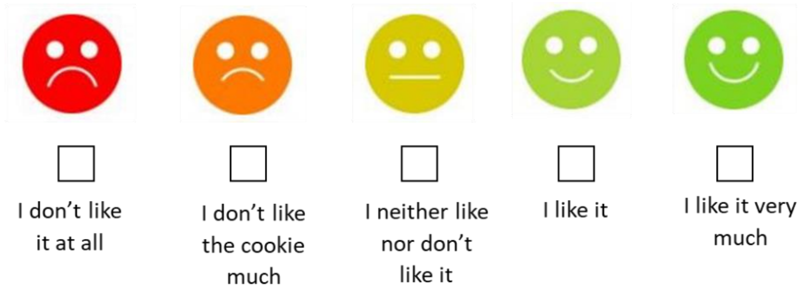
- Sugar (C) -Time in mouth/Crispness (S)
- % Chocolate chips (C) - Chocolate aroma (S)
- Fat (C) - Sweet taste (S)

SUPPLEMENTARY FIGURE 8 : Selection of reformulation possibilities from among the initial 39 linear regressions.

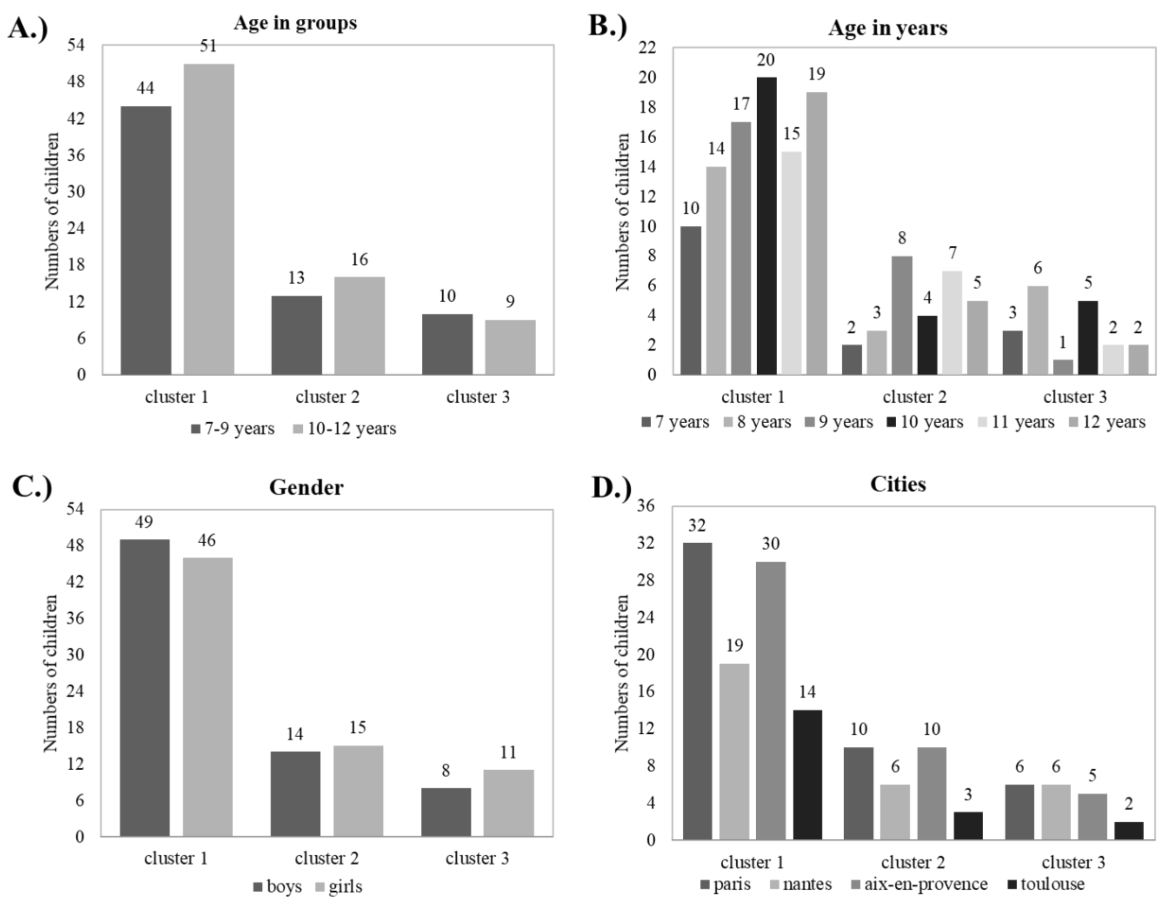


SUPPLEMENTARY FIGURE 9 : The 8 commercial chocolate chip cookies were selected from a representative cookie subset of the market with 18 cookies. For the selection of the hedonic study, 3 cookies were excluded as they were either no longer available on the market or showed different storage conditions. The base for the selection was the clustering with 15 cookies and 20 sensory (Contour regularity-V, Quantity chocolate chips – V, Visibility chocolate chips – V, Shape chocolate chips – V, Sandiness – M, Cracks surface – V, Crispness – V, Salty – At, Cookie size – V, Chocolate – A, Chocolate – At, Chocolate – O, Color – V, Hardness – H, Butter – A, Brittleness – H, Hardness mouth – V, Time in mouth – M, Sweet – T, Cookie height - V), 11 composition (% Chocolate chips, Sugar, Additive technological, % Cacao & chocolate powder, Additive sensory, Salt, Carbohydrates, Fiber, Protein, Saturated fat, Fat) and 5 physicochemical (Stress at rupture, Strain at rupture, Density, Water content, Spread ratio) variables. First of all, an Agglomerative Hierarchical Clustering was performed on all cookies with all sensory, composition and physicochemical variables to visualize an optimal cut off of the cluster numbers. After identifying 3 clusters, a k-means clustering was applied with the same conditions as for the AHC. Cluster 1 contained 11 cookies (within class variance 110.6), cluster 2 contained 3 cookies (within class variance 189.7) and cluster 3 was composed of one cookie.

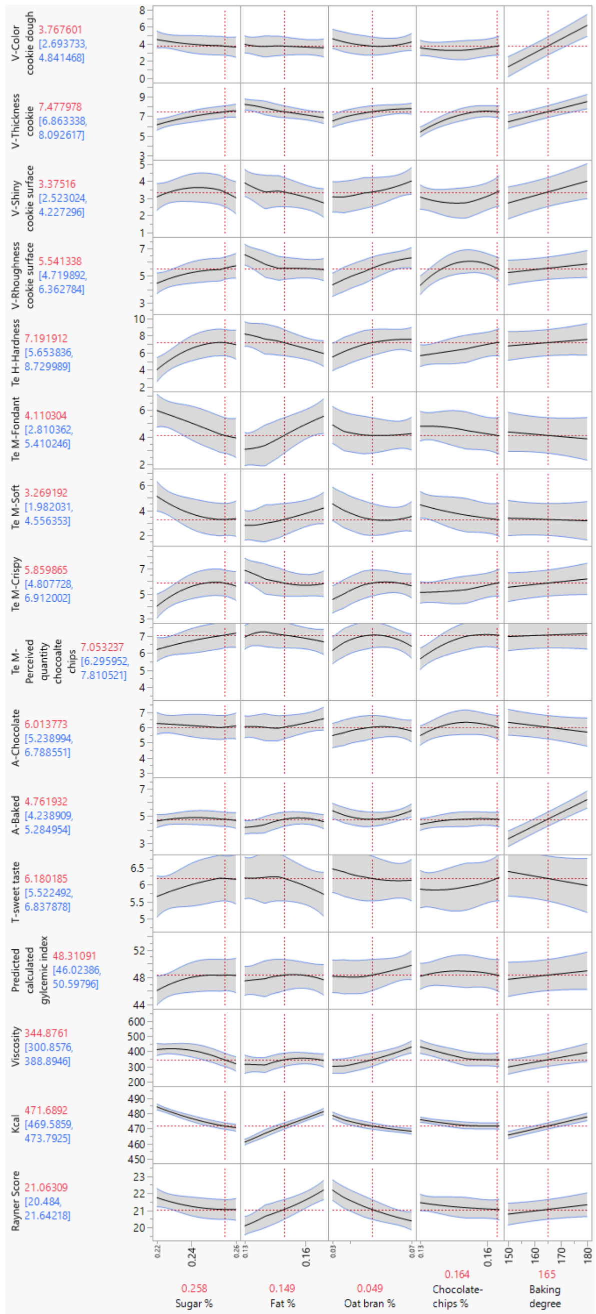
A maximum number of 8 product for the liking study was defined due to simplicity and feasibility reasons on the part of the children. Three cookies were selected from cluster 2 as this cluster showed the highest variance. As well the only cookie from cluster 3 was included. The remaining four cookies were then selected from cluster 1 with the help of a multicriteria mapping (Multiple Factor Analysis) (axes F1-F2, F3-F4) with 20 sensory, 11 composition, 5 physicochemical variables and 15 cookies. As all cookies including their cluster groups were mapped, it was possible to select most extreme and divers cookies based on sensory, composition and physicochemical cookie characteristics from cluster 1.



SUPPLEMETARY FIGURE 10 : Colored hedonic liking scale with five points.

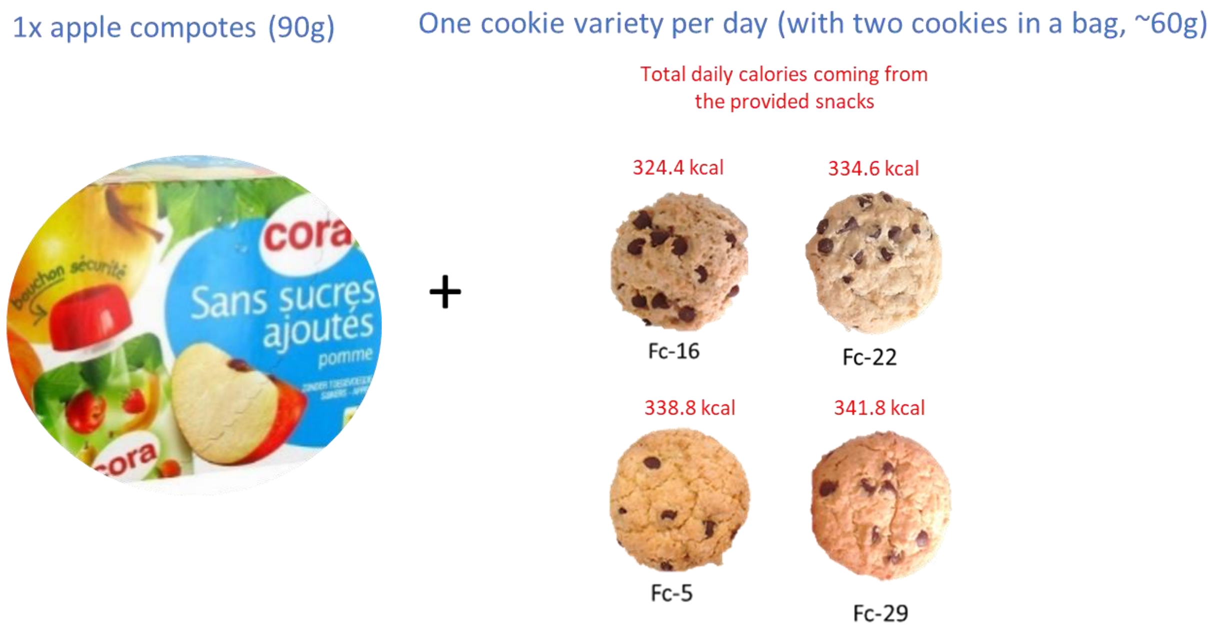


SUPPLEMENTARY FIGURE 11 : A-D Childrens' sociodemographic without significant effect among the three clusters.

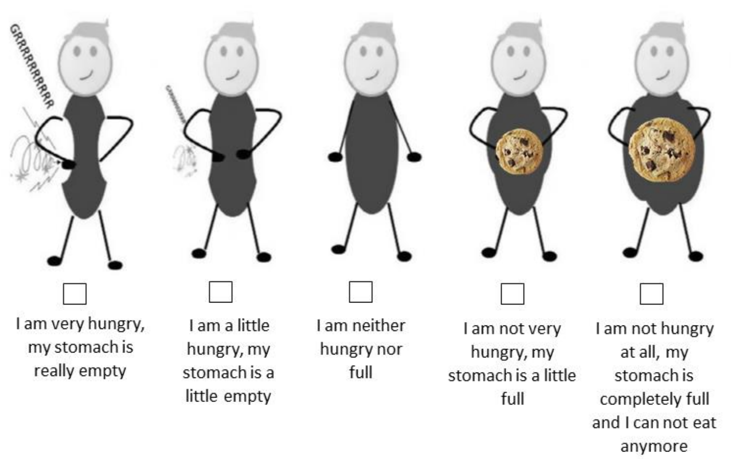


SUPPLEMENTARY FIGURE 12 : Mixture profiler for the model before the backward elimination, with 16 sensory, physico-chemical and nutrition variables.

Snack children



SUPPLEMENTARY FIGURE 13 : The snacking package contained two cookies of one cookie variety, including the apple compote (47.8 kcal per serving size of 90g) Therefore, all provided snacks were within the range of the recommended value of 200-400 kcal for children 10-12 years (Nestlé, 2012).



SUPPLENETARY FIGURE 14 : 5-point scale to measure the self-reported hunger level among children from the left side 1 = I am very hungry, my stomach is really empty to the right side 5 = I am not hungry at all, my stomach is completely full and I can not eat anymore. Adapted from Bennett & Blissett, 2014; Faith et al., 2002; Lange et al., 2019).

L. Résumé en français

Titre : Développement d'une stratégie de reformulation pour améliorer les qualités nutritionnelle et sensorielle de produit alimentaire. Cas des cookies aux pépites de chocolat

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Date de la soutenance : 16.06.2022

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Mots Clés : Propriétés nutritionnelles, Formulation, Analyse sensorielle, Comportement alimentaire, Enfants, Biscuits

Contexte et Enjeu

L'augmentation mondiale de l'obésité infantile constitue un grave problème de santé publique (NCD-RisC, 2017). Un facteur causal important est l'alimentation malsaine composée d'aliments hautement caloriques, ultra-transformés et très appétissants (Costa et al., 2018 ; Forde et al., 2013 ; Hall et al., 2019). Afin de prévenir le surpoids et l'obésité chez les enfants, l'amélioration de l'offre alimentaire est cruciale. Dans ce contexte, le projet **"STOP" (Science and Policy in Childhood Obesity Policy, EU Horizon 2020)** a été lancé, afin de **gérer et de prévenir l'obésité infantile** (enfants d'âge scolaire âgés de 7 à 12 ans) parmi les régions européennes (STOP, 2017). Financé dans le cadre du projet STOP, **ce doctorat vise à contribuer à l'amélioration de la qualité nutritionnelle de l'offre alimentaire.**

De toute évidence, les interventions passées visant à réduire et à gérer l'obésité ont échoué alors que la pandémie d'obésité ne cesse d'augmenter. Cependant, **la reformulation des aliments** (réduction des nutriments surconsommés tels que le sucre, les graisses et le sel) est un moyen intéressant de se concentrer d'abord sur la qualité et les propriétés des produits. De récents modèles multi-nutriments ont montré que la reformulation des aliments peut conduire à une réduction des apports quotidiens en énergie, en graisses, en sucre et en sel et à une augmentation significative des apports en fibres chez les enfants et les adolescents (Combris et al., 2011 ; Leroy et al., 2016 ; Masset et al., 2016 ; Muth et al., 2019).

Cependant, la réduction des sucres et des graisses dans le cadre de la reformulation des aliments implique de nombreuses difficultés, telles qu'une modification de la processabilité, de la texture et de la structure des aliments, de la perception sensorielle, du goût et enfin une perte de la fidélité des consommateurs avec des contraintes économiques pour les entreprises (Cooper, 2017). Par conséquent, il est nécessaire d'améliorer la qualité de l'offre alimentaire et de développer des approches innovantes pour surmonter les obstacles de la reformulation des aliments. Il est donc important de mieux exploiter le potentiel de la reformulation en montrant d'autres voies à l'industrie et aux pouvoirs publics afin de renforcer la reformulation alimentaire comme un levier contre l'obésité infantile.

Sur la base d'une étude bibliographique, deux approches de reformulation ont été proposées afin d'améliorer la qualité nutritionnelle de l'offre alimentaire et la santé des enfants. **La première stratégie** axée sur une réduction de la densité énergétique provenant des sucres et des graisses a été réalisée (Bogl et al., 2018 ; Combris et al., 2011 ; Masset et al., 2016 ; Muth et al., 2019). Outre la modification de la teneur en nutriments, il est également possible de réduire l'apport énergétique total en renforçant le rassasiement et la satiété par le biais d'une modification de la texture des aliments et de leur processus de dégradation orale (Fogel et al., 2017 ; Forde et al., 2013 ; Krop et al., 2018 ; Quah et al., 2019). **La deuxième stratégie** a donc été axée sur la modification de la texture, alors qu'il est clair que les changements de recettes (comme la réduction des sucres et des graisses) interagissent avec la structure et la texture finales du produit.

Comme nous l'avons souligné, la reformulation des aliments au sein d'une matrice alimentaire complexe à forte teneur en sucre et en matières grasses est un défi pour plusieurs raisons. Pour relever ce défi, nous proposons une nouvelle stratégie de reformulation des aliments, développée de manière globale pour tenir compte des déterminants multifactoriels et des interactions entre les composants alimentaires, les préférences alimentaires et une alimentation plus saine. L'objectif de cette thèse était donc d'identifier les leviers de reformulation de produits commerciaux pour créer une offre alimentaire plus saine, tout en améliorant les propriétés sensorielles clés et les préférences. Dans un second temps, l'objectif était de valider et d'évaluer l'impact du produit reformulé sur des indicateurs pertinents pour la santé tels que l'indice glycémique prédit, le processus oral et la satiété. **Pour cela, une approche multicritères, intégrant les caractéristiques nutritionnelles, sensorielles, physicochimiques et hédoniques a été proposée, suivie**

d'une approche expérimentale centrée sur l'étude de l'impact de la reformulation sur les indicateurs nutritionnels et la perception des enfants.

Etude Bibliographique

Prévalence et raisons plus important de l'obésité infantile

Les résultats de l'analyse bibliographique ont clairement démontré la problématique permanente de l'épidémie d'obésité infantile (NCD-RisC 2017). L'une des importantes raisons sous-jacentes à l'augmentation du surpoids et de l'obésité est l'évolution des consommateurs au cours des dernières décennies vers une alimentation malsaine composée d'aliments très appétissants, hautement caloriques (à forte teneur en graisses et en sucres) et ultra-transformés (Costa et al., 2018 ; Hörmann-Wallner et al., 2021). Pour étudier la source des aliments consommés qui contribuent à une surconsommation de sucre et de graisse, nous avons analysé les données de consommation de l'UE (EFSA, 2011). D'après les résultats, **les biscuits sucrée** - en particulier **les cookies** - ont tendance à avoir un impact élevé sur le régime alimentaire quotidien des enfants en raison de leur mauvais profil nutritionnel (riche en sucre et en graisses) et de la grande quantité consommée par les enfants. **Par conséquent, les cookies sont la catégorie de produits qui nous intéresse dans le cadre de ce doctorat.**

La reformulation des aliments comme levier possible pour gérer l'obésité infantile

Il a été démontré que la création d'un environnement alimentaire plus sain au sein du groupe cible le plus touché par l'obésité - les enfants d'âge scolaire - est cruciale pour améliorer leur régime alimentaire. Compte tenu de l'importance de cette intervention, ce doctorat se concentrera sur l'amélioration de l'offre alimentaire. **La reformulation des aliments** est un levier intéressant pour réduire les nutriments surconsommés ayant des effets négatifs sur la santé (sucre, graisse, sel) dans les aliments transformés et pour améliorer la qualité nutritionnelle de l'offre alimentaire. Certains travaux ont montré que la reformulation des aliments peut améliorer notre alimentation et notre santé (Gressier et al., 2021 ; Spiteri & Soler, 2018). **Par conséquent, ce doctorat se concentrera sur la reformulation des aliments, avec une étude de cas sur les cookies.**

Les ingrédients des cookies, leur rôle et les stratégies courantes de réduction des sucres et des graisses

Les principaux ingrédients des cookies sont **la farine, le sucre et les matières grasses.** Ils contribuent largement aux propriétés organoleptiques et déterminent l'appréciation des consommateurs. La composition de la pâte du biscuit influence la production et la manipulation de la pâte, la façon dont les biscuits cuisent et leur qualité finale (Pareyt & Delcour, 2008). Les autres ingrédients présents en moindre quantité sont les œufs, la levure chimique, le sel et l'arôme, ainsi qu'une variété d'inclusions possibles. Les cookies sont fabriqués selon trois étapes principales de transformation (Davidson, 2018) : le mélange et le formage, la cuisson et le refroidissement.

La farine de blé est la farine la plus utilisée dans les cookies. Elle est composée de glucides (principalement de l'amidon), de protéines, de matières grasses, de fibres, de cendres et d'oligo-éléments et de vitamines (Davidson, 2018). Pour les biscuits sucrés, **le saccharose** est considéré comme le sucre le plus important (Garvey et al., 2020 ; Maache-Rezzoug et al., 1998 ; Pareyt et al., 2009). Le niveau de sucre dans les biscuits peut affecter le goût sucré, les dimensions, la couleur, la dureté, la croustillance, le volume et la surface (O'Sullivan, 2020 ; Pareyt et al., 2009 ; Hoseney, 1994). Pour surmonter les défis de la processabilité, de la structure et de la perception, le sucre est souvent remplacé ou substitué par différents ingrédients ou additifs (tels que les édulcorants non nutritifs NNS ; les polyols, les alcools de sucre comme par exemple le maltitol ou l'érythritol) (Luo et al, 2019 ; Raikos & Ranawana, 2019). Cependant, l'utilisation d'additifs peut provoquer des effets secondaires sensoriels négatifs, voire des impacts négatifs sur la santé (Li et al., 2014, 2015 ; Karalexi et al., 2018 ; Swithers, 2015 ; Suez et al., 2014). **Le beurre, les graisses et les huiles végétales** sont ce qu'on appelle **des «shortenings»** dans la pâte à biscuits (Arepally et al., 2020). Ils ont des rôles clés spécifiques en matière de transformation et de machinabilité, ainsi que des rôles fonctionnels et sensoriels. Par exemple, la matière grasse fournit le shortening, la richesse et la tendreté, la sensation en bouche, le pouvoir lubrifiant et la saveur (O'Sullivan, 2020 ; Zoulias et al., 2002a,b). Comme pour la réduction du sucre, les stratégies courantes de réduction des graisses consistent à utiliser des substituts de graisse (polyesters d'acides gras et de saccharose, triglycéride à chaîne moyenne, etc.), des mimétiques de graisse (souvent à base de protéines ou de glucides) (Thondre & Clegg, 2019), des gommes (O'Connor & O'Brien, 2016) et des gels à base de son de blé et d'avoine (Milićević et al, 2020).

<u>Obstacles à la reformulation des aliments et solutions innovantes pour faire face aux limites de la reformulation</u>

Comme décrit précédemment, le sucre et la graisse sont les principaux ingrédients aux propriétés multifonctionnelles dans la pâte cookies. La production de produits de boulangerie dépend des conditions de traitement (température, humidité, temps) et de la formulation (présence de sucre et de graisse) (Hough

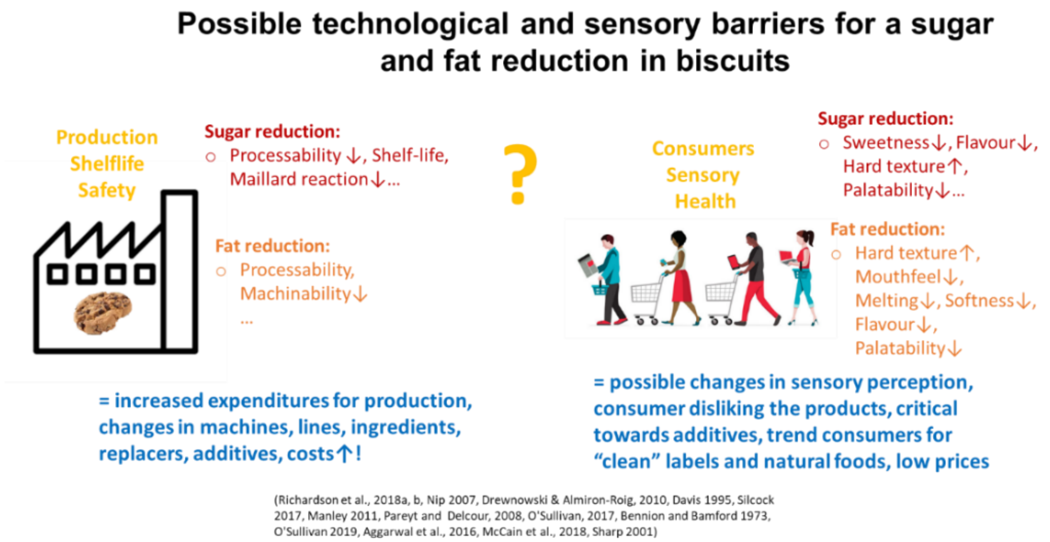

FIGURE 50 : Aperçu des obstacles technologiques et sensoriels possibles lors de la réduction du sucre et de la graisse dans le biscuit.

et al., 2001). Par conséquent, toute réduction de sucre et de graisse peut entraîner des **difficultés technologiques, sensorielles, hédoniques et** finalement **économiques** (FIGURE 1). Ceci est particulièrement délicat lorsqu'il s'agit de reformulation d'aliments ciblant les enfants, car ces derniers ont tendance à avoir des préférences pour les aliments gras et sucrés (Marty et al., 2018). Par conséquent, la réduction des graisses et des sucres dans la pâte à cookies devrait **avoir un fort impact négatif sur les évaluations hédoniques des enfants** (Biguzzi et al., 2015). Il est d'autant plus important d'inclure des mesures sensorielles et physicochimiques dans le processus de reformulation afin d'anticiper les éventuels obstacles et de trouver des voies optimales pour la reformulation.

Sur la base de la littérature, plusieurs approches innovantes de reformulation ont été mentionnées et étudiées. **Les interactions sensorielles** peuvent induire des interactions perceptives intermodales. Par exemple, grâce à une interaction intermodale, il a été possible de réduire jusqu'à 40 % la teneur en sucre des desserts lactés (en augmentant l'arôme de vanille et l'amidon), tout en conservant un bon niveau d'appréciation par les enfants (Velázquez et al., 2020). **Une manipulation plus poussée de la structure de l'aliment** peut contribuer à rendre un biscuit plus sain, en augmentant le processus de dégradation orale, sa satiété et en réduisant son indice glycémique (Anttila et al., 2004; Jia et al., 2020 ; Roberts, 2003). Dans la reformulation des aliments, les **fibres** peuvent servir de substituts aux matières grasses **tout en maintenant la texture et la sensation en bouche** (Conforti et al., 1997 ; Lee & Inglett, 2006 ; Milićević et al., 2020). En plus de cela, les fibres peuvent augmenter **la viscosité** des aliments et donc augmenter **le processus oral des aliments**, avec un impact sur la **satiété et le rassasiement** (Pentikäinen et al., 2014 ; Priyanka et al., 2019, Erinc et al., 2018 ; Thondre & Clegg, 2019). De plus, l'incorporation de céréales riches en fibres dans les aliments pourrait contribuer à diminuer **l'indice glycémique** (Jia et al., 2020). **Le bêta-**

glucane (présent en concentrations élevées dans le son d'avoine par exemple) est une fibre très intéressante qui présente plusieurs avantages potentiels pour la santé. Par ailleurs, il a été montré que **la modification de la granulométrie d'un ingrédient** pouvait être un levier de reformulation prometteur. (Richardson et al., 2018) ont par exemple montré qu'une taille de particules de sucre plus petite dans des brownies au chocolat augmentait l'intensité du goût sucré par les consommateurs adultes. Il a été possible de jouer sur la reformulation des aliments au-delà de la manipulation des macronutriments, avec un impact sur les paramètres de processus orale et une amélioration des textures des aliments. Cependant, le succès de la reformulation de certains aliments pourrait n'être valable que pour la catégorie d'aliments en question. Par conséquent, ces stratégies doivent être testées sur d'autres catégories d'aliments, y compris des aliments aux textures plus complexes. Pour y parvenir, une compréhension approfondie de la matrice alimentaire et des interactions entre les ingrédients est très importante. Il est donc crucial d'inclure, outre la composition, des informations sensorielles, physicochimiques et de goût dans le processus de reformulation.

Stratégie globale

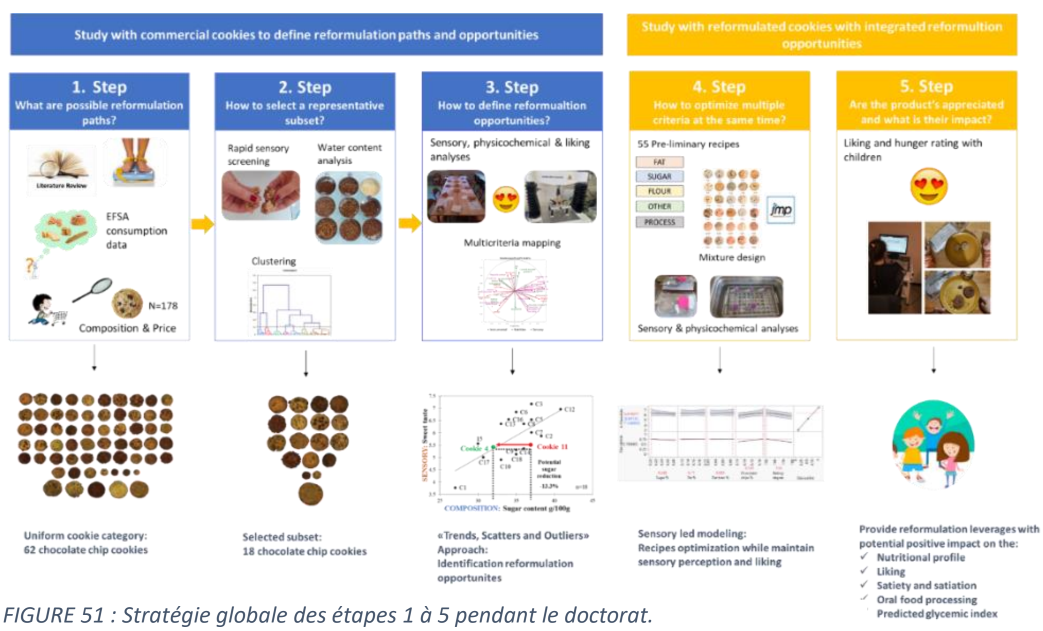

FIGURE 51 : Stratégie globale des étapes 1 à 5 pendant le doctorat.

Dans ce contexte, cette thèse vise à étudier les leviers permettant d'améliorer la qualité nutritionnelle de l'offre alimentaire pour les produits commerciaux tout en améliorant ou en conservant leurs propriétés sensorielles clés et le goût (étapes 1-4, FIGURE 2). De plus, ce travail vise à comprendre l'impact des produits reformulés sur des indicateurs pertinents pour la santé, tels que l'indice glycémique prédit des cookies, le niveau de faim par les enfants et l'impact sur le processus oral chez les adultes (étape 5, FIGURE 2).

Comment définir les voies de la future reformulation sur la base des *cookies commerciaux* (étapes 1 et 2) ?

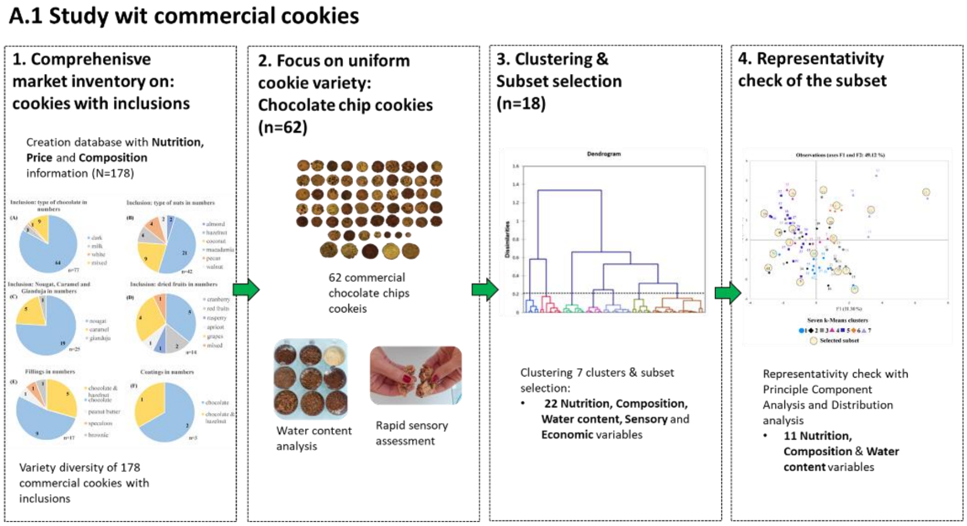

FIGURE 52 : Vue d'ensemble depuis l'inventaire complet du marché des cookies jusqu'à la sélection de sous-ensembles représentatifs.

Notre approche vise à fournir **une vision holistique du marché** qui pourrait profiter aux industries en évaluant les produits de leurs concurrents et, en fin de compte, leur permettre une meilleure compréhension du positionnement de leurs propres produits. Mais le marché alimentaire est complexe à analyser, avec de nombreuses recettes différentes provenant de nombreux fabricants différents.

Dans ce cadre, **le premier objectif** était de créer une base de données à l'aide d'un inventaire complet du marché des cookies français avec inclusions (FIGURE 3). **Le second objectif** était de définir un sous-ensemble de produits représentatifs du marché, sur la base de différents critères de composition, sensoriels, teneur en eau, économiques. La représentativité des sous-ensembles a ensuite été vérifiée par des analyses multivariées et univariées. Au total, **178 cookies** ont été identifiés sur le marché français, puis l'accent a été mis sur **62 cookies aux pépites de chocolat** uniquement. L'analyse complète du marché, centrée sur une seule catégorie de produits, a permis d'obtenir une vue d'ensemble de la diversité des produits. Les résultats ont montré une grande variété de cookies aux pépites de chocolat avec de grandes différences nutritionnelles, de composition, de teneur en eau et sensorielles. En outre, sur la base de critères multiples, **un sous-ensemble représentatif de 18 cookies** a pu être sélectionné parmi les groupes de cookies obtenus.

Ces résultats ont mis en évidence **les premières pistes pour une future reformulation dans cette catégorie de produits.** Ils ont montré l'importance d'inclure les informations sensorielles et physico-chimiques du produit au-delà des informations sur l'emballage pour identifier certaines opportunités de reformulation, afin d'améliorer la qualité nutritionnelle du produit. Il est également nécessaire de créer une base de données multicritères pour identifier idéalement des solutions de formulation plus saines qui minimisent les changements dans la perception sensorielle, l'appréciation par les enfants et la rentabilité. Cet objectif sera développé dans la prochaine étude, afin d'identifier les opportunités de reformulation pertinentes parmi les cookies commerciaux et d'étudier les facteurs d'appréciation et d'aversion parmi une sélection de huit cookies commerciaux.

Comment définir les opportunités de reformulation en fonction des *cookies commerciaux* tout en maintenant la perception sensorielle et le goût (étape 3) ?

La crainte d'une modification de la perception sensorielle, avec un impact négatif possible sur le goût et la fidélité du consommateur, constitue l'une des principales raisons de l'hésitation des industries à reformuler les aliments. Pour répondre à ce besoin, nous avons développé **une nouvelle stratégie d'exploration des possibilités de reformulation des aliments basée sur une approche multifactorielle.**

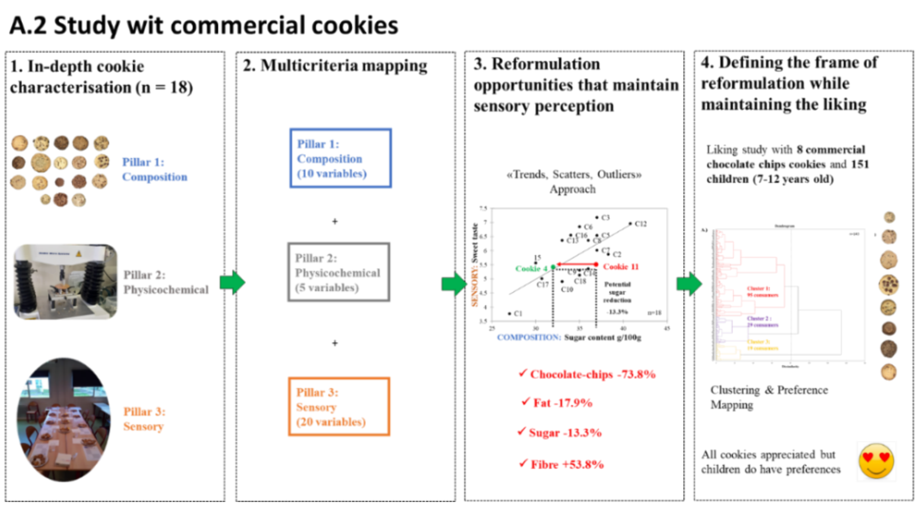

FIGURE 53 : Vue d'ensemble depuis la caractérisation des sous-ensembles de cookies jusqu'à la définition des possibilités de reformulation et le cadre de la reformulation possible chez les

Comme toute réduction de sucre et de graisse dans les biscuits peut avoir un impact sur l'appreciation des consommateurs, il est crucial d'inclure des informations sensorielles dans le processus de reformulation. Cette stratégie utilise des produits commerciaux (sous-ensemble sélectionné dans l'étude précédente) comme point de départ et vise à réduire de manière réaliste la teneur globale en calories et les niveaux de certains nutriments par des analyses multicritères, tout en maintenant la perception sensorielle et le goût des enfants. Cette étude décrit une approche de reformulation multicritères basée sur des cookies commerciaux, avec des analyses sensorielles, physicochimiques approfondies d'un sous-ensemble sélectionné de 18 cookies commerciaux aux pépites de chocolat (FIGURE 4).

Le premier objectif était d'étudier la diversité des propriétés des cookies et de sélectionner des variables clés de composition et sensorielles. **Des analyses sensorielles** (analyses descriptives quantitatives, 12 panélistes entraînés) et **physicochimiques** (texture, densité et rapport de tartinabilité) ont été réalisées, suivies d'une **cartographie multicritères** via une analyse factorielle multiple (10 variables de composition, 5 variables physicochimiques et 20 variables sensorielles). Pour définir ensuite les opportunités de reformulation tout en conservant les propriétés sensorielles clés, **une approche " TSO " (Trends, Scatters, Outliers)** basée sur la régression linéaire a été appliquée. **Le second objectif** était d'étudier **les déterminants de l'appréciation** parmi les facteurs sensoriels, de composition et physicochimiques qui déterminent le goût et les obstacles à l'acceptation des cookies commerciaux aux pépites de chocolat, en tenant compte des différences individuelles. Au total, **151 enfants** français âgés de **7 à 12 ans** de Paris, Aix-en-Provence, Nantes et Toulouse ont été recrutés par la société Eurofins en France. L'évaluation hédonique a été réalisée en 2020 par le biais d'un test auto-administré à domicile, utilisant une échelle hédonique (émoticônes) en cinq points incluant des ancres verbales. Au total, **8 cookies commerciaux** aux pépites de chocolat ont été sélectionnés dans un sous-ensemble représentatif du marché (18 cookies) selon des informations sensorielles, physico-chimiques et de composition. Pendant huit jours, les enfants ont évalué un type de cookie par jour lors du goûter après l'école.

Différentes analyses unidimensionnelles (ANOVA) et multidimensionnelles (HCA, MFA) ont été réalisées pour étudier les différences de goût entre les cookies ainsi que la diversité des modèles de préférence. Sur la base des groupes obtenus, les facteurs de préférence des enfants par groupe ont été étudiés par cartographie externe des préférences via un modèle quadratique.

Nos résultats globaux ont mis en évidence la faisabilité théorique de reformuler des cookies aux pépites de chocolat commerciaux tout en conservant leurs attributs sensoriels, tels que la saveur sucrée, la dureté, le croustillant et la quantité perçue de pépites de chocolat. Sur la base de la diversité des cookies commerciaux, les réductions et améliorations suivantes ont été montrées comme possibles avec l'approche "TSO" : **sucre -13,3%, graisse -17,9%, pépites de chocolat -73,8% et fibres +53,8%.** En outre, des possibilités d'optimisation pour une réduction de Rayner, du score de transformation et des additifs ont été identifiées, y compris l'utilisation d'ingrédients plus respectueux de l'environnement.

L'étude hédonique a montré que la catégorie de produits des cookies commerciaux aux pépites de chocolat était **globalement appréciée par les enfants âgés de 7 à 12 ans**, malgré une grande diversité de composition, sensorielle et physicochimique. Ce résultat est prometteur pour les futurs travaux de reformulation, car les produits présentant un profil nutritionnel amélioré n'ont pas été rejetés. De plus, d'après les trois profils de préférence identifiés dans nos modèles, les enfants expriment des préférences qui peuvent être différentes en fonction de l'IMC. En outre, **la texture a été identifiée comme l'un des principaux facteurs de préférence** (préférences globalement plus élevées pour une dureté et une croustillance plus faibles) ou d'aversion. D'autres variables de composition et physicochimiques sont importantes pour mieux comprendre pourquoi un certain biscuit est préféré ou rejeté. Ainsi, nous avons constaté des préférences globalement plus élevées pour une teneur accrue en sel, une teneur réduite en sucre et en pépites de chocolat, ainsi que pour une densité et une teneur en eau accrues.

En conclusion, cette approche multicritères constitue **une base solide pour établir des recettes préliminaires à l'avenir,** en tenant compte des préférences des enfants. Elle devrait notamment aider à reformuler les produits destinés aux enfants, en **améliorant les profils nutritionnels des cookies** tout en **conservant leurs attributs sensoriels**, qui déterminent les préférences. Nous espérons que cette approche pourra promouvoir l'utilisation de la reformulation des aliments comme un outil permettant d'accroître les choix alimentaires et la qualité du régime.

Comment optimiser plusieurs critères sur des *cookies reformulés* en même temps ? (étape 4)

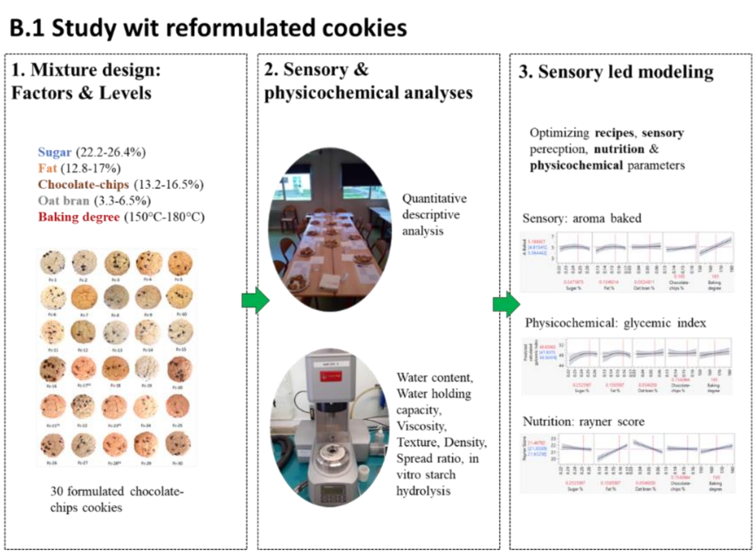

FIGURE 54 : Approche du plan de mélange à l'optimisation multifactorielle.

Il est très important de bien comprendre les rôles et interactions entre les ingrédients participant à la recette des cookies afin de pouvoir mener une reformulation efficace. Cela permettra d'améliorer la recette vers un produit plus sain, tout en maintenant la perception sensorielle et le goût. Cet article soumis propose **une approche de reformu-**

lation sensorielle avec un plan de mélange et une optimisation multicritères. Cette étude vise donc à mieux **comprendre les interactions des ingrédients au sein d'une matrice alimentaire complexe et à identifier les variables clés influençant la perception sensorielle, les paramètres physico-chimiques et nutritionnels avec un minimum de séries expérimentales.** Un autre objectif est de **définir des recettes optimales** tout en améliorant les attributs sensoriels clés, les paramètres nutritionnels et physico-chimiques (FIGURE 5).

Cette étude s'appuie sur les précédentes étapes de ce travail de doctorat, qui ont montré les premières pistes de reformulation, identifié les opportunités de reformulation pour une réduction des graisses, des sucres, des pépites de chocolat et l'amélioration des fibres et du goût général des cookies commerciaux aux pépites de chocolat. **55 recettes préliminaires** avec différents niveaux et types de sucre, de graisse, de farine et de céréales, de pépites de chocolat et de paramètres de cuisson ont ainsi été formulées et caractérisées par des analyses sensorielles et physico-chimiques. Sur la base de ces 55 recettes préliminaires, cinq facteurs (ingrédients) et niveaux ont été sélectionnés pour l'étape suivante, qui fait l'objet de cette partie des résultats. Quatre facteurs de mélange ont également été sélectionnés, tels que **le sucre (22,2-26,4 %), les matières grasses (12,8-17 %), les pépites de chocolat (13,2-16,5 %)** et **le son d'avoine (3,3-6,5 %)**, **inclus un facteur de process** (température de cuisson, 150°C, 165,°C, 180°C). Pour étudier ensuite les interactions entre les ingrédients et leur influence sur la perception sensorielle, les paramètres physico-chimiques et nutritionnels, **un plan de mélange** a donc été réalisé avec les cinq facteurs et niveaux mentionnés ci-dessus. Au total, 28 cookies différents ont été proposés à partir de ce plan et produits sur le plateau FRECE de l'UMR SayFood. Ils ont été caractérisés par des analyses sensorielles (QDA avec 10 panélistes) et physico-chimiques (densité, taux d'étalement, capacité de rétention d'eau, texture, hydrolyse de l'amidon in vitro, viscosité). Pour optimiser les recettes (facteurs sucre, matières grasses, pépites de chocolat, son d'avoine et degré de cuisson), des attributs sensoriels clés (5 texture, 2 arôme, 1 goût), des paramètres nutritionnels (kcal, score de Rayner) et physicochimiques (indice glycémique, viscosité) basés sur des régressions linéaires multiples avec fonction de désirabilité ont été appliqués. Tous les résultats sont présentés dans cette section de résultats.

Cette approche originale s'appuyant sur un plan de mélange a permis de mieux comprendre le rôle des ingrédients et leur interaction pour une matrice alimentaire complexe avec l'objectif de reformuler un produit commercial sous de multiples contraintes : **a) vers un produit plus sain (sucre -14,6%, graisse -28,9%, pépites de chocolat -8,5%, kcal -5,1%, score de Rayner -11,4%, indice glycémique prédit de -**

11,9%), **b) tout en optimisant la perception sensorielle et le goût, c) sans utilisation d'additifs ou de substituts.**

En outre, la matière grasse a été identifiée comme un ingrédient important pour adoucir la texture du biscuit, tandis que le son d'avoine a été identifié comme un ingrédient clé contribuant à maintenir la perception sensorielle, à augmenter la viscosité des cookies et à réduire la teneur en kcal. Cette approche originale a montré que l'utilisation d'un plan de mélange est un outil pertinent pour **mieux comprendre une matrice alimentaire complexe** et pour **reformuler un produit commercial vers un produit plus sain.** Cette approche de reformulation multicritères a montré qu'il est possible de réduire les macronutriments cibles et d'améliorer le profil global des produits sans pour utiliser de substituts ni d'additifs, tout en maintenant la perception sensorielle. D'autres études sont nécessaires pour examiner l'impact des cookies reformulés sur la perception et les préférences, ainsi que sur le comportement lié à la transformation orale des aliments et à la satiété.

Les cookies reformulés sont-ils appréciés des enfants et quel est leur impact sur la satiété des enfants ? (étape 5)

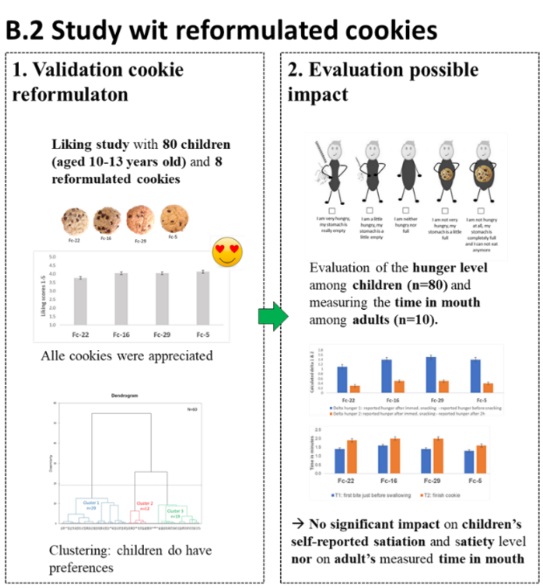

FIGURE 55 : Dernier étude de validation auprès d'enfants âgés de 10 à 13 ans.

L'approche de reformulation sensorielle décrite plus haut a montré qu'il était possible de réduire les macronutriments ciblés et d'améliorer les aspects santé sans ajouter de substituts et d'additifs, tout en maintenant ou en ciblant la perception sensorielle. Certains cookies ont été identifiés comme ayant un fort potentiel pour répondre à nos objectifs. Cette dernière section de la thèse et du manuscrit a **étudié l'impact des cookies reformulés sur le goût des enfants, le niveau de faim autodéclaré.** Par ailleurs, nous avons émis l'hypothèse que le processus de dégradation de l'aliment en bouche pouvait moduler le pouvoir rassasiant des cookies. Nous avons donc également mesuré **le temps de séjour en bouche de chaque formule de cookie par un panel d'adultes** (FIGURE 6). Tout d'abord, **80 enfants français âgés de 10 à 13**

ans de Paris et d'Aix-en-Provence ont été recrutés par la société Eurofins et inclus dans cette étude. L'évaluation du goût et du niveau de faim (avant le goûter, immédiatement après le goûter, deux heures plus tard) a été réalisée en 2021 par le biais d'un test auto-administré à domicile, à l'aide d'une échelle hédonique en cinq points (émoticônes) comprenant des ancrages verbaux. Au total, **4 différents cookies aux pépites de chocolat reformulés** (avec différents niveaux de sucre, de graisse, de pépites de chocolat, de son d'avoine et de degrés de cuisson) ont été sélectionnés dans un plan de mélange de 30 cookies. Chaque jour (en milieu d'après-midi), le menu de la situation de grignotage a été personnalisé afin de proposer 2 cookies, une purée de pommes et de l'eau, menu présentant des caractéristiques nutritionnelles similaires.

Pour proposer certains mécanismes expliquant les différences de goût, de satiété et de rassasiement (par comparaison avec les différences de niveaux de faim), différentes propriétés ont été déterminées : les paramètres de traitement oral des aliments et l'indice glycémique prédit. Les temps de consommation de ces quatre cookies (T1 et T2) ont en effet été enregistrés juste après la première bouchée avant d'avaler, et respectivement lorsque le biscuit a été entièrement mangé par 10 adultes.

Tous les cookies formulés ont été globalement appréciés par les 80 enfants, avec des scores d'appréciation élevés compris entre 3,8 et 4,1 sur l'échelle de 5 points. En conséquence, en comparant la composition de ces quatre produits reformulés, **ce résultat a montré qu'il est possible de maintenir le goût alors qu'une réduction des kcal (-5,9%), du sucre (-15,9%), des graisses (-24,7%) et des pépites de chocolat (-20%) par biscuit ou une augmentation du son d'avoine (+49,3%) ont été proposées.** Ces leviers de réduction se réfèrent à quatre produits reformulés différents, ces leviers de reformulation n'ont donc pas été réalisés sur un seul cookie. Par ailleurs, les résultats d'une classification automatique(cluster 1 n=29 enfants ; cluster 2 n=12 enfants ; cluster 3 n = 19 enfants) ont confirmé que **les enfants ont des préférences et des zones de rejet différentes. En revanche, la composition des cookies n'a eu aucun impact significatif sur la satiété et le rassasiement autodéclarés par les enfants. De même, aucune différence significative n'a été constatée pour les cookies reformulés et leur temps de mise en bouche mesuré chez les adultes.**

En conclusion, cette **approche multicritères** a permis de **reformuler un produit commercial pour en faire un produit plus sain, tout en maintenant la perception sensorielle et le goût des enfants** de 10 à 13 ans. Les quatre cookies reformulés ont été globalement appréciés. Outre une réduction des nutriments cibles, une amélioration de l'indice glycémique prévu et du score de Rayner a été possible. Pour essayer d'avoir un impact plus important sur le rassasiement et la satiété, des études supplémentaires pourraient être intéressantes pour augmenter la teneur en son d'avoine ou la source de bêta-glucane, pour tester d'autres cookies à partir de la conception du mélange et pour tester également un produit de référence, sans aucun contenu de son d'avoine ou de bêta-glucanes. En outre, une analyse descriptive sensorielle et des études sur le comportement du processus oral sont nécessaires pour mieux comprendre la perception et le comportement en bouche des enfants. Les jeunes enfants devraient également être pris en compte. Cette étude a souligné l'importance de prendre en compte les préférences interindividuelles des enfants pour les produits, car il n'existe pas de produit qui soit aimé ou rejeté par tous. De plus, rendre un produit plus attrayant visuellement peut influencer positivement l'envie de manger un produit. En outre, des recherches supplémentaires sont nécessaires en ce qui concerne les enfants ayant un IMC élevé, leur goût et leur satiété.

Conclusion générale

Cette **approche multicritères** de la reformulation a démontré qu'un **inventaire du marché comme point de départ contribue au succès de la reformulation des cookies,** afin d'améliorer **la qualité nutritionnelle, les propriétés sensorielles et le goût des produits.** En outre, cette étude a confirmé la nécessité d'aller au-delà des informations sur la composition lorsqu'il s'agit d'améliorer à la fois la qualité nutritionnelle, les propriétés sensorielles et l'appréciation. De plus, les approches telles que **la sélection d'un sous-ensemble représentatif, la cartographie multicritères, la méthode théorique "TSO" et la création de recettes préliminaires basées** sur le sous-ensemble ont été des outils utiles pour dériver des leviers de reformulation performants tout en optimisant la perception sensorielle et l'appréciation des recettes par les enfants.

Cette approche de reformulation multicritères prenant en compte la nutrition, la composition, les variables sensorielles et physico-chimiques a démontré qu'il est possible de réduire **la teneur en sucre, en graisse et en pépites de chocolat et d'augmenter la teneur en son d'avoine tout en optimisant les propriétés sensorielles clés.** De plus, il a été possible d'améliorer la charge **calorique, l'indice glycémique prédit, le score de Rayner et la viscosité des cookies.** Le tout en conservant un bon niveau d'appréciation. Mais notre recherche a également montré la possibilité de réduire la teneur en graisses et en sucres tout en maintenant les préférences, même lorsque les propriétés sensorielles et physico-chimiques sont différentes.

En outre, cette approche de reformulation multicritères a également été un outil pour identifier de possibles voies pour réduire **le degré de transformation,** diminuer le **nombre d'additifs** et utiliser des **ingrédients naturels**, respectueux de l'environnement, qui sont modérément ou faiblement transformés. De plus, la texture des cookies a été identifiée comme un levier intéressant pour améliorer **le processus oral** des enfants, car différentes textures de cookies telles que dur, croustillant, moelleux ou plus visqueux ont toutes été appréciées. Ces résultats sont prometteurs pour de futures recherches visant à améliorer les paramètres de degradation orale des aliments chez les enfants, afin d'avoir **un impact positif sur leur satiété et la gestion de leur poids.**

Cette étude a montré que les informations **physicochimiques** et **sensorielles** sont très importantes pour mieux comprendre et anticiper les facteurs de **préférence des enfants.** En outre, les résultats montrent qu'il est nécessaire cibler la stratégie de reformulation en fonction de chaque groupe de consommateurs spécifique, car les consommateurs présentent des différences interindividuelles dans leurs habitudes de consommation, comme par exemple des enfants d'âges ou d'IMC différents. Notre étude a également démontré que **les différences interindividuelles dans la perception sensorielle et les préférences** peuvent également être une chance pour l'industrie, afin de définir différentes stratégies de reformulation réussies ciblant des consommateurs spécifiques.

Notre étude a également encouragé à repenser la préférence confirmée mais aussi "supposée" des enfants pour un goût sucré élevé. Nous suggérons que parmi les produits de céréaliers sucrés à forte teneur en matières grasses et en sucre, il est plus difficile de différencier les perceptions sensorielles clés telles que le goût sucré par exemple. Par conséquent, une réduction de la teneur en sucre pourrait être plus élevée que prévu sans affecter le goût sucré. Les conclusions de cette approche de reformulation multicritères sont importantes pour l'industrie, car nos résultats suggèrent que les industries pourraient ne pas perdre de parts de marché en reformulant les produits biscuits sucrés. En outre, **cette approche pourrait renforcer la reformulation volontaire des aliments pour différentes catégories de produits.**

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