The Role of Dietary Fibre Ingredients in Supporting Food Reformulation Strategies

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Declaration

I hereby certify that the material, which I now submit for assessment on the programme of study leading to the award of Master of Science is entirely my own work and has not been taken from the work of others save to the extent that such work has been cited and acknowledged within the text of my own work. No portion of work contained in this thesis has been submitted in support of an application for another degree or qualification to this or any other institution.

Signed: Claire Crowley Date: 25/04/2022

Claire Crowley

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Abstract

Diet- related diseases such as overweight and obesity are a major public health issue worldwide with incidences of overweight and obesity spiralling in Ireland and other EU countries. Research has shown that poor eating choices and behaviours and non-compliance with recommended dietary intakes are attributable to the scale of overweight and obesity being seen. Food reformulation has been viewed as a public health strategy to improve the nutrient profile of processed foods to improve nutrient intakes of populations without changes to the nutrient composition being perceptible to the consumer. Evidence has shown that dietary fibre ingredients can be used to modify nutrient compositions of processed foods as fat and sugar replacers. Results from studies analysed in this study strongly establish that inulin has a role to play in improving the nutrient composition of three food categories: baked goods, ice cream and breakfast cereals with minimal impact to physical and sensory characteristics. Results have shown that the products formulated with inulin had comparable properties to the control formulations. Nutrition data from 229 breakfast cereals collected shows that there are opportunities to reformulate with dietary fibre ingredients to improve the nutrient profile and improve nutrient intakes as strong sales data confirm the popularity breakfast cereals as a food choice in Ireland. Further work is needed to establish the optimised inulin level in each of the food categories for reformulation strategies and conduct further research into the feasibility of inulin in food reformulation strategies.

List of Abbreviations

BMI	Body Mass Index
CVD	Cardiovascular Disease
DALY	Disability-adjusted Life-years
DP	Degree of Polymerisation
DRV	Dietary Reference Value
EFG	Emulsion Filled Gel
EU	European Union
FDF	Food & Drink Federation
FDI	Food Drink Ireland
FOS	Fructo-oligosaccharide
FSA	Food Standards Agency
FSAI	Food Safety Authority of Ireland
GF	Gluten-free
GOS	Galacto-oligosaccharide
GR	Glycaemic Response
HLG	High Level Group on Nutrition and Physical Activity
HOSO	High Oleic Sunflower Oil
IR	Insulinemic Response
IUNA	Irish Universities Nutrition Alliance
NANS	National Adult Nutrition Survey
NCD	Non-Communicable Disease
NPD	New Product Development
NSIFCS	North/South Ireland Food Consumption Survey
ODP	Optimised Descriptive Testing
OPIOG	The Obesity Policy Implementation Oversight Group
PHE	Public Health England

PLSR	Partial Least Squares Regression
QALY	Quality Adjusted Life Years
RCT	Randomized Controlled Trial
RTE	Ready to Eat
SACN	Scientific Advisory Committee on Nutrition
SAT	Sensory Acceptance Testing
SSB	Sugar Sweetened Beverage
TFA	Trans-fatty acids
UK	United Kingdom
WHO	World Health Organisation

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Chapter 1: Introduction

The focus of this thesis is to assess the role and benefits of dietary fibre incorporation in processed foods in supporting food reformulation strategies. The thesis will define the concept of food reformulation and review the role that dietary fibre ingredients can play in improving the nutrient profile of processed foods through food reformulation methods. The thesis will evaluate the impact of different dietary fibre ingredients in reformulating processed foods to reduce the level of fat and sugar which are associated with obesity and overweight when consumed in high proportions. The introductory chapter will provide an overview of the background of the prevalence of overweight and obesity and the associated health consequences. The introductory chapter will also look at compliance with recommended dietary guidelines to assess the role that food reformulation has to play.

1.1 Background to Diet and Health

Obesity and overweight levels are at crisis point and obesity is now a global public health emergency. The availability and acessibility of processed foods has led to a steep rise in the incidence of diet-related non-communicable diseases (NCD). Incidence of NCDs including diabetes, obesity and cardiovascular disease are attributable to individual's poor dietary choices and high consumption of ultra processed foods which are high in unhealthy nutrients and devoid of adequate amounts of dietary fibre, minerals and vitamins (Monteiro *et al.*, 2018). A healthy diet is key in maintaining a healthy body weight and preventing the risk of diet-related diseases (Department of Health, 2021).

The mounting evidence of the harmful effects of substandard diet and health, including overweight, obesity, diabetes, and cardiovascular diseases has prompted national and international governments to take action to reduce the intake of sugar, fat and sodium to the recommended dietary reference values (DRVs). Several population-level interventions have been suggested such as pricing interventions, food sourcing interventions, imposed restrictions on children's marketing, nutrition information labelling, healthy eating campaigns and product reformulation (Hashem, He and MacGregor, 2019). These interventions are driven by national governments and public health bodies to reduce the high economic burden of diet-related diseases. These interventions have the potential to reduce population intakes of unhealthy nutrients to achieve a better-balanced diet across populations. In recent years, the focus has shifted from interventions that require input in consumer decision-making to interventions supporting the reformulation of processed foods to improve the nutrient profile and ultimately improve the nutrient intakes of populations (Gressier *et al.*, 2021). Urgent action is needed to alter the growth trajectory of obesity and diet-related diseases, and while innovation and new product development (NPD) will play a key role in contrbuting to healthier products on the marketplace urgent effective strategies are critical to addressing the nutrient imbalance of processed foods already available on the market.

1.2 Prevalence of Non-Communicable Diseases

Western population diets across the globe and here in Ireland are suboptimal and misaligned with dietary recommendations in many respects. Research has shown that a poor diet is associated with an increased risk of NCDs (Ng *et al.*, 2021). Diet-related diseases such as obesity and overweight can be directly attributed to population's poor eating habits with an overdependence on nutritionally imbalanced processed foods and substandard intakes of important nutrients such as dietary fibre and micronutrients (Monteiro *et al.*, 2018).

Global obesity rates have almost trebled over the last thirty years (WHO, 2021). Global statistics reveal that over 615 million adults were obese in 2016 representing 13% of the population and 1.9 billion adults were overweight representing 39% of the adult population (WHO, 2021). The World Health Organisation (WHO) definition of obesity is a “Body Mass Index (BMI) greater than or equal to 30” and “overweight is a BMI greater than or equal to 25” (WHO, 2021). Obesity and overweight are largely preventable and can be controlled through a healthy diet and physical activity.

Ireland ranks as having one of the highest levels of obesity in Europe (Overweight and Obesity, Eurostat 2019). The latest statistics from Eurostat reveal that 26% of Irish adults in 2019 were obese with a further 56% of Irish adults classified as overweight (Overweight and Obesity, Eurostat 2019). According to the report, only Malta has a higher proportion of its population classified as obese (28%) with the EU average rate of obesity being 16% (Overweight and Obesity, Eurostat 2019). Rates of overweight were also high as illustrated in Figure 1.1 showing that the EU average of overweight was 53% in the EU, with Ireland having an overweight rate above the EU average of 54%. Results from the most recent Healthy Ireland Survey revealed that just over a third of adults (35%) are currently trying to lose weight (Healthy Ireland, 2021). Covid-19 has also impacted Ireland’s populations weight with 29% of respondents reporting they have gained weight since the start of the pandemic restrictions (Healthy Ireland, 2021).

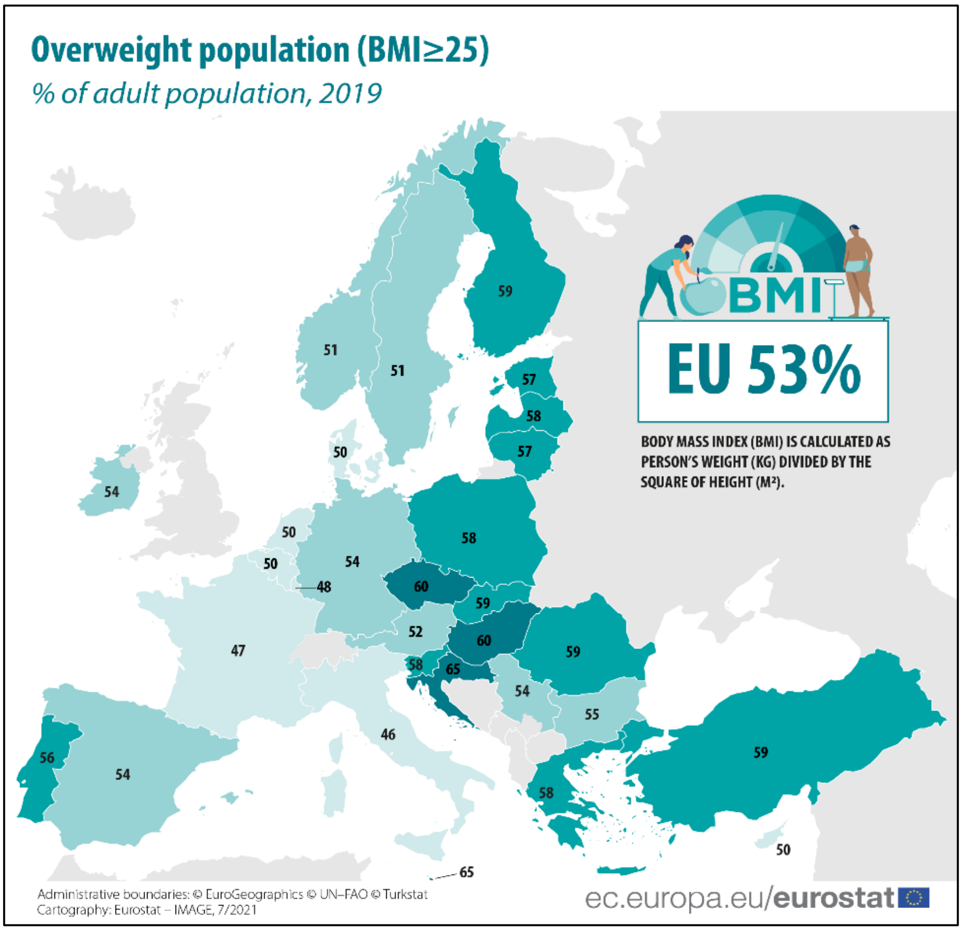
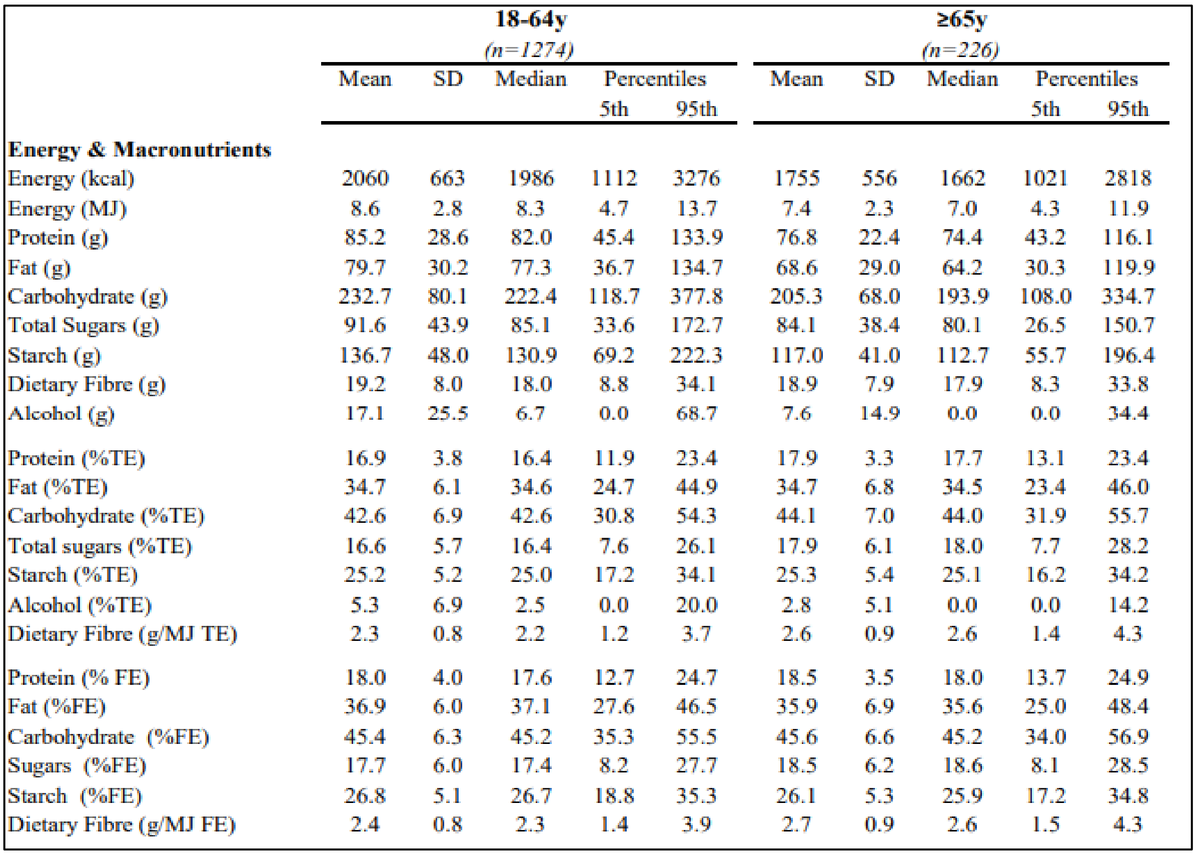


Figure 1.1. Map of overweight population (BMI ≥ 25) in the European Union, 2019 (taken from Overweight and Obesity, Eurostat 2019).

1.3 Nutrient Intakes in Ireland

The National Adult Nutrition Survey (NANS) (2008 – 2010) is the most current nationally representative dietary survey of adults 18 – 90 years for the Irish population (IUNA, 2008). The survey was underataken by the Irish Universities Nutrition Alliance (IUNA) and completed between 2008 and 2010 with a total of 1500 adults aged 18 to 90 years (740 men and 760 women) participated in the study (IUNA, 2008). Mean and median daily intakes of energy and macronutrients including dietary fibre are presented in Table 1.1 for Irish adults (aged 18-64 years and greater than 65 years) by age group.

Table 1.1 shows the mean intake for fat as 34.7% and a mean intake of 16.6% for total sugars for the Irish adult population 18 - 64 years at the time of the survey. Mean total fat intake was the same for the age group over 65 years with a higher mean recorded for the total sugars intake (17.9%). Among 18 to 64 year olds, the mean dietary fibre intake as shown in Table 1.2 was 19.2 grams with men having a higher intake of dietary fibre (21.1g) versus women (17.3g). Dietary fibre intakes for adults aged 65 years and over were comparable (18.9g).



	18-64y *(n=1274)*					≥65y *(n=226)*				
	Mean	SD	Median	Percentiles		Mean	SD	Median	Percentiles	
				5th	95th				5th	95th
Energy & Macronutrients										
Energy (kcal)	2060	663	1986	1112	3276	1755	556	1662	1021	2818
Energy (MJ)	8.6	2.8	8.3	4.7	13.7	7.4	2.3	7.0	4.3	11.9
Protein (g)	85.2	28.6	82.0	45.4	133.9	76.8	22.4	74.4	43.2	116.1
Fat (g)	79.7	30.2	77.3	36.7	134.7	68.6	29.0	64.2	30.3	119.9
Carbohydrate (g)	232.7	80.1	222.4	118.7	377.8	205.3	68.0	193.9	108.0	334.7
Total Sugars (g)	91.6	43.9	85.1	33.6	172.7	84.1	38.4	80.1	26.5	150.7
Starch (g)	136.7	48.0	130.9	69.2	222.3	117.0	41.0	112.7	55.7	196.4
Dietary Fibre (g)	19.2	8.0	18.0	8.8	34.1	18.9	7.9	17.9	8.3	33.8
Alcohol (g)	17.1	25.5	6.7	0.0	68.7	7.6	14.9	0.0	0.0	34.4
Protein (%TE)	16.9	3.8	16.4	11.9	23.4	17.9	3.3	17.7	13.1	23.4
Fat (%TE)	34.7	6.1	34.6	24.7	44.9	34.7	6.8	34.5	23.4	46.0
Carbohydrate (%TE)	42.6	6.9	42.6	30.8	54.3	44.1	7.0	44.0	31.9	55.7
Total sugars (%TE)	16.6	5.7	16.4	7.6	26.1	17.9	6.1	18.0	7.7	28.2
Starch (%TE)	25.2	5.2	25.0	17.2	34.1	25.3	5.4	25.1	16.2	34.2
Alcohol (%TE)	5.3	6.9	2.5	0.0	20.0	2.8	5.1	0.0	0.0	14.2
Dietary Fibre (g/MJ TE)	2.3	0.8	2.2	1.2	3.7	2.6	0.9	2.6	1.4	4.3
Protein (% FE)	18.0	4.0	17.6	12.7	24.7	18.5	3.5	18.0	13.7	24.9
Fat (%FE)	36.9	6.0	37.1	27.6	46.5	35.9	6.9	35.6	25.0	48.4
Carbohydrate (%FE)	45.4	6.3	45.2	35.3	55.5	45.6	6.6	45.2	34.0	56.9
Sugars (%FE)	17.7	6.0	17.4	8.2	27.7	18.5	6.2	18.6	8.1	28.5
Starch (%FE)	26.8	5.1	26.7	18.8	35.3	26.1	5.3	25.9	17.2	34.8
Dietary Fibre (g/MJ FE)	2.4	0.8	2.3	1.4	3.9	2.7	0.9	2.6	1.5	4.3

Table 1.1. Mean, standard deviation, median and percentile values (5^{th} and 95^{th}) of daily energy and macronutrient consumptions for the entire Irish population (18 – 64 years & ≥ 65 years) (TE = Total Energy, FE = Food Energy) (taken from (IUNA, 2008).

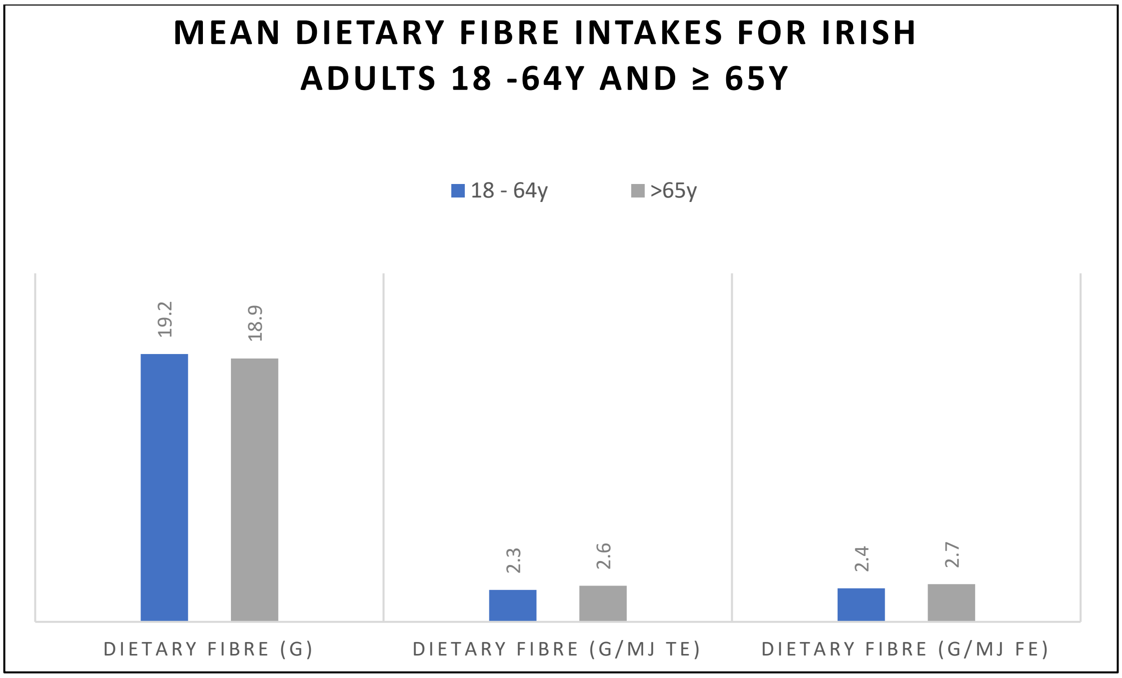


Figure 1.2. Mean dietary fibre intakes (g, g/MJ TE & g/MJ FE) by age group (TE = Total Energy, FE = Food Energy) (adapted from data within (IUNA, 2008).

Chapter 2: Literature Review on Food Reformulation as a Public Health Strategy

2.1 Food Reformulation: Definition and Rationale

In the framework of food processing, food reformulation denotes to modifying the chemical or nutrient composition of processed foods for any purpose i.e., to improve the taste or texture or extend the product shelf life (Kaldor, 2018). In the context of this thesis and diet-related diseases, food reformulation refers to altering the composition of processed foods to improve the nutrient profile and make the product healthier (Kaldor, 2018). Product reformulation aims to lower the 'unhealthy' nutrients of products at the time of production e.g., saturated fat, trans fats, sugar, salt and maintain the same product qualities as the standard product before reformulation i.e., flavour, texture and shelf-life (van Raaij, Hendriksen and Verhagen, 2008). Adopting this approach does not rely on significant behavioural changes by the consumer, it is an upward stream action to improve the populations' diets without affecting their normal shopping behaviours. Therefore, the goal of food reformulation is an improvement in the nutrient intake at the population level while simultaneously protecting the population against diet related NCDs.

Traditionally food reformulation policies have focused predominantly on the reduction in sodium or trans-fatty acids (TFA) in foods however in recent years attention has turned to address added sugar, saturated fat, and energy reduction. There have also been some initiatives launched to improve the nutrient profile of processed foods through the focus on addition rather than removal by boosting the whole-grain, fibre, or specific fats such as omega-3 content. Such initiatives include the Action on Fibre pledge intraradical by the UK Food & Drink Federation (FDF) which sees a number of actions its members have committed to bridging the gap between fibre intakes and the recommended fibre intakes (Action on Fibre, 2021). Participating members in the initiative include Cereal Partners Worldwide UK, Quorn, Kellogg's, Innocent and Nestle (Action on Fibre, 2021).

In Ireland's Roadmap for Food Product Reformulation food reformulation is defined as "changing the nutrient content of a processed food product to either reduce the content of negative nutrients such as sodium, saturated fat, trans fat or energy (kilojoules) or to increase the content of beneficial nutrients such as dietary fibre, wholegrains, fruit, vegetables and unsaturated fats" (Department of Health, 2021). In this way, reformulation aims to improve nutrient intakes at a population level in a meaningful way by improving the overall nutrient profile of foods. Reformulation is typically focused on removing or reducing sugar and energy density however reformulation can also involve improving food to add nutrients associated with NCD prevention i.e., dietary fibre, whole grains, vitamins, and minerals (van Raaij, Hendriksen and Verhagen, 2008).

Changes in the food composition can be slight and not detectable to the consumer and in this approach consumers are not obliged to alter their eating behaviors but nonetheless benefit from a healthier diet (Kaldor, 2018). A study assessing the effects of silent reformulation on retailer's own-brand products to decrease the energy content found that for seven out of the eight reformulated products the reformulation resulted in a reduction in calorie sales (Jensen and Sommer, 2017). Adopting this reformulation method would enhance dietary intake without altering food selection which could lead to potential health improvements and a decline in the obesity and other NCD rates (Gressier *et al.*, 2021). This delivers some evidence to support food manufacturer's efforts in enacting slight silent changes to contribute to improving the diets at a high level (Gressier *et al.*, 2021).

The entire nutrient profile of a food is becoming progressively recognized rather than focusing on isolated nutrients, however, this poses difficulty for reformulation strategies which typically focus on enhancing or modifying a single nutrient and reformulation plans need to be wary of the wider picture in terms of overall nutrient composition (Buttriss, 2020a). It is recognized that it is difficult for consumers to understand and follow healthy eating guidelines therefore reformulation of products already available on the marketplace, to improve their nutrient composition, is an important role in making positive steps to improve the health of the target populations. This applies particularly to processed foods where the nutrient reduction or improvement is not advertised through a nutrition claim on the food label or packaging (Buttriss, 2020a).

Food and drink companies in Ireland, the United Kingdom (UK) and the European Union (EU) have focused their efforts on improving the overall nutrient composition of their foods as part of their strategic objective to offer healthier food products to their customers. Companies are focused on reducing the sugar, fat and salt nutrients while maintaining quality attributes and consumer acceptability.

2.2 Impact of Diet & Nutrition on Disease

If urgent meaningful action isn't taken to control the prevalence of obesity, obesity is predicted to grow globally (Pineda *et al.*, 2018). A study conducted by Pineda *et al.*, 2018 found that obesity is projected to increase in 44 countries globally by 2025 and if present obesity rates continue, 33 of the 53 countries are expected to have an obesity incidence of 20% or higher. For countries with high-quality data including Ireland, Ireland was projected to have the highest obesity rates, with 43% (95% CI 28-58%) of the population expected to fall into the obese category by 2025 as presented in Table 2.1 (Pineda *et al.*, 2018). The prevalence of obesity is also projected to increase to >30% in several countries including England and Scotland. These statistics are worrying and show a predicted increase in obesity rates across Europe by 2025.

Country	Prevalence of obesity % by 2025 (95% CI)
Ireland	43 (28; 58)
England	34 (28; 40)
Estonia	34 (24; 44)
Finland	20 (11; 29)
France	24 (21; 27)
Germany	19 (16; 22)
Greece	40 (35; 45)
Italy	13 (10; 16)
Lithuania	24 (10; 38)
Netherlands	14 (10; 18)
Russian Federation	29 (24; 34)
Scotland	37 (21; 43)
Sweden	17 (12; 22)
Wales	28 (20; 36)

Table 2.1. Predicted prevalence of obesity (BMI ≥30 kg/m²) by 2025 for countries with high-level data scores in the WHO European Region (adapted from Pineda *et al.*, 2018).

Findings by the Global Burden of Disease Study aiming to measure the effect of suboptimal diet on NCD mortality and morbidity, the burden of disease attributable by specific dietary factors was significant (Afshin *et al.*, 2019). In 2017, 11 million deaths and 255 million disability-adjusted life-years (DALYs) were associated with dietary risk factors (Afshin *et al.*, 2019). High-sodium diets, low intakes of wholegrain in the diet and low intakes of fruits were found to be the three leading dietary risk factors for mortality rate and DALYs worldwide and across countries accounting for over 50% of mortality rates and 66% of DALYs caused by diet (Afshin *et al.*, 2019). The results provide a complete depiction of the health impact of poor eating habits at a population level. This study effectively measured the probable impact of suboptimal nutrient intake on NCD mortality and morbidity, reinforcing the necessity for improving the quality of population diets.

In an ecological cross-sectional study, Monteiro *et al.*, 2018 found a significant positive association between the accessibility of ultra-processed foods and nationwide incidence of obesity in the adult age group. As presented in the below Figure 2.1 the prevalence of obesity for Ireland during the survey year 1999 was measured to be 18%. As previously outlined in the study by Pineda et al., 2018 this is set to increase to 43% by 2025 indicating an increase of 25% over a period of 26 years.

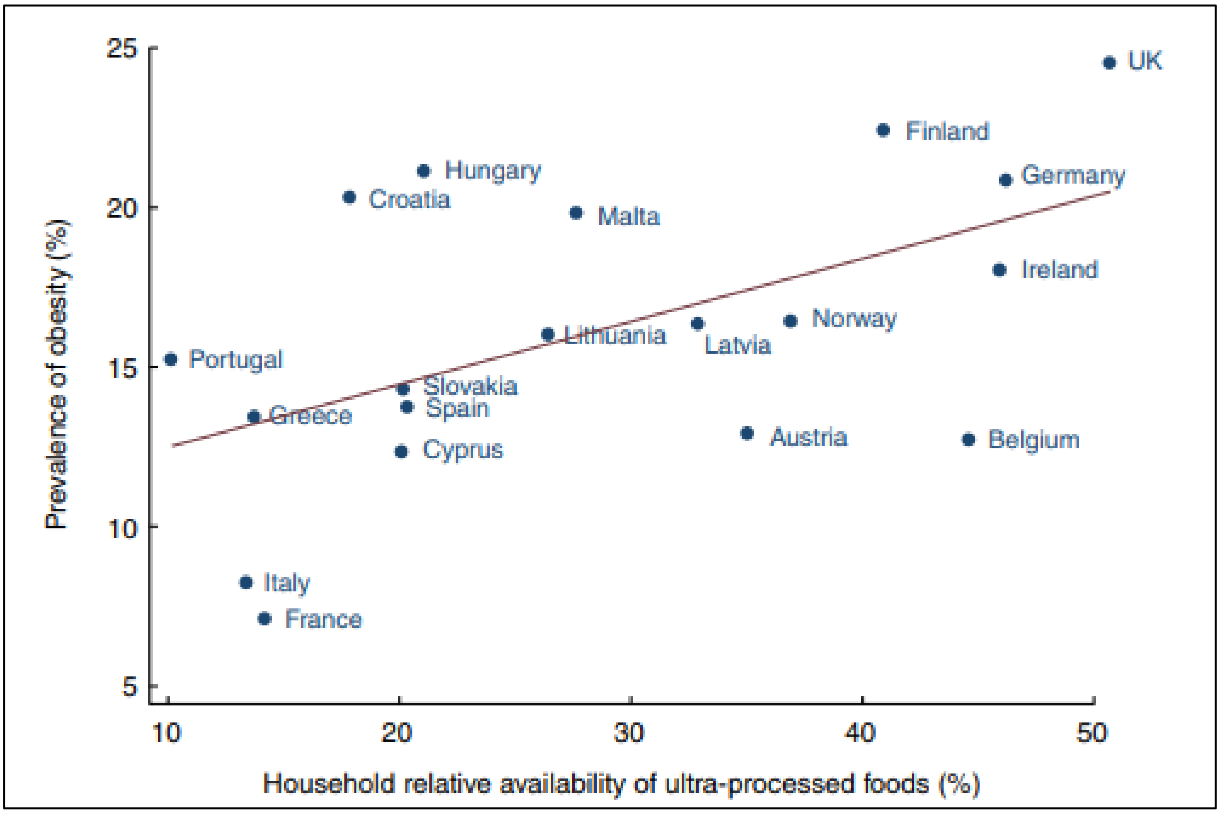


Figure 2.1. Regression of prevalence of obesity (%) among adults versus household availability of ultra-processed foods (% of total energy) in 19 European countries (1991 – 2008) (taken from Monteiro *et al.*, 2018).

2.3 Current EU & UK Food & Drink Reformulation Programs

Almost every European country has at least one strategy for diet and health, and these often include recommendations for reductions in nutrients salt, fat, and sugar in foods through improving the nutrient composition of foods (Belc *et al.*, 2019). These reformulation strategies are independently developed by each EU country and are developed based on voluntary agreements between the food industry and the regulatory authorities within that country (Belc *et al.*, 2019). Ireland has aligned its food and drink reformulation targets with the Public Health England (PHE) framework constructed on the large volume of indigenous food manufacturers supplying to the UK markets whom are already working towards accomplishing PHE targets (Department of Health, 2021).

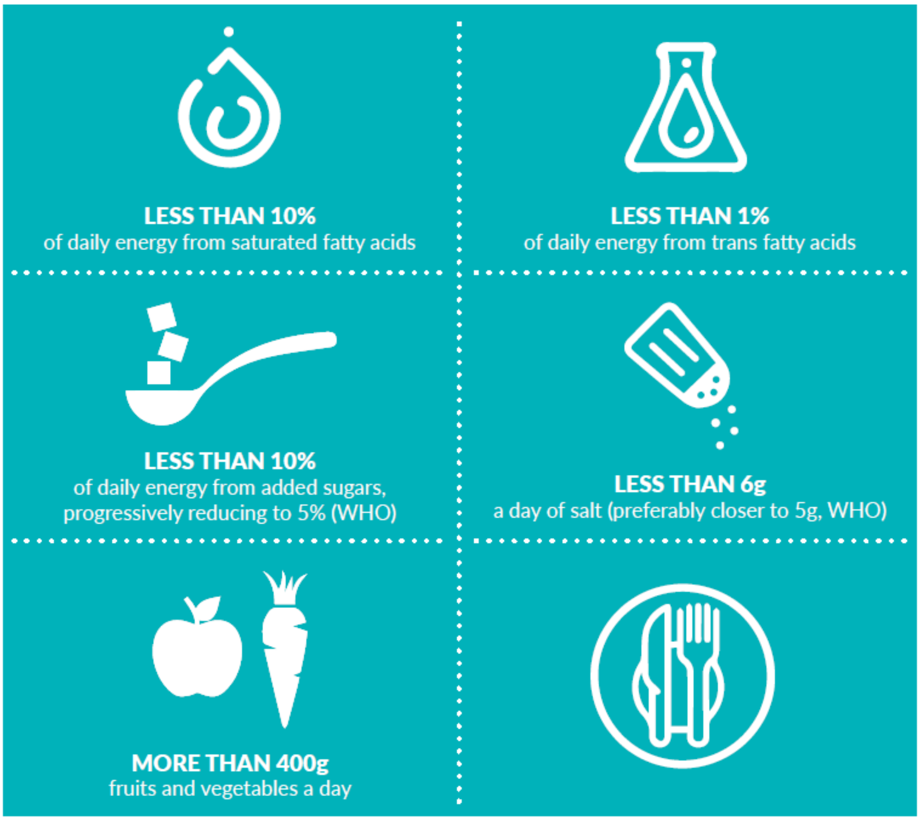
The increasing rate of obesity incited the EU Commissions High Level Group on Nutrition and Physical Activity (HLG) to formulate the framework for national initiatives on nominated nutrients in 2011 (McMenemy, Kelly and Sweeney, 2020). The aim of the framework is to contribute toward accomplishing population intake of nutrients salt, sugar, and fats in line with WHO recommendations (Belc *et al.*, 2019). The initial target nutrient was focused on salt reduction with member countries agreeing to reformulate products to reduce populations intake of salt to no more than 5 grams intake daily. Work on the salt reduction goal began in 2011 to reduce salt in food by 16% over a four-year time span. This was followed up with a saturated fat target to reduce the population saturated fat intake by at least 5% by 2016 and a further 5% reduction by 2020. In 2015, an additional target was introduced in which an added sugars annex encouraging a voluntary reduction of 10% in added sugars in processed food by 2020 (Department of Health, 2021).

2.3.1 Public Health England Reduction and Reformulation Program

PHE have set out a food reformulation program focusing on salt, sugar, saturated fat, and calories. Initial salt reduction targets were set in 2014 as part of the Food Standards Agency (FSA) salt reduction programme and these were revised in September 2020 with a target date of 2024 by PHE who are now leading the salt reduction programme as part of their sugar reduction and wider reformulation programme (PHE, 2020). Their sugar reduction programme is focused on children's intake of sugar with a target set of a 20% reduction in the proportion of sugar in the selected food categories by 2020 (PHE, 2020). Nine food groups have been selected that contribute the greatest to children's sugar intakes which are also part of Ireland's reformulation targets as outlined in Table 2.3 (PHE, 2020).

2.3.2 The Roadmap for Food Product Reformulation in Ireland

In 2016 Ireland recognized the EU Roadmap for Action on Food Product Improvement and food reformulation was given priority status by the Obesity Policy Implementation Oversight Group (OPIOG) in 2017 (Public Health England, 2020). In December 2021, the Department of Health Ireland launched Ireland's Roadmap for Food Product Reformulation in Ireland as part of the OPIOG. This Roadmap provides a much needed framework for Ireland's food industry and set targets for voluntary food reformulation in Ireland for 2015 – 2025 (Department of Health, 2021). Current nutritional targets for the Irish population are summarised in Table 2.2 showing the maximum levels of nutrients that should be consumed by the Irish population.



LESS THAN 10%
of daily energy from saturated fatty acids

LESS THAN 1%
of daily energy from trans fatty acids

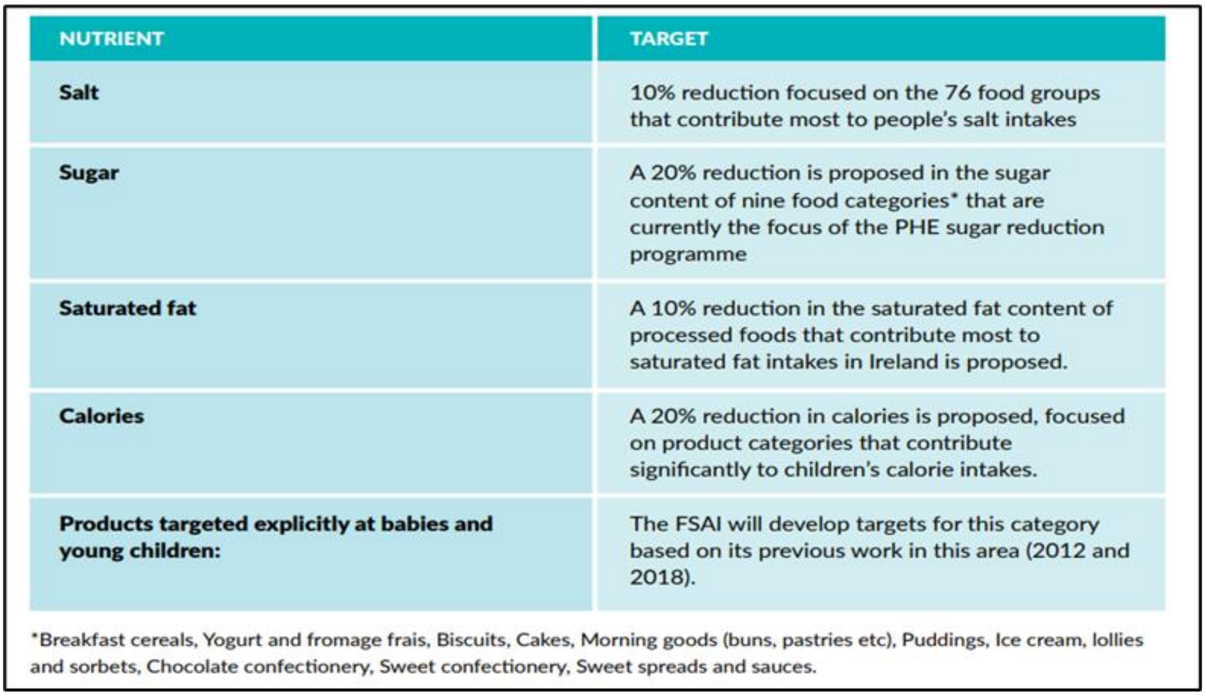
LESS THAN 10%
of daily energy from added sugars, progressively reducing to 5% (WHO)

LESS THAN 6g
a day of salt (preferably closer to 5g, WHO)

MORE THAN 400g
fruits and vegetables a day

Table 2.2. Current Nutritional Targets for the Irish Population aged ≥ 5 years (taken from (Department of Health, 2021).

The reformulation targets outlined are carefully aligned to those in place in the EU and UK where reformulation polices are also in place and where many food companies share the same market with Ireland. This aligns well as Irish food manufacturers operating and producing in Ireland and selling to both the Irish and UK markets are already working towards achieiving England's PHE reformulation targets (Department of Health, 2021). As part of the Roadmap specific reformulation targets have been outlined focusing on lowering levels of nutrients salt, sugar, saturated fat and calorie which are presented in Table 2.3.



NUTRIENT	TARGET
Salt	10% reduction focused on the 76 food groups that contribute most to people's salt intakes
Sugar	A 20% reduction is proposed in the sugar content of nine food categories* that are currently the focus of the PHE sugar reduction programme
Saturated fat	A 10% reduction in the saturated fat content of processed foods that contribute most to saturated fat intakes in Ireland is proposed.
Calories	A 20% reduction in calories is proposed, focused on product categories that contribute significantly to children's calorie intakes.
Products targeted explicitly at babies and young children:	The FSAI will develop targets for this category based on its previous work in this area (2012 and 2018).

*Breakfast cereals, Yogurt and fromage frais, Biscuits, Cakes, Morning goods (buns, pastries etc), Puddings, Ice cream, lollies and sorbets, Chocolate confectionery, Sweet confectionery, Sweet spreads and sauces.

Table 2.3. The Roadmap for Food Product Reformulation in Ireland: Food and Drink Reformulation Targets for Ireland 2015 - 2025 (taken from Department of Health, 2021).

2.4. Effectiveness of Food Reformulation on Diet and Health

When considering food formulation as a measure to improve the overall nutrient composition of the food it is crucial to investigate and validate the effectiveness of food reformulation in improving individuals nutrient intake. Successful food reformulation strategies will enhance populations nutrient intakes by changing the composition of the food without changing consumers eating patterns (Federici *et al.*, 2019). The overall nutritional profile of foods and the diet is an important factor rather than targeting single nutrients in isolation e.g. sodium, sugar, saturated fat.

There have been situations in the past where failure to recognise the overall aim has been costly and detrimental to individuals health (Buttriss, 2020b). For example reformulating food to reduce the sugar content can actually elicit an increase in fat within a product and, by association, energy density which is the opposite desired outcome for food reformulation strategies. Furthermore in the search to replace satutrated fats from animal sources in the diet, attention has switched to coconut oil in recent years as a healthy fat (Buttriss, 2020a). Although coconut oil contains heart healthy polyunsaturated and monunsaturated fatty acids, it still has a remarkably high saturated fatty acid profile and should therefore be used sparingly in the diet.

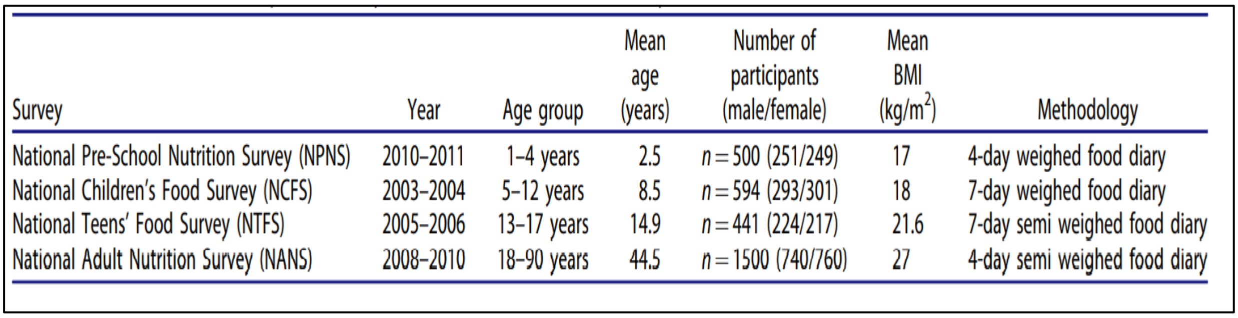
A broader and multi-nutrient targeted approach to reformulation would provide complete improvement of foods nutritional profile and prevent some counterproductive compromises between reduced and alternative nutrients e.g. production of low-fat yoghurt whereby the fat is replaced with sugar resulting in a high sugar content (Maillot, Privet and Masset, 2020).

A review of the literature shows there is limited evidence of the influence of reformulation on both nutrient intakes and health. Reformulation has a large scope with numerous considerations such as voluntary or mandatory food reformulation programs, the range of products targeted for reformulation, the type of nutrients formulated and the timeline for implementation. It is very difficult to carry out clinical trials to measure the impact of reformulation on population health, and most published studies use mathematical models to forecast how reformulation will impact on nutrient intakes and health status (Federici *et al.*, 2019).

A systematic review of modeling studies studying the effect of food reformulation on nutrient intakes and health was carried out between 2000 and 2017 (Federici *et al.*, 2019). A total of 33 studies were included in the review with 20, 5 and 3 studies focusing on sodium, sugar and fat reformulation respectively, and 5 studies targeting multiple nutrients. The outcomes for the study were changes in individual nutrient intakes of targeted nutrients, effects on health outcomes including obesity, type 2 diabetes, cardiovascular disease (CVD), and changes in health related quality of life measures, i.e. Quality Adjusted Life Years (QALYs) and Disability Adjusted Life Years (DALYs) (Federici *et al.*, 2019).

Individual sodium intake reductions were reported in the range 0.009 to 1.82g/day and this was dependent on the number of nutrients reformulated, the range of targeted foods and scenario assessed. In general there was an element of consistency observed across the studies, with higher levels of sodium reformulation resulting in higher reductions in sodium intake and this was more notable for reformulation studies focusing on all processed foods compared to a narrower scope of products (Federici *et al.*, 2019). Reformulation studies to reduce sugar intakes targeted Sugar Sweetened Beverages (SSBs) and other types of foods including pizza, breakfast cereals etc. to all types of ultra processed foods. Reductions in calorie intake for SSBs were steady across studies and relative to the level of sugar reformulated. Briggs et al., 2017 estimated that a reduction in the sugar content of SSBs by 5% and 23% would lower calorie intake by approximately 4 kcal and 23 kcal per day respectively. Similarly when studying the impact of sugar reformulation on selected high sugar foods, Yeung et al., 2017 projected a decrease in energy intake ranging between 11 to 27 kcal per day.

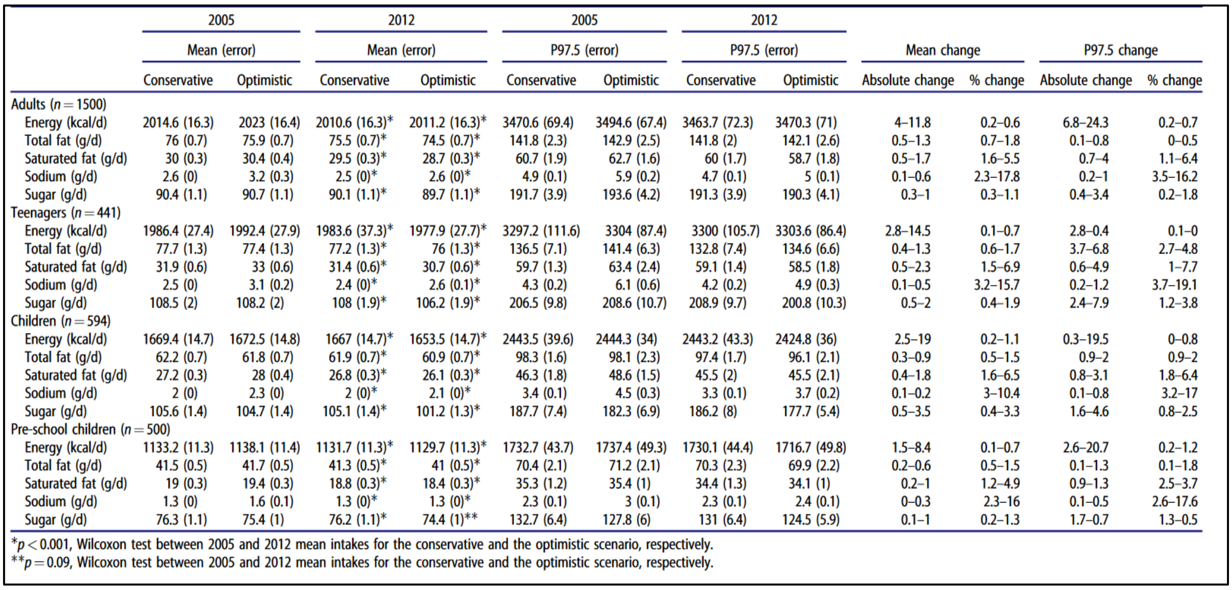
Pigat et al., 2018 explored the quantitative impact that voluntary reformulation strategies by the food industry in Ireland have had on Irish consumers nutrient intake. This was measured using a probabilistic intake model to assess the changes in nutritional intakes using data from national food consumption surveys with nuritent data and market share data (Pigat *et al.*, 2018). Food consumption data was taken from four national surveys undertaken by IUNA as listed in Table 2.4. These national food consumption surveys are representative of the demographic of Ireland for the given year and age cateogory at the time of the rollout of the survey.



Survey	Year	Age group	Mean age (years)	Number of participants (male/female)	Mean BMI (kg/m^2)	Methodology
National Pre-School Nutrition Survey (NPNS)	2010–2011	1–4 years	2.5	$n = 500$ (251/249)	17	4-day weighed food diary
National Children's Food Survey (NCFS)	2003–2004	5–12 years	8.5	$n = 594$ (293/301)	18	7-day weighed food diary
National Teens' Food Survey (NTFS)	2005–2006	13–17 years	14.9	$n = 441$ (224/217)	21.6	7-day semi weighed food diary
National Adult Nutrition Survey (NANS)	2008–2010	18–90 years	44.5	$n = 1500$ (740/760)	27	4-day semi weighed food diary

Table 2.4. Details of Irish Food Compostion Surveys by IUNA (www.iuna.net) used for Pigat *et al.*, 2018 study (taken from Pigat *et al.*, 2018).

The results from this study showed statistically significant differences in both mean and P 97.5 intakes between 2005 and 2012 for the majority of population and nutrient combinations. The results as shown in Table 2.5 revealed that most Irish consumers consumed at least one of the reformulated products. A possible mean daily energy intake reduction of up to 12 kcal/d for adults was observed in the optimistic scenario which represents up to 0.6% reduction for the % change in intake. The mean total daily fat intakes encompassing both conservative and optimistic scenarios saw a reduced intake of 0.5 - 1.3g/d in the adult age group. Sugar consumption among frequent consumers (P97.5) decreased by 0.4-3.4 g/d for adults ($p < 0.001$) and 0.3-1 g/d for normal adult consumers ($p < 0.001$). For specifically reformulated foods sugar intake was also reduced with a mean change of 0.3 - 1 g/d for normal adults consumers and 1.7 - 4.5 g/d for high consumers of sugar.



	2005		2012		2005		2012					
	Mean (error)		Mean (error)		P97.5 (error)		P97.5 (error)		Mean change		P97.5 change	
	Conservative	Optimistic	Conservative	Optimistic	Conservative	Optimistic	Conservative	Optimistic	Absolute change	% change	Absolute change	% change
Adults ($n = 1500$)												
Energy (kcal/d)	2014.6 (16.3)	2023 (16.4)	2010.6 (16.3)*	2011.2 (16.3)*	3470.6 (69.4)	3494.6 (67.4)	3463.7 (72.3)	3470.3 (71)	4–11.8	0.2–0.6	6.8–24.3	0.2–0.7
Total fat (g/d)	76 (0.7)	75.9 (0.7)	75.5 (0.7)*	74.5 (0.7)*	141.8 (2.3)	142.9 (2.5)	141.8 (2)	142.1 (2.6)	0.5–1.3	0.7–1.8	0.1–0.8	0–0.5
Saturated fat (g/d)	30 (0.3)	30.4 (0.4)	29.5 (0.3)*	28.7 (0.3)*	60.7 (1.9)	62.7 (1.6)	60 (1.7)	58.7 (1.8)	0.5–1.7	1.6–5.5	0.7–4	1.1–6.4
Sodium (g/d)	2.6 (0)	3.2 (0.3)	2.5 (0)*	2.6 (0)*	4.9 (0.1)	5.9 (0.2)	4.7 (0.1)	5 (0.1)	0.1–0.6	2.3–17.8	0.2–1	3.5–16.2
Sugar (g/d)	90.4 (1.1)	90.7 (1.1)	90.1 (1.1)*	89.7 (1.1)*	191.7 (3.9)	193.6 (4.2)	191.3 (3.9)	190.3 (4.1)	0.3–1	0.3–1.1	0.4–3.4	0.2–1.8
Teenagers ($n = 441$)												
Energy (kcal/d)	1986.4 (27.4)	1992.4 (27.9)	1983.6 (37.3)*	1977.9 (27.7)*	3297.2 (111.6)	3304 (87.4)	3300 (105.7)	3303.6 (86.4)	2.8–14.5	0.1–0.7	2.8–0.4	0.1–0
Total fat (g/d)	77.7 (1.3)	77.4 (1.3)	77.2 (1.3)*	76 (1.3)*	136.5 (7.1)	141.4 (6.3)	132.8 (7.4)	134.6 (6.6)	0.4–1.3	0.6–1.7	3.7–6.8	2.7–4.8
Saturated fat (g/d)	31.9 (0.6)	33 (0.6)	31.4 (0.6)*	30.7 (0.6)*	59.7 (1.3)	63.4 (2.4)	59.1 (1.4)	58.5 (1.8)	0.5–2.3	1.5–6.9	0.6–4.9	1–7.7
Sodium (g/d)	2.5 (0)	3.1 (0.2)	2.4 (0)*	2.6 (0.1)*	4.3 (0.2)	6.1 (0.6)	4.2 (0.2)	4.9 (0.3)	0.1–0.5	3.2–15.7	0.2–1.2	3.7–19.1
Sugar (g/d)	108.5 (2)	108.2 (2)	108 (1.9)*	106.2 (1.9)*	206.5 (9.8)	208.6 (10.7)	208.9 (9.7)	200.8 (10.3)	0.5–2	0.4–1.9	2.4–7.9	1.2–3.8
Children ($n = 594$)												
Energy (kcal/d)	1669.4 (14.7)	1672.5 (14.8)	1667 (14.7)*	1653.5 (14.7)*	2443.5 (39.6)	2444.3 (34)	2443.2 (43.3)	2424.8 (36)	2.5–19	0.2–1.1	0.3–19.5	0–0.8
Total fat (g/d)	62.2 (0.7)	61.8 (0.7)	61.9 (0.7)*	60.9 (0.7)*	98.3 (1.6)	98.1 (2.3)	97.4 (1.7)	96.1 (2.1)	0.3–0.9	0.5–1.5	0.9–2	0.9–2
Saturated fat (g/d)	27.2 (0.3)	28 (0.4)	26.8 (0.3)*	26.1 (0.3)*	46.3 (1.8)	48.6 (1.5)	45.5 (2)	45.5 (2.1)	0.4–1.8	1.6–6.5	0.8–3.1	1.8–6.4
Sodium (g/d)	2 (0)	2.3 (0)	2 (0)*	2.1 (0)*	3.4 (0.1)	4.5 (0.3)	3.3 (0.1)	3.7 (0.2)	0.1–0.2	3–10.4	0.1–0.8	3.2–17
Sugar (g/d)	105.6 (1.4)	104.7 (1.4)	105.1 (1.4)*	101.2 (1.3)*	187.7 (7.4)	182.3 (6.9)	186.2 (8)	177.7 (5.4)	0.5–3.5	0.4–3.3	1.6–4.6	0.8–2.5
Pre-school children ($n = 500$)												
Energy (kcal/d)	1133.2 (11.3)	1138.1 (11.4)	1131.7 (11.3)*	1129.7 (11.3)*	1732.7 (43.7)	1737.4 (49.3)	1730.1 (44.4)	1716.7 (49.8)	1.5–8.4	0.1–0.7	2.6–20.7	0.2–1.2
Total fat (g/d)	41.5 (0.5)	41.7 (0.5)	41.3 (0.5)*	41 (0.5)*	70.4 (2.1)	71.2 (2.1)	70.3 (2.3)	69.9 (2.2)	0.2–0.6	0.5–1.5	0.1–1.3	0.1–1.8
Saturated fat (g/d)	19 (0.3)	19.4 (0.3)	18.8 (0.3)*	18.4 (0.3)*	35.3 (1.2)	35.4 (1)	34.4 (1.3)	34.1 (1)	0.2–1	1.2–4.9	0.9–1.3	2.5–3.7
Sodium (g/d)	1.3 (0)	1.6 (0.1)	1.3 (0)*	1.3 (0)*	2.3 (0.1)	3 (0.1)	2.3 (0.1)	2.4 (0.1)	0–0.3	2.3–16	0.1–0.5	2.6–17.6
Sugar (g/d)	76.3 (1.1)	75.4 (1)	76.2 (1.1)*	74.4 (1)**	132.7 (6.4)	127.8 (6)	131 (6.4)	124.5 (5.9)	0.1–1	0.2–1.3	1.7–0.7	1.3–0.5

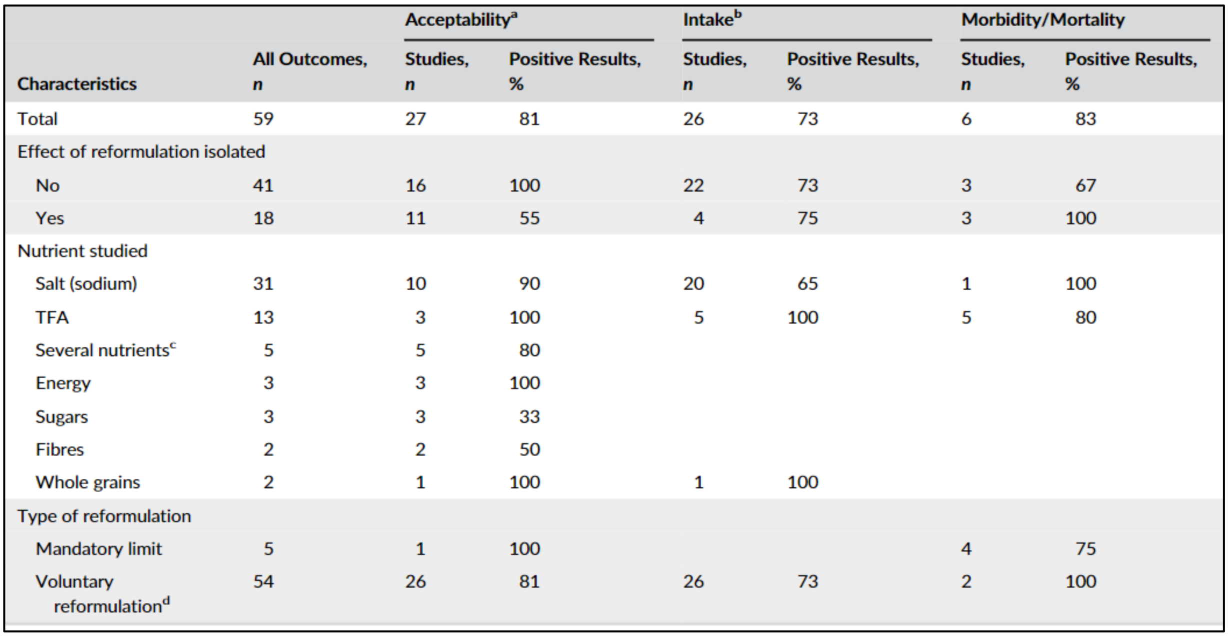
*$p < 0.001$, Wilcoxon test between 2005 and 2012 mean intakes for the conservative and the optimistic scenario, respectively.
**$p = 0.09$, Wilcoxon test between 2005 and 2012 mean intakes for the conservative and the optimistic scenario, respectively.

Table 2.5. Effect of voluntary reformulation measures on mean and P97.5 (conservative to optimistic scenario) on total nutrient daily consumption of energy, total fat, saturated fat, sodium and sugar in different cohorts of age groups, including absolute and percentage change as a range of conservative to optimistic situations (taken from Pigat *et al.*, 2018).

This study revealed almost all statistically significant results showing the positive impact of voluntary food reformulation measures undertaken by Irish manufacturers on Irish consumers nutrient intakes. The success of food reformulation initiatives such as the salt reduction program undertaken by the Food Safety Authority of Ireland (FSAI) was seen with a 45% decrease in mean daily sodium intakes from reformulation programs highlighting the effectiveness of food reformulation strategies (Gressier et al., 2021). However this study did acknowledge the limitations especially concerning the different surveys used and therefore differences in survey methodology and assessment years. This study did also not assess the impact food reformulation has on fibre intake which is important in the context of an overall balanced nutrient intake. Similar studies in Europe have included fibre when assessing the impact of food reformulation on nutrient intakes however it is difficult to directly compare and apply these modelling studies to the Irish population when fibre intakes differ significantly across regions. For overall nutrient profile improvement it is benefical to improve the fibre content of foods however a baseline is needed to understand the impact of food reformulation in the context of added fibre on nutrient intakes following reformulation with added fibre.

In a systematic review by Gressier et al., 2021 on the power of reformulation on food choice on different outcomes the findings revealed that reformulated foods were acceptable by the consumer and consumed by the population ensuing in better-quality nutrient intakes for the consumers who consumed these reformulated products. 26 studies included in the review examined the effect of reformulated foods on TFA and salt intakes and 70% of the studies resolved that reformulation actions improved the intake of the target nutrient (Table 2.6). Studies that assessed clinical outcomes also showed enhanced nutrient intakes at 77%. The degree of nutrient improvement varied significantly for the target reformulation nutrients with outcomes of 80% to near 100% reduction of TFA achieved in reformulated products versus substantially lower decreases for energy density (0.4% - 3%) and sugar (2% - 3%) (Gressier *et al.*, 2021).

These studies resolved there was an improvement in nutrient intakes due to reformulation processes confirming that reformulation strategies can lead to a positive result in improving population diets. Six studies exploring the trial impact of reformulation on health status i.e., morbidity and mortality exhibited an improvement in health status for five studies however these concentrated on the effect of the elimination of trans fatty acids which created a model situation for a quantifiable result on health status (Table 2.6) (Gressier *et al.*, 2021). Results on health status were not assessed for other target nutrients i.e., fat, sugar, and salt therefore it is hard to determine the overall quantifiable influence on health status on the reformulation of these nutrients (Gressier *et al.*, 2021).

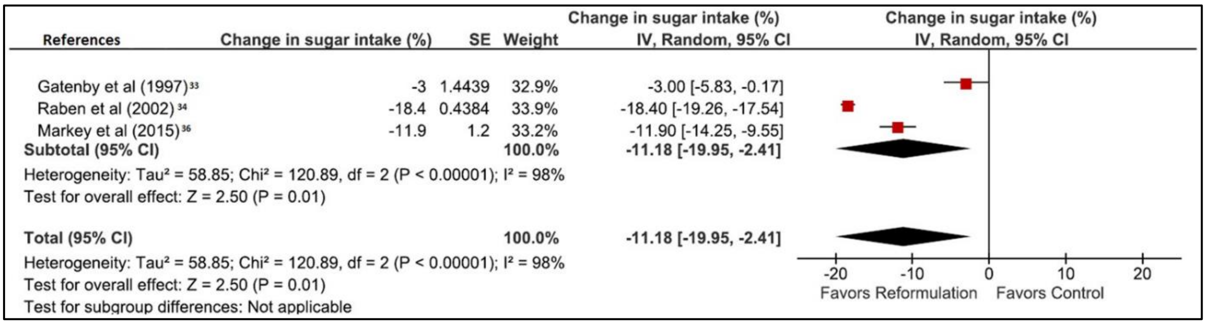


		Acceptability[a]		Intake[b]		Morbidity/Mortality	
Characteristics	All Outcomes, *n*	Studies, *n*	Positive Results, %	Studies, *n*	Positive Results, %	Studies, *n*	Positive Results, %
Total	59	27	81	26	73	6	83
Effect of reformulation isolated							
No	41	16	100	22	73	3	67
Yes	18	11	55	4	75	3	100
Nutrient studied							
Salt (sodium)	31	10	90	20	65	1	100
TFA	13	3	100	5	100	5	80
Several nutrients[c]	5	5	80				
Energy	3	3	100				
Sugars	3	3	33				
Fibres	2	2	50				
Whole grains	2	1	100	1	100		
Type of reformulation							
Mandatory limit	5	1	100			4	75
Voluntary reformulation[d]	54	26	81	26	73	2	100

Table 2.6. Amount of studies and proportion showing positive results for acceptability of reformulated products, daily intakes and morbidity or mortality reduction resulting from the employment of a reformulation strategy (taken from Gressier *et al.*, 2021)

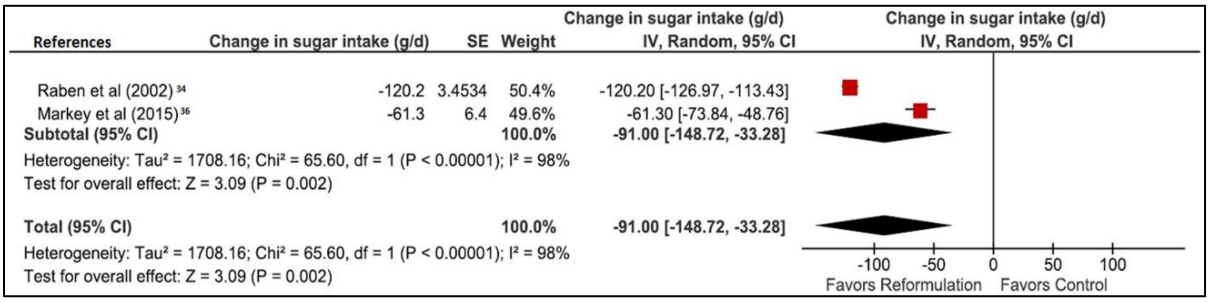
The effect of product reformulation methods on sugar intake and health consequences has been extensively assessed considering high sugar consumption is one of the key nutrients of concern in relation to rising rates of overweight and obesity. Analysis from randomized controlled trials (RCT) showed a lower intakes of sugar and improved BMI following sugar reformulation however the meta-analysis recognizes there was considerable heterogeneity between the RCTs and a number of factors may have been reported for in the results (Hashem, He and MacGregor, 2019).

The variations in the outcomes: sugar intake (g), sugar intake (g/d) and body weight (kg) in the RCTs included are presented in figures 2.2 – 2.4. The projected overall decrease reported were −11.18% in percentage of sugar intake, −91.0g in daily sugar consumption, and −1.04 kg in body weight (Hashem, He and MacGregor, 2019). These findings are significant and highlight the positive effects that food reformulation measures can have on different nutrient intakes and body weight.



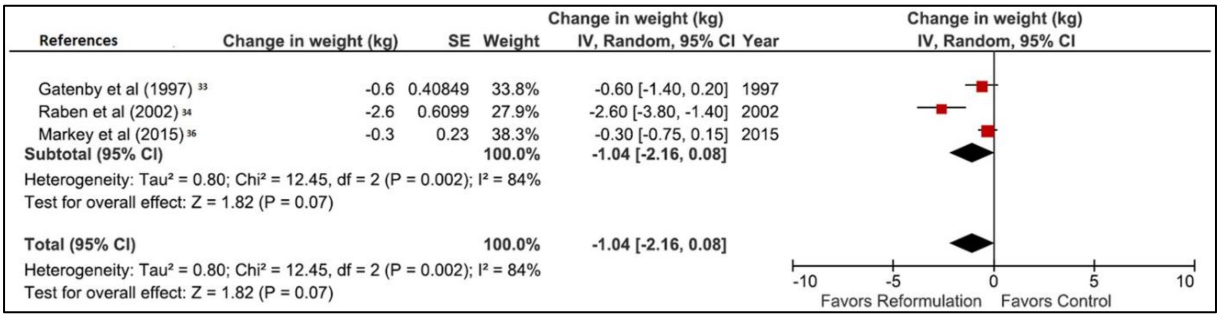
References	Change in sugar intake (%)	SE	Weight	Change in sugar intake (%) IV, Random, 95% CI
Gatenby et al (1997)[33]	-3	1.4439	32.9%	-3.00 [-5.83, -0.17]
Raben et al (2002)[34]	-18.4	0.4384	33.9%	-18.40 [-19.26, -17.54]
Markey et al (2015)[36]	-11.9	1.2	33.2%	-11.90 [-14.25, -9.55]
Subtotal (95% CI)			**100.0%**	**-11.18 [-19.95, -2.41]**
Heterogeneity: Tau² = 58.85; Chi² = 120.89, df = 2 (P < 0.00001); I² = 98%				
Test for overall effect: Z = 2.50 (P = 0.01)				
Total (95% CI)			**100.0%**	**-11.18 [-19.95, -2.41]**
Heterogeneity: Tau² = 58.85; Chi² = 120.89, df = 2 (P < 0.00001); I² = 98%				
Test for overall effect: Z = 2.50 (P = 0.01)				
Test for subgroup differences: Not applicable				

Figure 2.2. Change in sugar intake percentage (%) (taken from Hashem, He and MacGregor, 2019).



References	Change in sugar intake (g/d)	SE	Weight	Change in sugar intake (g/d) IV, Random, 95% CI
Raben et al (2002)[34]	-120.2	3.4534	50.4%	-120.20 [-126.97, -113.43]
Markey et al (2015)[36]	-61.3	6.4	49.6%	-61.30 [-73.84, -48.76]
Subtotal (95% CI)			**100.0%**	**-91.00 [-148.72, -33.28]**
Heterogeneity: Tau² = 1708.16; Chi² = 65.60, df = 1 (P < 0.00001); I² = 98%				
Test for overall effect: Z = 3.09 (P = 0.002)				
Total (95% CI)			**100.0%**	**-91.00 [-148.72, -33.28]**
Heterogeneity: Tau² = 1708.16; Chi² = 65.60, df = 1 (P < 0.00001); I² = 98%				
Test for overall effect: Z = 3.09 (P = 0.002)				

Figure 2.3. Change in sugar intake (g/d) (taken from Hashem, He and MacGregor, 2019).



References	Change in weight (kg)	SE	Weight	Change in weight (kg) IV, Random, 95% CI	Year
Gatenby et al (1997)[33]	-0.6	0.40849	33.8%	-0.60 [-1.40, 0.20]	1997
Raben et al (2002)[34]	-2.6	0.6099	27.9%	-2.60 [-3.80, -1.40]	2002
Markey et al (2015)[36]	-0.3	0.23	38.3%	-0.30 [-0.75, 0.15]	2015
Subtotal (95% CI)			**100.0%**	**-1.04 [-2.16, 0.08]**	
Heterogeneity: Tau² = 0.80; Chi² = 12.45, df = 2 (P = 0.002); I² = 84%					
Test for overall effect: Z = 1.82 (P = 0.07)					
Total (95% CI)			**100.0%**	**-1.04 [-2.16, 0.08]**	
Heterogeneity: Tau² = 0.80; Chi² = 12.45, df = 2 (P = 0.002); I² = 84%					
Test for overall effect: Z = 1.82 (P = 0.07)					

Figure 2.4. Change in weight (kg) (taken from Hashem, He and MacGregor, 2019).

2.5 Silent Reformulation Approach

A logic model was designed by Gressier, Sassi and Frost, 2020 using available studies on the impact of food reformulation on the food environment, consumer behaviour and nutrient consumptions. This model as presented in Figure 2.5 demonstrates the process flow in which food reformulation influences human health beginning with altering the food environment to generate healthier food choices for individuals (Gressier, Sassi and Frost, 2020). Depending on whether the reformulated product is made public or not to the consumer the effect of the reformulation can have a different outcome. When a reformulated food product replaces the orginal product and the reformulated food is marketed as a new product i.e. 30% reduced sugar the consumer may choose to ignore the new product resulting in no benefit in impoved nutrient intake. However when a healthier reformulated product substitutes an original product and the changes are not marketed to the consumer, consumers do not have to make a choice and the nutritionally improved reformulated food becomes the default product for consumers. In this way unnanounced reformulation leads to a healthier diet for the population and reduced burden of dietary related diseases.

Silent food reformulation is an alternative food reformulation approach by making the changes ‘silent’ i.e. not declaring the reformulation openly to consumers except by updating the nutrition information on product labels to reflect the change in the nutrient profile of the food (Jensen and Sommer, 2017). While the improvement in the nutrient profile may not be publicly acknowledged, by reformulating in this manner it has the potential to positively impact consumer’s diets without forcing consumers to make a decision on choosing the healthier product or not. This approach avoids marketing stratgies targeting health concious consumers where the general population would not benefit from the improvement in nutrient profile.

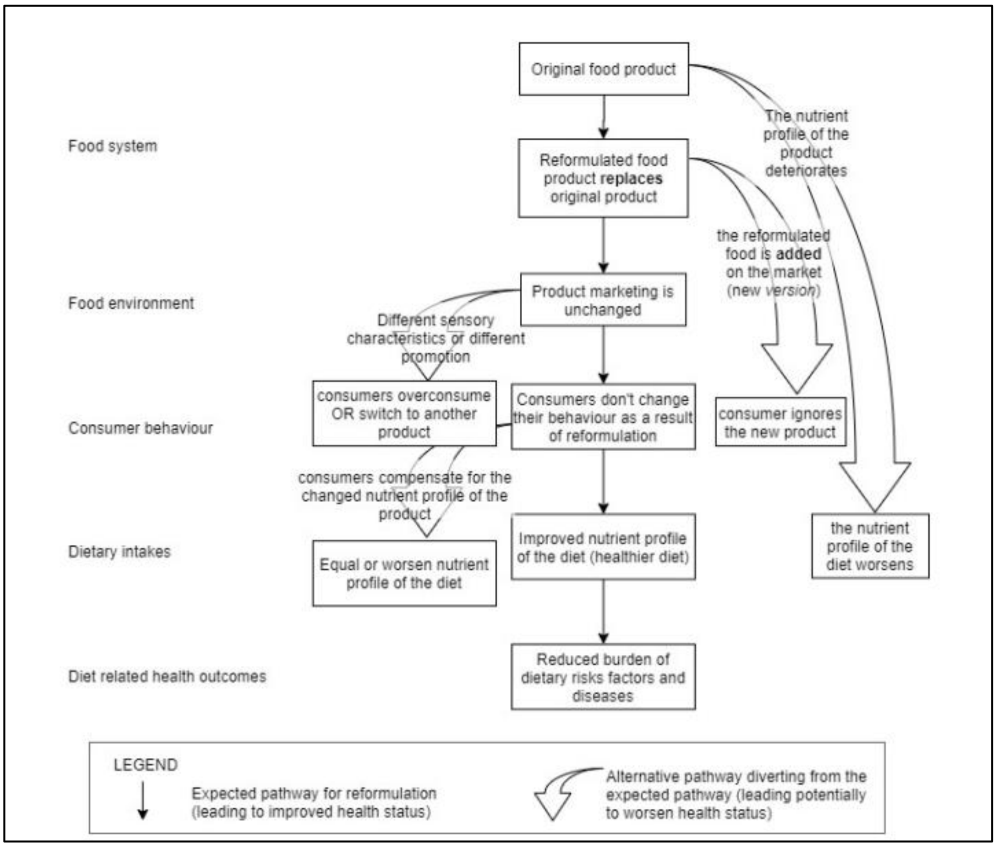


Figure 2.5. Logic model of the impact of reformulating existing food products, and diversion routes from the expected health benefits (taken from Gressier, Sassi and Frost, 2020).

2.6 Dietary Fibre

The inclusion of dietary fibre to processed foods through the process of food reformulation has the possibility to positively impact the nutritional composition of foods.

2.6.1 Role of Dietary Fibre in the Diet

Dietary fibre is well established as an important nutrient in the diet for its role in nutrition and health. There is an abundance of research on the health benefits of dietary fibre in the diet including an association between a normal BMI and overall metabolic health, a healthy microbiome and lowered risk of CVD and mortality (Barber *et al.*, 2020). However, one of the most recognised functions of dietary fibre is its role in regulating the composition of the gut microbiota (Cronin *et al.*, 2021). A diet rich in dietary fibre is necessary to positively influence the composition and diversity of the microbiome by providing beneficial substrates for gut microbiota to feed on (Cronin *et al.*, 2021). Individuals with suboptimal intakes of dietary fibre in the diet have a lower level of microbial ecology in the gut microbiome (Makki *et al.*, 2018). The different types of dietary fibre are summarised in Figure 2.6.

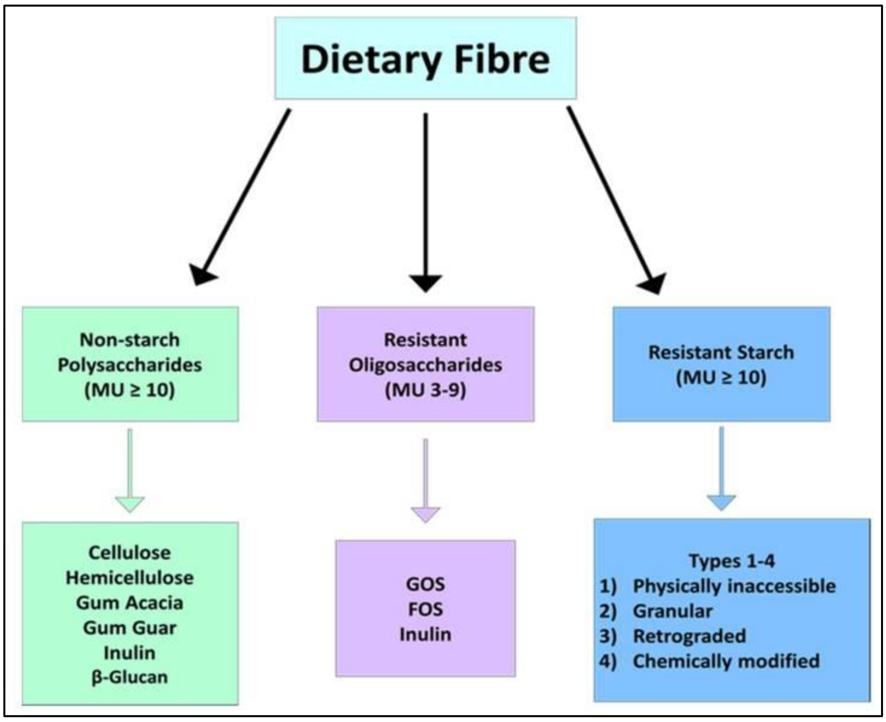


Figure 2.6. Schematic diagram presenting the different types of fibre broken down into the types of fibre by the number of monomeric units and names. Abbreviations: ME: monomeric unit, GOS: galacto-oligosaccharide and FOS: fructo-oligosaccharide (taken from Cronin *et al.*, 2021).

2.6.2 Dietary Fibre Intakes & Food Groups

The widely used terminology and concept of processed foods and ultra-processed foods has created concern and confusion about the influence of food processing techniques on nutritional profile of foods. Whole grains and cereal products cannot be consumed without some level of processing which can lead to a reduction in the level of dietary fibre in these processed cereal products. A review conducted by Stephen *et al.*, 2017 shows that recommended dietary intake for total fibre intake in Ireland is 25 – 30g which aligns closely with the recommended intake in the EU (>25g daily) and the UK. As previously outlined, the most up to date statistics on dietary fibre intakes in Ireland recorded a mean dietary fibre intakes of 19.2g (18-64y) and 18.9g (≥65y) (IUNA, 2008).

This data shows that most Irish diets lack the recommended intakes of dietary fibre, therefore reformulating staple foods through the incorporation of fibre should be considered as an opportunity to add fibre to processed foods and deliver an increase in dietary fibre intake among the Irish population. Reformulation of processed foods using dietary fibre ingredients can be a meaningful way to achieve improved nutrient intakes. Results of dietary fibre intakes from food groups from the NANS as seen in Figure 2.7 show that 'meat', 'bread', 'potatoes' and 'milk and yoghurt' are contribute the most to energy intake, accounting for 45% of total energy consumption in adults aged 18-64 years and 49% in those aged 65-90 years ('The National Adult Nutrition Survey (NANS) (2008-2010).

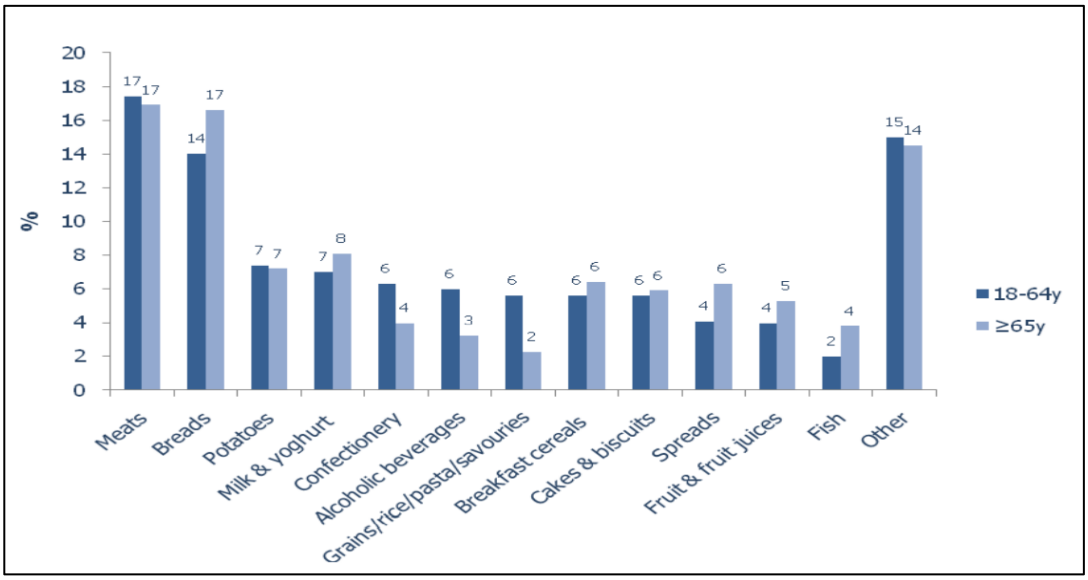


Figure 2.7. Percent contribution of food groups to energy intake for age groups 18-64y and 65 years and over (taken from ('The National Adult Nutrition Survey (NANS) (2008-2010).

The greatest contributors to fibre intakes in the Irish adults aged 18 – 64 years were breads (26%), vegetables (17%), potatoes (13%), fruit & fruit juices (10%) and breakfast cereals (9%). Similar foods contributed the highest dietary fibre intake for adults aged 65 years and over. To achieve improved dietary fibre intakes at population level the contribution of dietary fibre in food groups that contribute most to dietary intakes must be increased. One meaningful way to increase fibre consumption is through its integration in staple foods such as bread and bread products, breakfast cereals, cakes and biscuits etc. as these foods contribute both energy intake and dietary fibre intake for adults 18 - 64 years and 65 years and over.

2.6.3 Inulin as a Dietary Fibre Ingredient

Inulin and fructans are a type of non-starch water-soluble polysaccharide and are found naturally in chicory root, Jerusalem artichoke, onion, cereal grains and other food sources (Stephen *et al.*, 2017). Inulin can also be synthetically produced from sucrose. Inulin is added to processed foods to replace fat and sugar nutrients and it provides only 25 to 35% energy compared to digestible carbohydrates, with a sweetness level of approximately 10% comparable to sucrose (Shoaib *et al.*, 2016). The addition of inulin to processed foods is advantageous in many ways contributing both nutritional and functional benefits. The dietary and health benefits to humans are illustrated in Figure 2.8.

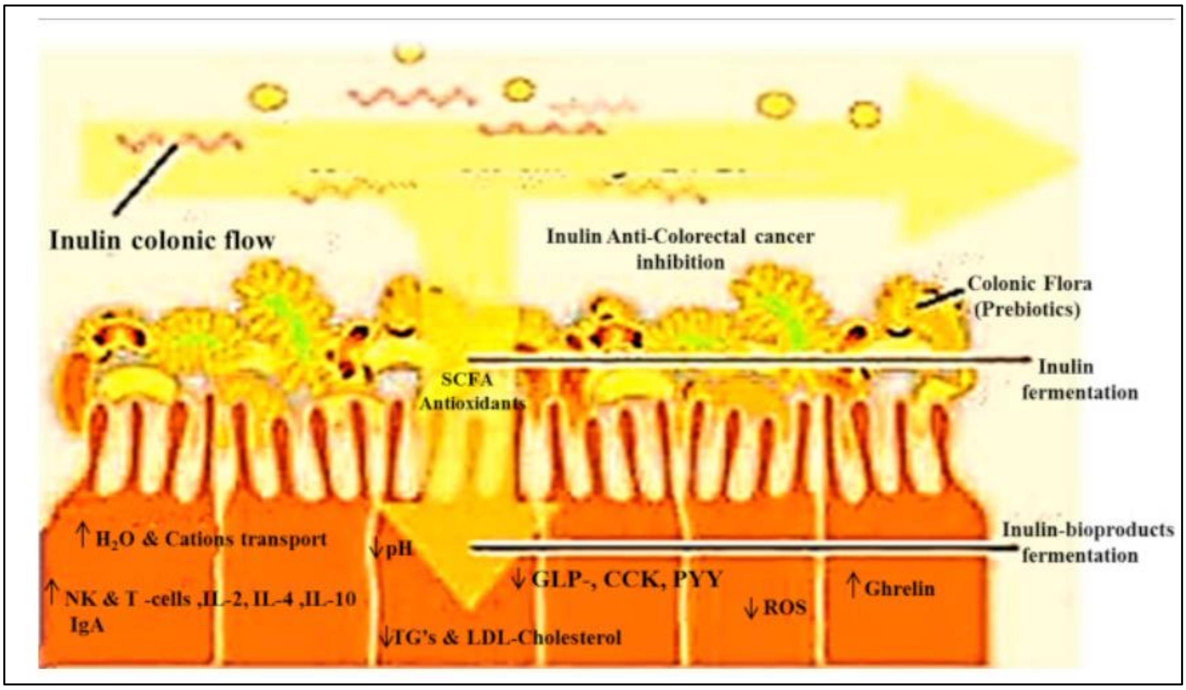


Figure 2.8. Overview of inulin fermentation, absorption in colon and its function in human body (taken from Shoaib *et al.*, 2016).

Inulin-type fructans (inulin and oligofructose) are dietary fibres which are fermentable and are constructed of fructosyl units linked via β(21) glycosidic bonds (Lightowler *et al.*, 2018). Inulin-type fructans are resistant to digestion in the small intestine due to the β-configuration of the anomeric C2 in the fructose monomers (Lightowler *et al.*, 2018). Inulin and oligofructose are classified as 'non-digestible carbohydrates' that do not raise the glycaemic index (GI) following ingestion. In this way, inulin and oligofructose can be used to replace carbohydrates that increase the GI in processed foods and beverages and lower the postprandial blood glucose response (Lightowler *et al.*, 2018).

Inulin is a storage carbohydrate in plants and is resistant to digestion in the small intestine due to its arrangement however it is digested in the large intestine (Shoaib *et al.*, 2016). Inulin is an important part of the dietary fibre structure and is labelled as dietary fibre on processed foods. In-vitro and in-vivo studies investigating the calorific value of dietary fibre ingredients such as inulin and oligofructose have reported the energy value of inulin and oligofructose to be 1.5 kcal/g (Shoaib *et al.*, 2016)

2.6.4. Food Applications of Inulin

A literature review conducted by Shoaib *et al.*, 2016 investigated the various food applications for the use of inulin in different food categories. The review focused on 16 different studies and reviews to show the different food uses of inulin. The review found that inulin has usage in 12 different food categories with the most consumed food categories shown in Table 2.7. Many of the food applications were staple food items including bakery products, breakfast cereals, dairy products, meat products etc. Most of the studies suggest a concentration level in the range of 2 – 10% to have the desired outcome in the food category such as replacing sugar and fat, contributing to texture and mouthfeel, and functioning as a prebiotic and fibre enrichment.

Applications	Function	Concentration level (%w/w)	Studies
Bakery	Prebiotic & fibre Preservation of moisture Sugar replacer	2 - 15	Nieto-Nieto *et al.*, 2015, Rodríguez-García, Sahi and Hernando, 2014
Breakfast cereals	Fibre & prebiotic Crispness & volume increase	2 - 25	Foschia *et al.*, 2013
Dairy products	Fat & sugar replacer Synergy with sweetness Texture & mouthfeel Foam stabilisation Fibre & prebiotic	2 - 10	Meyer *et al.*, 2011
Frozen desserts	Fat & sugar replacer Texture improver Melting behaviour Fibre & prebiotic Lower energy density	2 - 10	Krasaekoopt and Watcharapoka, 2014
Chocolate	Sugar & fat replacer Fibre Heat resistance (melting behaviour)	5 - 30	Aidoo, Afoakwa and Dewettinck, 2015

Table 2.7. Summary of study findings, showing the food applications, functions and concentration level (%w/w) of inulin (adapted from Shoaib *et al.*, 2016).

Studies available on the influence of inulin incorporation showed a positive influence on the quality of extruded snacks by increasing the cereal expansion and contributing a favourable crisp texture. The use of inulin as a fat and sugar replacer was observed in several food categories showing that inulin has potential benefits in the context of food reformulation to improve the nutrient profile of existing food products on the market. Among the reviews, Foschia *et al.*, 2013 reported positive effects regarding dietary fibre enrichment on the quality of extruded snacks such as breakfast cereals.

2.6.5 Technological Challenges of Reformulating Breakfast Cereals with Inulin

The production of high fibre Ready to Eat (RTE) breakfast cereals is a challenge for food manufacturers as the incorporation of dietary fibre ingredients into breakfast cereal formulations presents technological issues that must be overcome. The addition of dietary fibre in extruded cereals can lead to negative effects on the quality of the cereal including lowered expansion volume, higher hardness and density and a reduction in crispness (Robin, Schuchmann and Palzer, 2012). These are all product quality attributes that are integral to the eating quality of breakfast cereals and consumer acceptance.

However, the expansion properties of extruded cereals will differ depending on the type of fibre used as soluble fibres such as inulin deliver a higher expansion and more improved texture compared to insoluble fibres such as cereal bran fibre (Robin, Schuchmann and Palzer, 2012). The expansion process will be affected in different ways by soluble fibres and insoluble fibres and the fibre characteristics will also be affected during the extrusion process (Robin, Schuchmann and Palzer, 2012). Extrusion cooking of breakfast cereals involves heating to a high temperature and shear process that can result in a loss of added dietary fibre to the formulation following the extrusion process. Therefore, it is integral to evaluate the retention of dietary fibre in the finished product to determine if the addition of inulin and oligofructose can have a beneficial impact on the nutritional composition of breakfast cereals.

2.7 Thesis Outline

A review of the literature has shown that food reformulation can be an effective strategy to improve the nutrient intakes and health status of populations by reducing levels of sodium, sugar and fat in processed foods and subsequently decrease intakes of the reformulated nutrients. The silent reformulation approach has been viewed as beneficial to improving nutrient intakes by not infleuncing consumers purchasing behaviours. The literature has also shown that dietary fibre has many health promoting characteristics but despite this knowledge, fibre intakes among the general population fall well below recommendations as outlined previously in the NANS. Studies have shown that specific food groups can be enriched or reformulated with dietary fibre to replace sugar and/or fat levels in processed foods. In this way fibre can impart a dual effect by reducing another non-nutritive nutrient such as sugar and improving the dietary fibre content of foods.

In this respect dietary fibre is becoming increasingly more studied as a food ingredient to improve the nutrient composition of processed foods on the market and in the development of new foods including staple and functional foods. This provides a meaningful way to boost fibre intakes but also as a functional replacement for another nutrient such as fat or sugar.

Chapter 3: Methods

3.1 Methods – Study Design

This section provides a framework for the methods used to establish how dietary fibre ingredients can be used to positively influence the nutrient profile of foods and support food reformulation strategies. The research method used has been a blend of desk-based study of peer reviewed published scientific journals and data attained from government and non-governmental organisation sources. A primary research method has also been utilised to collect label data from food retailer websites and in store food labels to show the impact that reformulation with dietary fibre can have on improving the nutrient profile of commercially available products.

3.1.1 Thesis Outline of Research

Several research studies have demonstrated that dietary fibre can play an important role in reducing the fat and/or sugar content of foods. Therefore, the research question, presented in this thesis is, can reformulation using dietary fibre ingredients be a successful food reformulation strategy to help achieve a superior nutritional composition whilst helping to maintain the technical and sensory characteristics of the reformulated product. The thesis question will also look at opportunities to reformulate available breakfast cereals on the marketplace and assess the potential impact of reformulation on nutrient intakes using sales data.

To address the research question, Chapter 1 reviewed the definition and rationale of food reformulation and outlined the impact of poor eating habits and imbalanced nutrient intakes on rising global rates of NCDs, particularly obesity and overweight. Within Chapter 2, the background was given to food reformulation as a public health strategy to improve public health and an overview was also provided of potential to reformulate with dietary fibre ingredients to enhance the overall nutrient profile of processed foods.

Chapter 3 will summarise the methodology and study design, to address the research question, while Chapter 4 will outline the results and findings relative to the role of fibre in reducing the proportion of unhealthy nutrients such as added sugar and fat while also achieving an increase in fibre content for processed foods commonly consumed by the Irish population. Chapter 5 will critically review and discuss the findings, drawing substantiated conclusions on the accuracy of the research question posed. The final chapter, Chapter 6, will synopsise the key findings and future direction.

3.1.2 Scope

The scope of the research question concentrates on the role of dietary fibre in supporting an improved nutrient profile in processed foods and its overall role to achieve successful food reformulation strategies through improving nutrient intakes at population level. The scope will explore the use of fibre ingredients in the commercial reformulation of processed foods. The predominant dietary fibre ingredient being investigated as a potential viable ingredient is inulin. A total of three food groups have been selected, two of which have been selected due to their current relevance within Ireland’s Roadmap for Food Product Reformulation as priority food groups. These are RTE breakfast cereals and ice-cream which falls under the category of desserts. A third food group, baked goods, has also been selected to show that food reformulation incorporating dietary fibre can also be successful in indulgent or non-staple food groups. The reformulation with dietary fibre benefits explored, include physical properties, organoleptic properties, and improved nutrient composition of the reformulated food groups.

3.1.3 Selection of Studies

Studies were considered eligible if they addressed the effect of a dietary fibre ingredient inclusion on the nutritional, textural and/or sensory properties of the new product formulation versus the control formulation. Studies were also considered acceptable if aimed at reducing individual intakes of sugar, saturated fat and improved dietary fibre intake. For studies addressing sugar consumption, all definitions of sugar were used, including added sugars, total sugars, and free sugars. For studies addressing fat reduction, the following definitions were used; total fat, saturated fat, trans fat and lipids. For studies addressing reformulation with fibre the following definitions were accepted: dietary fibre, fibre, inulin, inulin fructans, fructans, oligosaccharides and fructooligosaccharides.

3.1.4 Data Inclusions

Secondary data as part of this thesis was attained from investigational studies. Data for analysis has been attained from recently published journals, typically within the last five years.

Data collected, for the most part, has been attained from recent publication, typically within the last five years. Whereby data has been used predating five years, the data is still current and relevant and has not been replaced with new data.

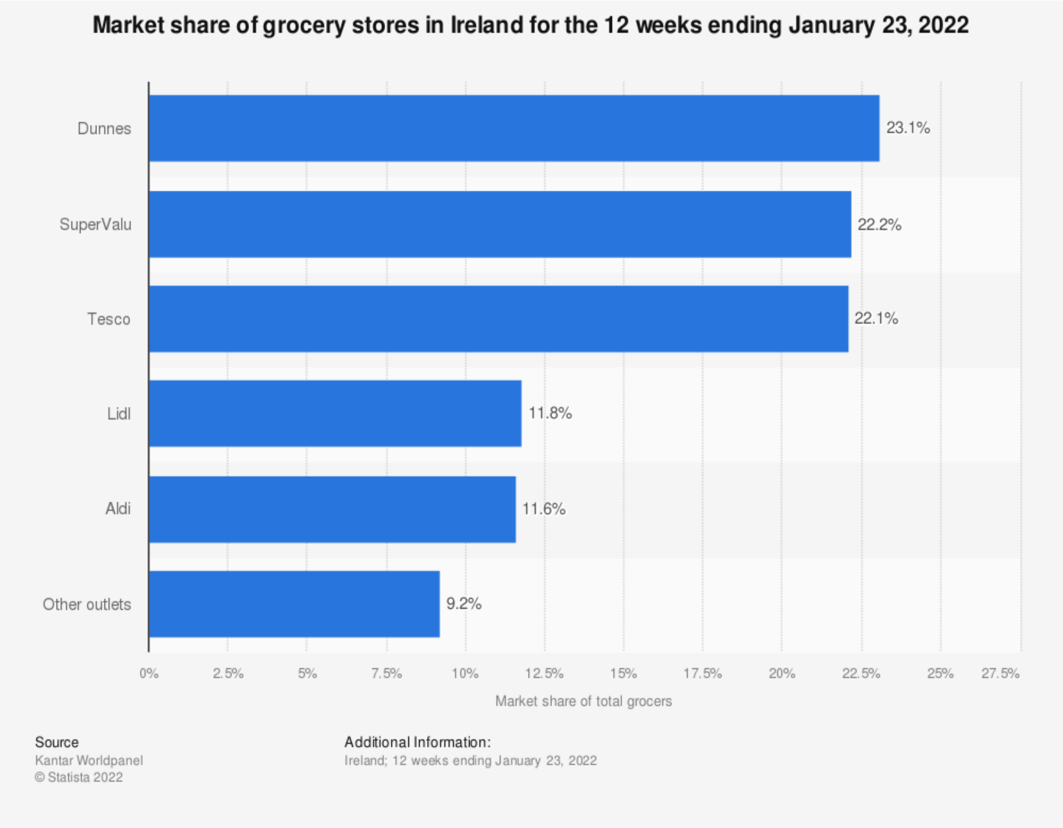
3.1.5 Exclusions

Non-peer reviewed data has been omitted from the study design. Unsupported data has also been omitted from this study.

3.2 Materials

3.2.1 Sample Selection, Categorization and Collection

Nutrition information for RTE breakfast cereals was collected from the Irish market, both from in store and online retailers (n=5) between February to March 2022. Selection of retailers was assessed based on most recent percentage market share available as presented in Figure 3.1. Dunnes Stores were identified to have the largest market share of grocery stores in Ireland in the latest available statistics at 23.1%. Supervalu had the second largest market share (22.2%), followed closely by Tesco with a market share of 22.1%. The main discounters Lidl and Aldi had market shares each of 11.8% and 11.6% respectively. All breakfast cereal products that were available for purchase in the 5 retailers at the time of data collection were included in the study.


Market share of grocery stores in Ireland for the 12 weeks ending January 23, 2022

Source
Kantar Worldpanel
© Statista 2022

Additional Information:
Ireland; 12 weeks ending January 23, 2022

Figure 3.1. Market share of retailers in Ireland for the 12 weeks ending January 23, 2022 (taken from (Statista, 2022).

3.2.2 Products Description and Data Collection

This study includes data regarding 229 RTE breakfast cereals collected from 25 brands (50.2% of the products surveyed were branded products such as Nestlé, Kellogg's, or Flahavans) and the remaining products were own-brand products (49.8%) from retailers Tesco, Dunnes Stores, Supervalu, Aldi, and Lidl. Data was collected over a 3-week period from February to March 2022. The retailers Tesco and Supervalu had online websites with nutrition information available for all products and these websites were used to collect data for branded and own brand breakfast cereal products.

The search was conducted by searching in the 'Breakfast Cereals', 'Gluten Free Breakfast Cereals', 'Wheat Free' and 'Free From' aisles. A search was also conducted using an assortment of keywords associated with this product category (e.g., breakfast cereals, granola, muesli, gluten-free etc.) to ensure all breakfast cereal products available for sale during that time were captured on both retailer websites (Prada *et al.*, 2021). Store visits were undertaken to Dunnes Stores, Lidl and Aldi and product data was collected using a smartphone to take photographs and capture all information on the food packaging including the front of pack, ingredients, nutrition table, nutrition and health claims and retail price. All products located in the 'breakfast cereal' and 'health aisle' for the given period were captured except for Aldi which did not have a designated 'health' aisle.

The following information was collected for each product: product name and brand, ingredients, nutrition information (energy, fat, saturated fat, carbohydrate, sugar, fibre, and salt per 100g), weight or pack size and retail price. Where multiple pack sizes existed for a product variety, the largest pack size was selected as the larger space may permit more claims to be made than a smaller pack size. Products excluded included breakfast biscuits and cereal products that need to be prepared first before serving such as porridge and similar hot cereal products that require cooking. Package quantity for breakfast cereals varied between 275g and 1000g.

3.2.3 Product Categorisation

Following collection of nutrient data, all breakfast cereals were allocated to one of seven categories using a modified categorization system from published research (Croisier *et al.*, 2021) outlined in Table 3.1.

Category	Category Description
Brans	Includes cereal made mainly from wheat bran.
Wheat Biscuits	Includes cereal made from whole wheat shaped into a biscuit, typically eaten with milk.
Flaked/Puffed	Includes cereal made from toasted puffed or popped grains or flakes made from corn, wheat, oats, rice.
Children's Cereal	Includes cereal primarily from the flaked/puffed and wheat biscuits categories targeted at children containing children-orientated design e.g., cartoon characters, cartoonish font/design and/or including 'children' or ‘kids’ on the packaging.
Granola and Clusters	Includes cereal containing 'granola' or 'clusters' in the product name/description, made primarily from rolled oats with added sugars and/or oils baked until crisp and golden brown. May contain additional ingredients nuts, seeds, dried fruit.
Muesli	Includes raw or unbaked cereal containing 'muesli', 'bircher' or 'swiss' in the product name/description, made primarily from rolled oats without added oil. Typically contains added fruit, seeds and nuts.
Health & Wellbeing	Includes cereal with added benefits or nutrition/health claims, includes ‘free from’ products. Products were located in a designated 'health' aisle.

Table 3.1. Classification of Breakfast Cereal Categories (adapted from Croisier *et al.*, 2021).

3.2.3.4 Volume Sales Data for Breakfast Cereals

Volume sales data by breakfast cereal category was sourced from Euromonitor Passport for 2021 and accessed through Technological University Dublin. Volume sales data by brand was not available for any year on Euromonitor Passport as outlined in section 3.4 study limitations.

3.3 Statistical Analysis

Data collected from photographs and retailer websites were recorded into a Microsoft® Excel® spreadsheet (Microsoft 365 MSO Version 16.0.13801.21072 64 bit) for analysis. The data collected on the Microsoft Excel spreadsheet was imported to Minitab Statistical Software (Version 19). Descriptive statistics (e.g., mean, median, standard deviation, minimum and maximum) were used to describe the sample based on the amount of nutrient (total fat, saturated fat, carbohydrate, sugar, fibre, and salt) and energy (kcal) per 100g of product.

Analysis using a paired Mann-Whitney U-test was used to study the differences between inulin (chicory root fibre) containing products and non-inulin products. For all analyses, a $p \leq 0.05$ was considered significant.

3.4 Study Limitations

Volume sales data for the breakfast cereal category by brand was not available on Euromonitor as this data does not exist. The study design of this thesis included assessing the impact of reformulating the breakfast cereal data collected by applying changes in nutrient intakes from studies on breakfast cereals to assess the impact that these changes would have on the reformulated nutrient intake and measure the changes in nutrient intakes using sales weighted volume data by brand.

Chapter 4: Results

Dietary fibre ingredients have the capability to improve the texture and reduce the fat and sugar content of a wide variety of foods while maintaining the technological and sensory attributes. In this chapter the beneficial role of added dietary fibre ingredients to food formulations to improve the nutrient profile and maintain the product characteristics of the different foods will be outlined. The main commercial dietary fibre ingredients studied include inulin and oligofructose across three main food groups: baked goods, ice cream and RTE breakfast cereals.

4.1 Reformulation of Baked Goods

The primary aim of reformulation is to improve the overall nutrient composition of the reformulated food, either by improving a single nutrient in isolation or by improving several key nutrients in the same reformulation process. One of the most widely studied dietary fibre ingredients researched to improve the nutrient profile of different food applications is inulin.

4.1.1 Effect of Inulin on Nutritional Quality of Baked Goods

Several studies have been conducted investigating the impact of inulin incorporation to processed foods as a fat replacer. Emulsion filled gels (EFG) have been proposed to replace fat and/or saturated fat in a range of products including bakery products and fresh sausages (Curti *et al*., 2018, Pintado *et al*., 2018). A diverse range of ingredients such as inulin, chia flour, oat bran, extra virgin olive oil, β-carotene have uses in the formulation of EFG's (Nourbehesht, Shekarchizadeh and Soltanizadeh, 2018) (Pintado *et al.*, 2018).

A study conducted by Paciulli et al., 2020 for a 60 day period, studied the effects of 0, 20, 40 and 50% fat substitution on shortbread cookies produced using an EFG comprising of inulin and extra virgin olive oil. The formulations were prepared using commercially available inulin in the form of Orafti® HPX at a level of 19% w/w to partially replace butter. Results of the fat analysis of the samples as detailed in Figure 4.1 show a significant reduction in the saturated fat content of the cookies. Formulations with 20%, 40% and 50% EFG substitution had saturated fat reductions of 3.1g, 5.4g and 7.8g respectively representing changes of 22%, 38% and 54%.

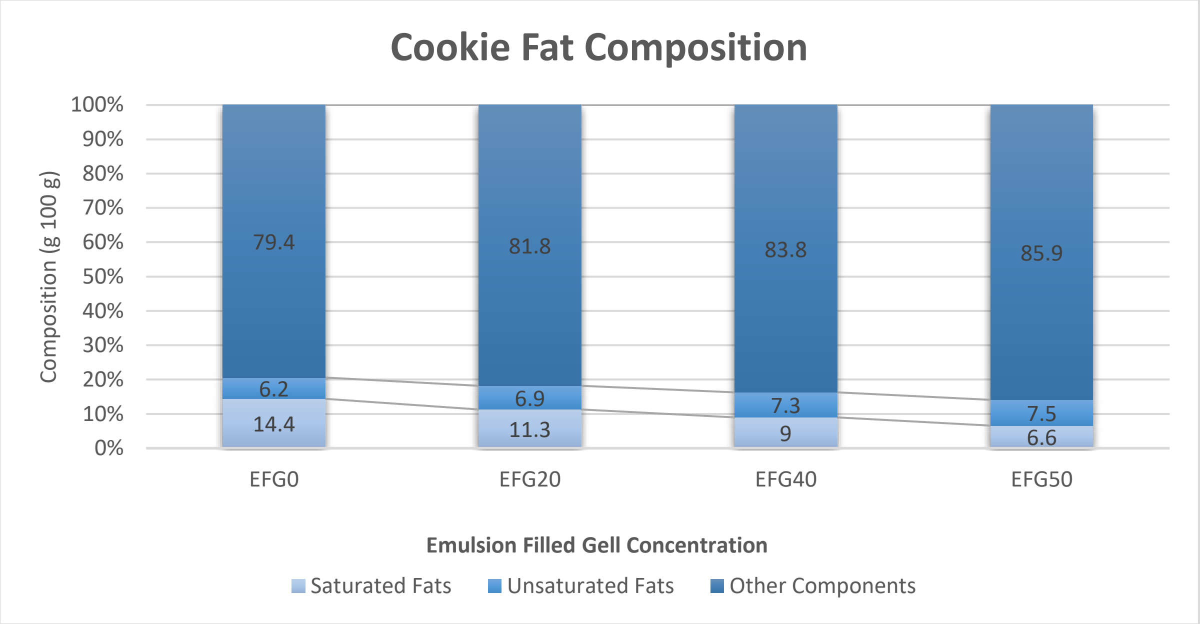


Figure 4.1. Fat composition of shortbread cookies with different fat substitution levels and focus on the saturated/unsaturated lipid fraction (adapted from data from Paciulli *et al.*, 2020).

Muffins are a high-fat food with high levels of butter and oil added for flavour, texture, and organoleptic properties. Total and saturated fat content was significantly ($p < 0.05$) reduced in muffins formulated with inulin and konjac glucomannan as well as an overall improvement in the nutrient profile (Ng *et al.*, 2021). Total mean fat reductions were reported ranging from 3.3% w/w to 9.72% w/w. Meaningful reductions were also seen in the saturated fat content ranging from 1.24% w/w to 3.61% w/w. Table 4.1 outlined the proximate composition of each inulin konjac formulation versus the control with the IK number indicating the level of inulin konjac concentration. While there were no significant differences reported for total carbohydrates, a notable increase in the dietary fibre content was observed owing to the partial substitution with fibre-rich inulin.

Samples	Control	IK30	IK45	IK60	IK75
Total Fat	14.9 ± 0.42^{a}	11.60 ± 0.71^{b}	9.53 ± 0.11^{c}	7.00 ± 0.35^{d}	5.18 ± 0.06^{e}
Saturated Fat	5.27 ± 0.06^{a}	4.03 ± 0.21^{b}	3.29 ± 0.06^{c}	2.42 ± .012^{d}	1.66 ± 0.17^{e}
Total Carbohydrate	53.05 ± 0.64^{a}	52.35 ± 1.48^{a}	52.85 ± 0.35^{a}	54.30 ± 0.14^{a}	54.80 ± 0.28^{a}
Dietary Fibre	1.33 ± 0.33^{a}	1.41 ± 0.03^{a}	1.52 ± 0.07^{a}	1.57 ± 0.08^{a}	1.67 ± 0.02^{a}

Table 4.1. Proximate composition (% w/w) of muffins containing concentrations of inulin-konjac suspension. Values with different lowercase letters in the same row were significantly different ($p \leq 0.05$) (adapted from data within Ng *et al.*, 2021).

Inulin can also be combined with other ingredients in baked goods preparations to partially replace the fat source of traditional cake recipes. In an experimental study, conducted based on sponge cake formulations containing pureed butter beans, and a mixture of inulin and Rebaudioside A (Reb A) as a replacement for fat and sugar, a significant reduction in the fat and sucrose levels were seen (Richardson *et al.*, 2021). The fat contents were lowered significantly with each degree of fat reduction, ranging from 12.6% for the SC30/0 formulation to 4.5% for the SC30/75 formulation ($p < 0.05$). All relevant proximate composition analysis results relevant to this study are presented in Table 4.2. All four dietary fibre enriched sponge cake samples led to significant increases in the dietary fibre content of the cakes ranging from 53% to 153%.

Samples	SC0/0	SC30/0	SC30/25	SC30/50	SC30/75
Total Fat	12.9 ± 0.41^{a}	12.6 ± 0.74^{a}	10.1 ± 0.26^{b}	7.5 ± 0.35^{b}	4.5 ± 0.33^{d}
Total Carbohydrate	58.4 ± 0.28^{a}	55.0 ± 0.60^{b}	54.2 ± 0.25^{b}	55.5 ± 0.10^{b}	54.2 ± 0.55^{b}
Sucrose	28.9 ± 0.66^{a}	20.4 ± 0.55^{b}	21.0 ± 0.55^{b}	21.0 ± 0.54^{b}	21.1 ± 0.41^{b}
Total Sugars	29.8 ± 0.52^{a}	20.8 ± 0.41^{b}	21.4 ± 0.33^{b}	21.5 ± 0.58^{b}	21.4 ± 0.65^{b}
Dietary Fibre	1.3 ± 0.57^{a}	2.0 ± 0.71^{b}	2.4 ± 0.22^{bc}	2.8 ± 0.46^{c}	3.3 ± 0.22^{cd}

Table 4.2. Proximate composition (%) of sponge cake samples showing mean and ± standard deviation with different lowercase letters in the same row significantly different ($p < 0.05$) (adapted from data from within Richardson *et al.*, 2021).

Modified recipes of traditional bakery products produced using high oleic sunflower oil (HOSO) and inulin were shown to have a positive influence on the nutrient profile of cookies, sponge cake, croissants and muffins (Doménech-Asensi *et al.*, 2016). Commercial inulin

Frutafit® IQ was added to the 4 formulations in the range of 2.8% to 4.5% and chemical analysis of the modified formulations revealed a significant reduced fat content across all products while a significant reduction in total sugars was seen for cookies and muffins ($p<0.05$). A further improvement in dietary fibre was reported for all categories.

The role of inulin in reformulating muffins has been evaluated on an industrial scale by developing muffins that replicate commercially available muffins (Harastani *et al.*, 2021). Using inulin and green banana flour to replace sugar and/or fat in different formulations, a range of nutrient improvements were achieved. Noteworthy improvements as presented in Figure 4.2 were recorded beginning with just a 10% sugar substitution. A theoretical 10% sugar reduction was attained when inulin was incorporated at 10% which increased to 29% when inulin was added at substitution level 30%.

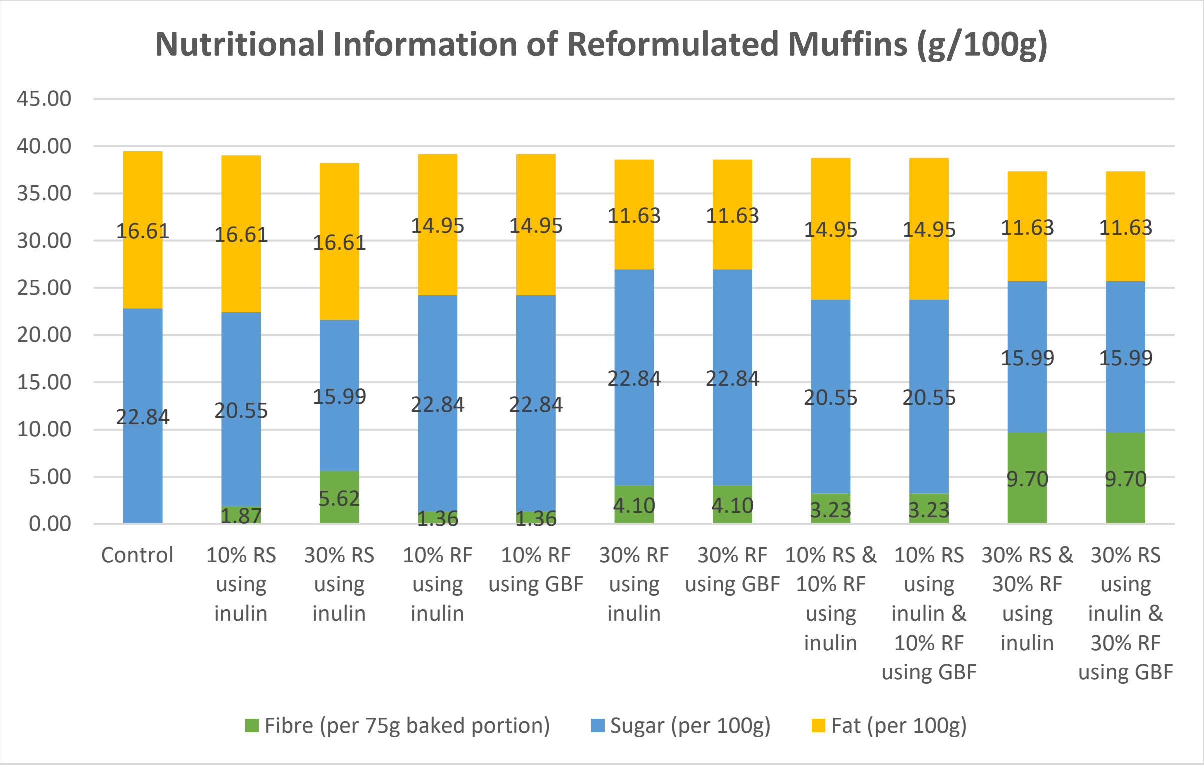


Figure 4.2. Theoretical nutritional properties of reduced fat and sugar muffins formulated with inulin and green banana flour (GBF) (adapted from data within Harastani et al., 2021).

A review of the literature shows that the incorporation of inulin to replace or reduce the sugar content of baked goods has not been widely studied. However, the available studies show that inulin can be successful in reducing the sugar content of baked goods without negatively impacting on physical and sensory characteristics (Mieszkowska and Marzec, 2016; Richardson *et al.*, 2021; Tsatsaragkou *et al.*, 2021).

Tsatsaragkou et al., 2021 found that the substitution of sugar by 30% with inulin in biscuits led to a reduction in total sugar from 22% to 15%, This sugar reduction was achieved using two commercially available inulins with different degrees of polymerisation (DP): Orafti® HSI with a DP from 2 – 60 and Fibruline® Instant with a DP of approximately 10.

Inulin added to sponge cake recipes can partially replace the sucrose content resulting in a reduced sucrose content for reformulated sponge cake samples as shown previously in Table 4.2 (Richardson *et al.*, 2021). Sucrose levels decreased substantially when sucrose was substituted by 30% by inulin, resulting in a decrease from 29% to 21%, and total sugar concentrations followed a similar significant decrease ($p < 0.05$). A significant increase in dietary fibre was reported for the replacement of 30% sucrose by the inulin and Reb A combination ($p < 0.05$) accredited to the fibre content in inulin.

The inclusion of inulin to reformulate gluten-free biscuits has been more recently researched with data from Di Cairano et al., 2022 showing that biscuits formulated with resistant starch (RS) and 30% sucrose replacement by inulin had an overall improved nutrient profile compared to the control sample and mean commercial sample. The nutrient composition of the reformulated biscuits was compared with commercial GF biscuits, the results are presented in Figure 4.3.

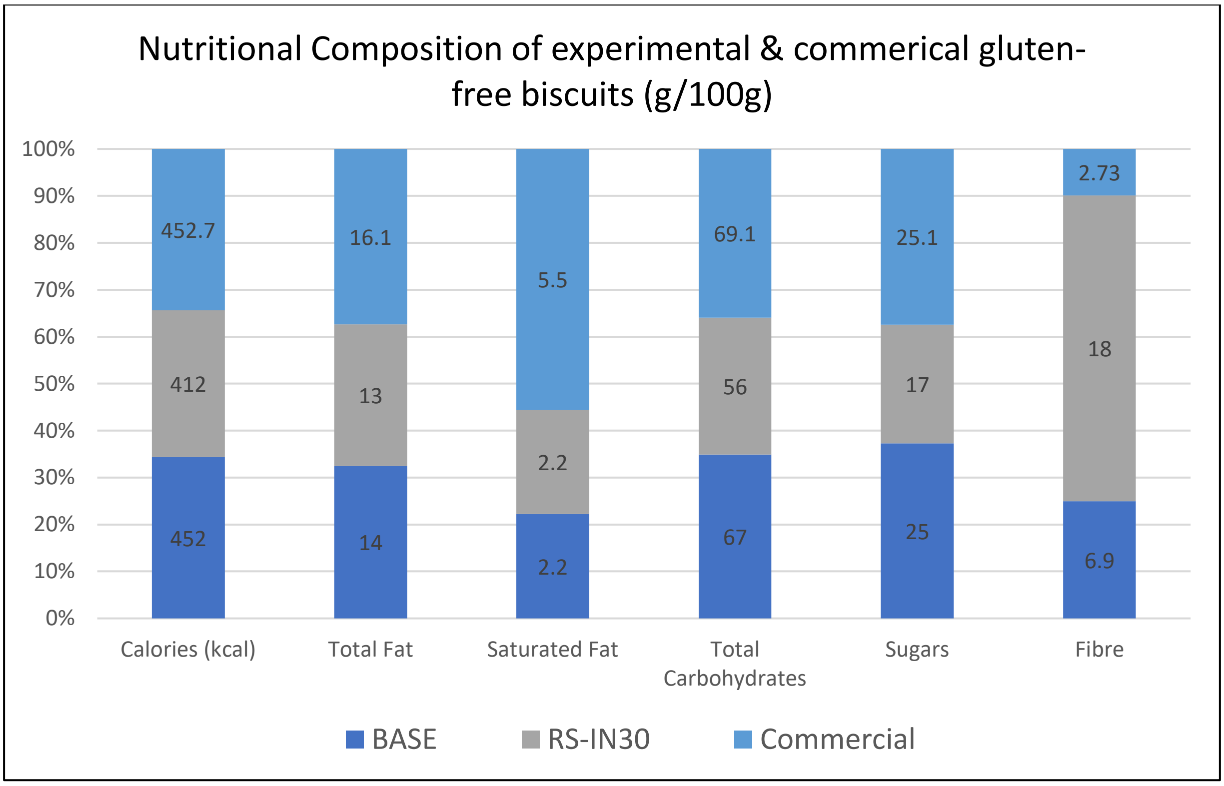


Figure 4.3. Nutritional composition of experimental and commercial gluten free biscuits expressed in g/100g for formulations BASE (biscuits with 100% sucrose and 0 RS), RS-IN30 (biscuits with resistant starch and 30% sucrose replacement by inulin) and Commercial (mean values of nutritional labels of 57 gluten free biscuits available on the Italian market) (adapted from data within Di Cairano et al., 2022).

4.1.2 Effect of Inulin on Physical Properties of Baked Goods

Physical properties such as colour, hardness, texture, springiness, diameter etc. are all important quality attributes of baked products that contribute to the eating quality and overall consumer acceptance. In each of the studies analysed, physical properties of the reformulated products were evaluated in each study adding to the feasibility of the reformulation studies as the goal of reformulation is to ensure the reformulated product is closely comparable to the standard product.

4.1.2.1 Effect on Texture and Colour Properties

Analysis of the physical properties of reformulated sponge cake samples showed a significant increase in hardness across all 30% sugar reduced formulations ($p < 0.05$) (Richardson *et al.*, 2021). Chewiness was also affected with a significant decrease observed following a 30% sugar reduction (SR). In terms of colour, reduced sugar cakes incorporating inulin and Reb A had no significant effect on the crumb or crust colour characteristics as shown in Figure 4.4. However, when fat was reduced this impacted the crust and crumb colour properties. A 50% FR in the 30% RS sample created a significantly lighter (45.5L*) crust colour compared to the control and 30% RS formulations (39.8L* and 40.5L*) and the lightness increased significantly further with a further 25% reduction in fat (49.8L*). Lightness was also affected for the crumb colour when fat was reduced, with significant increases in crumb lightness recorded for the 50% and 75% fat reduced samples ($p < 0.05$).

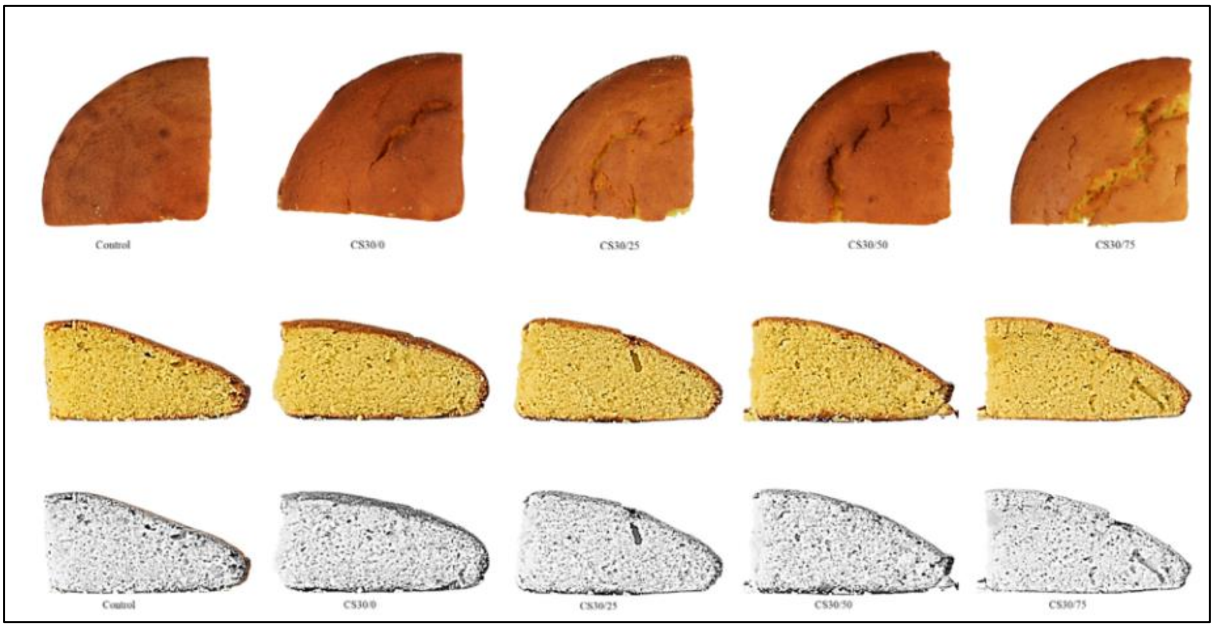
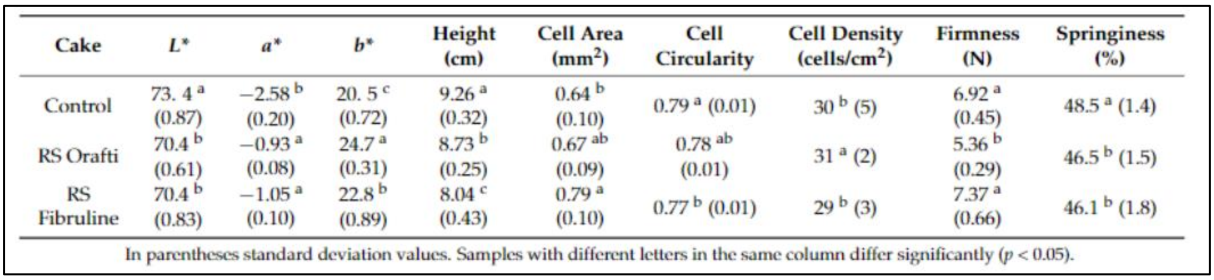


Figure 4.4. Crust and crumb images of sponge cake sugar & fat reduced samples. From left to right: control, 30% RS, 30% RS 25% RF, 30% RS 30% RF, 30% RS 50% RF, 30% RS 75% RF (taken from Richardson et al., 2021).

Reverse results for colour analysis were observed for sugar reduced cakes formulated with two different types of inulin (Tsatsaragkou *et al.*, 2021). The results as shown in Table 4.3 showed the two inulin formulations were significantly darker in colour compared to the control sample (73.4L*) and more red and yellow in colour indicating that reduced sugar and added inulin has an impact on the colour. Cake height was also negatively impacted when sugar was replaced, the RS Orafti formulation produced a cake height of 8.73 cm and the RS Fibruline formulation had an even lower height of 8.04 cm, both of which are significantly ($p < 0.05$) lower than the control cake height of 9.26 cm. RS Orafti showed a significantly higher cell density ($p < 0.05$) in comparison to the control and RS Fibruline cakes. Both inulin cakes produced a significantly higher ($p < 0.05$) springiness when sugar was substituted, and firmness was significantly lower for the RS Orafti cake compared to the control and RS Fibruline cakes.

The effect of substituting sugar by 30% using Orafti®HSI inulin in biscuits had the opposite result to the cake formulations. By incorporating inulin to replace sugar this did not have any significant difference on the darkness of the observed finished biscuit products. RS Orafti did have a significant effect ($p < 0.05$) on the hardness yielding less firmer biscuits than the control biscuit containing 22% sugar.

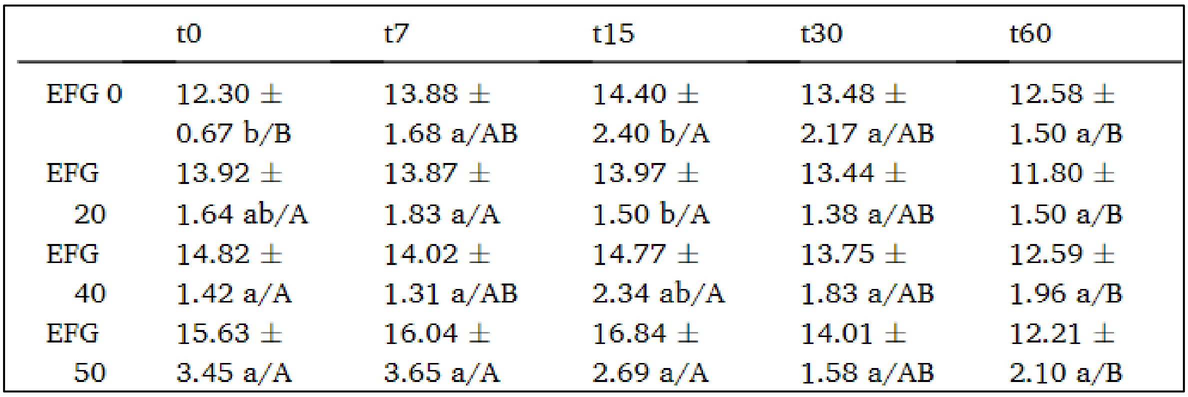


Cake	L^*	a^*	b^*	Height (cm)	Cell Area (mm^2)	Cell Circularity	Cell Density ($cells/cm^2$)	Firmness (N)	Springiness (%)
Control	73. 4 ^{a} (0.87)	−2.58 ^{b} (0.20)	20. 5 ^{c} (0.72)	9.26 ^{a} (0.32)	0.64 ^{b} (0.10)	0.79 ^{a} (0.01)	30 ^{b} (5)	6.92 ^{a} (0.45)	48.5 ^{a} (1.4)
RS Orafti	70.4 ^{b} (0.61)	−0.93 ^{a} (0.08)	24.7 ^{a} (0.31)	8.73 ^{b} (0.25)	0.67 ^{ab} (0.09)	0.78 ^{ab} (0.01)	31 ^{a} (2)	5.36 ^{b} (0.29)	46.5 ^{b} (1.5)
RS Fibruline	70.4 ^{b} (0.83)	−1.05 ^{a} (0.10)	22.8 ^{b} (0.89)	8.04 ^{c} (0.43)	0.79 ^{a} (0.10)	0.77 ^{b} (0.01)	29 ^{b} (3)	7.37 ^{a} (0.66)	46.1 ^{b} (1.8)

In parentheses standard deviation values. Samples with different letters in the same column differ significantly ($p < 0.05$).

Table 4.3. Cake properties: Mean values of colour parameters, cake height and crumb cellular characteristics, firmness, and springiness. Control (full sugar cake), RS Orafti (30% sugar reduced cake with Orafti®HSI inulin), RS Fibruline (30% sugar reduced cake with Fibruline®Instant inulin) (taken from Tsatsaragkou *et al.*, 2021).

The reduction of fat in shortbread cookies was seen to significantly increase the hardness of cookies ($p < 0.05$) as detailed in the below Table X, with higher fat substitution levels and storage time progressively increasing the hardness level (Paciulli *et al.*, 2020). Longer storage times of 30 and 60 days saw a reduction in hardness for both the control sample and EFG samples showing there was no significant effect on hardness between the samples during the longer storage times. In this study, colour attributes were influenced predominantly by the level of EFG substitution, rather than the effect of storage time. Formulations containing 20% less fat and 50% less fat were significantly darker in colour, while the 40% less fat sample had a non-significant lighter colour.



	t0	t7	t15	t30	t60
EFG 0	12.30 ± 0.67 b/B	13.88 ± 1.68 a/AB	14.40 ± 2.40 b/A	13.48 ± 2.17 a/AB	12.58 ± 1.50 a/B
EFG 20	13.92 ± 1.64 ab/A	13.87 ± 1.83 a/A	13.97 ± 1.50 b/A	13.44 ± 1.38 a/AB	11.80 ± 1.50 a/B
EFG 40	14.82 ± 1.42 a/A	14.02 ± 1.31 a/AB	14.77 ± 2.34 ab/A	13.75 ± 1.83 a/AB	12.59 ± 1.96 a/B
EFG 50	15.63 ± 3.45 a/A	16.04 ± 3.65 a/A	16.84 ± 2.69 a/A	14.01 ± 1.58 a/AB	12.21 ± 2.10 a/B

Table 4.4. Hardness (N) of cookies with different fat replacement levels during storage (taken from Paciulli et al., 2020).

In Ng et al., 2021 study on the reformulation of muffins with inulin and konjac, significantly higher hardness levels were observed for the fat reduced muffins compared to the control muffin. Hardness was found to increase as higher levels of fat were substituted. However, the higher inulin konjac concentrations (IK60 and IK75) did not impact the hardness levels as significantly as the control muffins or lower concentrations of inulin konjac (control: 59.15%, IK30: 46.88%, IK45: 58.32%). Despite the reduced fat muffins showing a higher hardness level on Day 0 than the control muffin, the pace of staling caused by starch retrogradation was substantially slower ($p < 0.05$).

Muffin texture properties were impacted by the incorporation of inulin and GBF in the study by Harastani et al., 2021. The study found that all reduced sugar and/or fat muffins were significantly firmer than the control muffin formulation and firmness was notably affected by the level of sugar and/or fat substitution ($p < 0.05$). As shown in Figure 4.5 muffins with the highest reduction in sugar and fat levels (30% less sugar, 30% less fat) exhibited the greatest firmness levels compared to the control muffin. However, a reduction of 10% sugar and 10% fat represented the lowest increase in firmness compared to higher levels of fat and sugar reduction in the study. Results of the springiness properties revealed that muffin springiness was not significantly impacted by sugar and/or fat reduction except for samples which had a 30% fat and sugar reduction with both inulin and GBF formulations. Colour analysis results of this study revealed non-significant differences for colour attributes lightness, redness and yellowness between the reformulated muffins containing inulin and the control muffin.

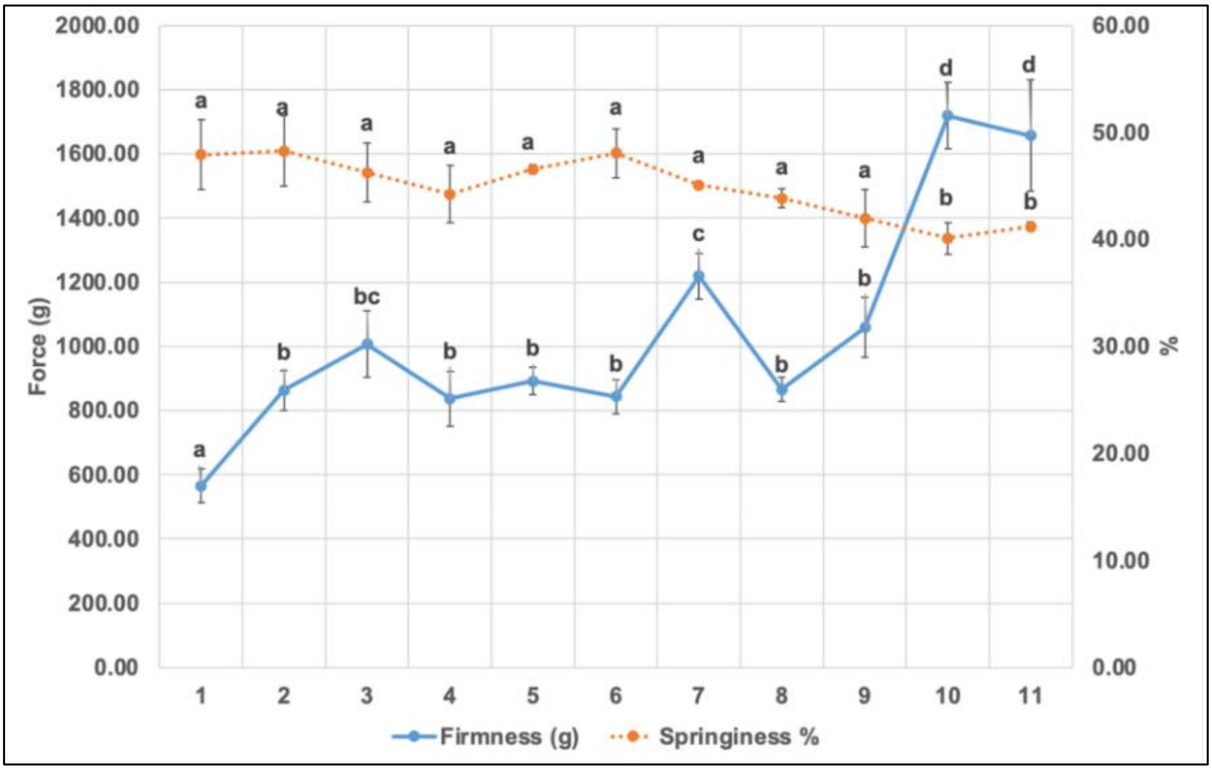


Figure 4.5. The firmness (g) and springiness (%) of different muffin formulations. Where different letters are shown this represents a significant difference in the mean ($p < 0.05$) . 1 = control, 2 = 10% SR inulin, 3 = 30% SR inulin, 4 = 10% FR inulin, 5 = 10% FR GBF, 6 = 30% FR inulin, 7 = 30% FR GBF, 8 = 10% SR + FR inulin, 9 = 10% SR inulin 10% FR GBF, 10 = 30% SR + FR inulin, 11 = 30% SR inulin 30% FR GBF (taken from Harastani *et al*., 2021).

4.1.2.2 Effect of Inulin on Sensory Properties of Baked Goods

Reformulated biscuit samples containing inulin can have comparable sensory properties to standard full fat and sugar biscuits as demonstrated in several studies. Taste is an important factor in consumer acceptance of reformulated products and Tsatsaragkou et al., 2021 found that a 30% sugar reduction for the cake preparations resulted in a significantly less sweetness for both inulin types (RS Orafti® = 38.4, RS Fibruline® = 42.2) in comparison to the control cakes (50.0) ($p < 0.05$). However, there was no significant difference for sweetness detected for the RS Orafti® biscuits compared to the control ($p > 0.05$). In general, most sensory attributes for the 30% SR biscuits were not significantly affected by the incorporation of inulin ($p > 0.05$). Higher degrees of differences were recorded for the SR cake samples in comparison to the control, particularly appearance and aftereffects.

Sensory evaluation of the fat and sugar reduced muffins by Harastani et al., 2021 incorporating inulin and GBF revealed general positive results as presented in the below Figure 4.6. Overall seven out of 10 muffin reformulations had overall acceptance by the panellists showing that the net changes in sensory properties were not negatively scored by the panellists. The lowest sensory scores were awarded to the 30% reduced fat and 30% reduced sugar formulations containing inulin and GBF.

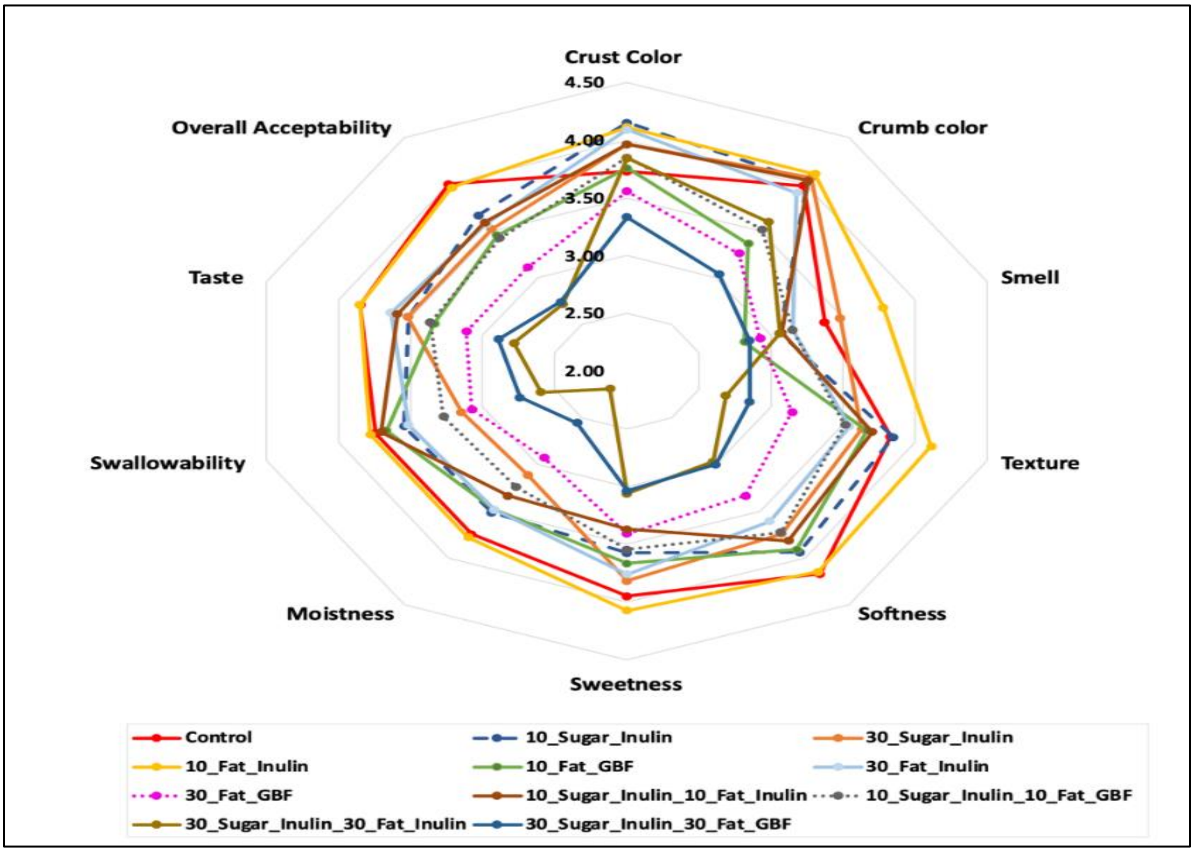


Figure 4.6. Sensory properties of reduced sugar and fat formulations (n = 60) (taken from Harastani et al., 2021).

In Richardson et al., 2021 study the effect of 25% sugar reduction displayed positive results across all sensory parameters with appearance, texture, flavour and overall acceptability recording higher non-significant values. Increasing levels of sugar reduction impacted negatively on the texture and overall acceptability for the 50% SR and all parameters for the 75% SR except for aroma ($p < 0.05$). A 30% SR and varying levels of fat replacement found no significant differences for sensory parameters appearance, colour, and texture. The sample with a 30% SR and 75% FR was identified as the only sample with significantly negative scores for aroma and flavour and liking demonstrating that samples with 30% SR and FR up to 50% had comparable sensory scores to the control sample. Further detail of the association between 30% reduced sugar sponge cake formulations with progressive levels of fat reduction is presented in a partial least squares regression (PLSR) plot in the below Figure 4.7.

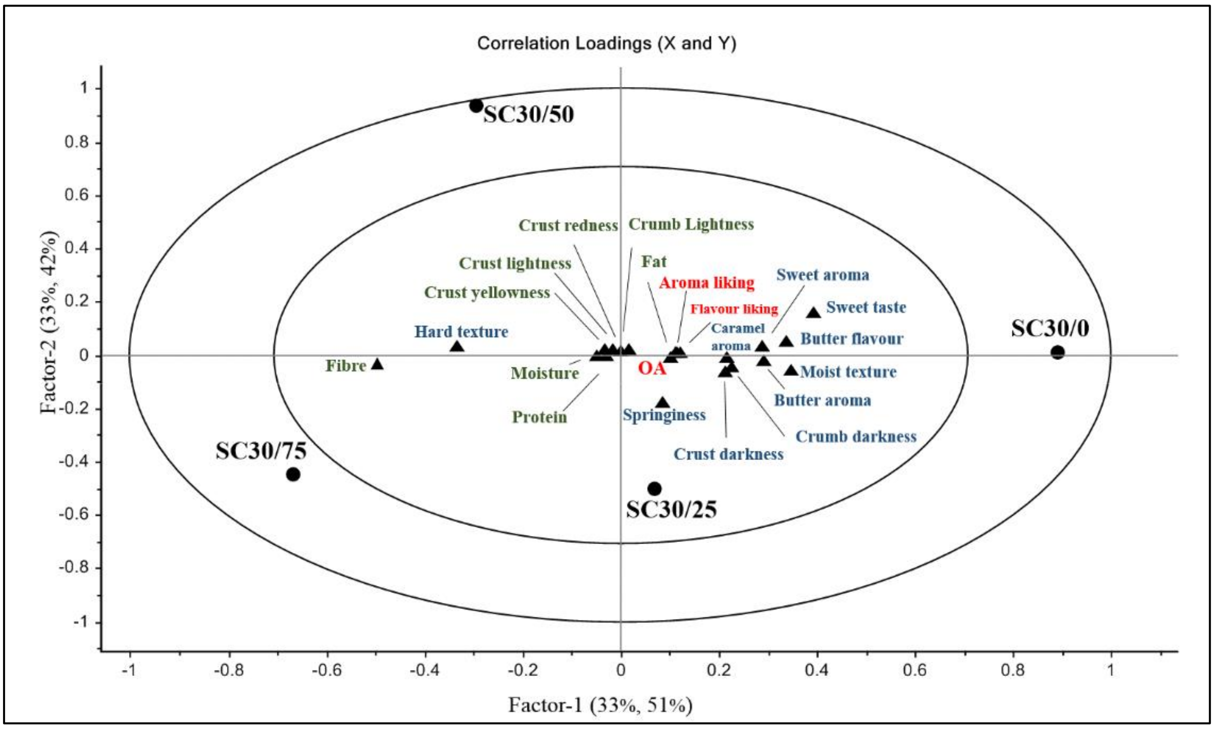


Figure 4.7. PSLR plot for the relationship between 30% RS sponge cakes with increasing levels of fat replacement: 0, 25, 50 and 75% showing hedonic sensory variables and sensory and physiochemical attributes (taken from Richardson et al., 2021).

Paciulli et al., 2020 study also evaluated the influence of butter substitution on the sensory properties of the cookies during storage. Results of the sensory analysis as detailed in Figure 4.8 show that an increasing EFG level decreased butter aroma and butter odour however this led to a slight increase in the toasted odour perception by panellists.

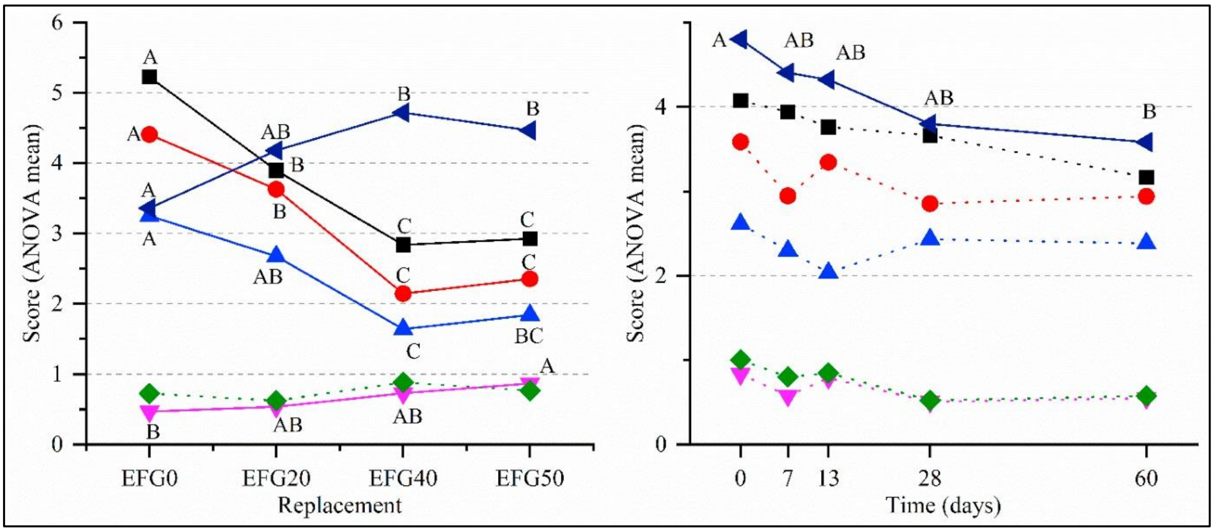


Figure 4.8. Sensory scores assigned to cookies with different fat substitution levels (FORM) and during 60 days of storage (ST). ■ Butter Odour ● Butter Aroma ▲ Porosity ▼ Toasted Odour ◆ Toasted Aroma ◄ Hardness. Abbreviations: EFG, emulsion filled gel; EFG0, EFG20, EFG40, EFG50, cookies with 0, 20, 40, 50% butter substitution with EFG. Different letters indicate significant differences among mean scores ($p < 0.05$). Dotted lines indicate no significant effect of the independent variable (taken from Paciulli et al., 2020).

4.2. Reformulation of Ice Cream

4.2.1 Effect of Inulin on Nutritional Quality of Ice Cream

Ice cream, a high fat food due its compositional standards and often containing added sugar, is another food application where inulin has been studied as both a fat replacer and sugar replacer. Studies conducted by Shoaib *et al*., 2016, Kowalczyk, Znamirowska and Buniowska, 2021, Samakradhamrongthai *et al*., 2021, da Silva Faresin et al., 2022 and detailed in Table 4.5 investigated the use of inulin at varying concentrations to achieve a fat and/or sugar reduction.

Study	Ice Cream Type	Inulin %	Outcome
Samakradhamrongthai et al., 2021	Reduced fat ice cream	2 – 5	Fat reduction up to 2.30%
da Silva Faresin et al., 2022	Full Fat Ice Cream	2	Fat reduction up to 50%
Pintor, Escalona-Buendía and Totosaus, 2017	Low Fat Ice Cream	3	30% butyric fat reduction
Kowalczyk, Znamirowska and Buniowska, 2021	Sheep Milk Ice Cream	1.5 - 4	No effect on fat content
Narala et al., 2022	Pea Protein Ice Cream	2 - 8	Not analysed

Table 4.5. Detail of study findings, reviewing the effect of inulin incorporation at varying levels in ice-cream formulations to achieve a fat and/or sugar reduction (adapted from Shoaib *et al*., 2016, Kowalczyk, Znamirowska and Buniowska, 2021, Samakradhamrongthai *et al*., 2021, Pintor, Escalona-Buendía and Totosaus, 2017, Narala et al., 2022).

Among these studies, encouraging results were observed by Samakradhamrongthai et al., 2021 who investigated the effect of inulin derived from chicory on the fat content of reduced fat ice cream formulations. Inulin was incorporated into the formulations in the range of 2 – 5% while the sugar and whipped creams also varied. The results of the lipid analysis as presented in Figure 4.8 show the fat contents ranged from 8.27% to 15.2%. The formulation with the lowest fat content of 8.27% had inulin added at the highest level of 5% and the lowest level of whipped cream added.

An optimized reduced fat ice cream with a fat content of 13.87% and favorable sensory acceptance was produced when inulin was incorporated into the formulation at 4%. At this level, inulin directly replaced 2.3% of the total fat content of the formulation in the optimized formulation (8.58% sugar, 22.18% cream, 4.02% inulin) compared to the inulin free ice cream formulation (Samakradhamrongthai *et al.*, 2021). Figure 4.9 shows the percentage of inulin added and the associated fat content of each formulation.

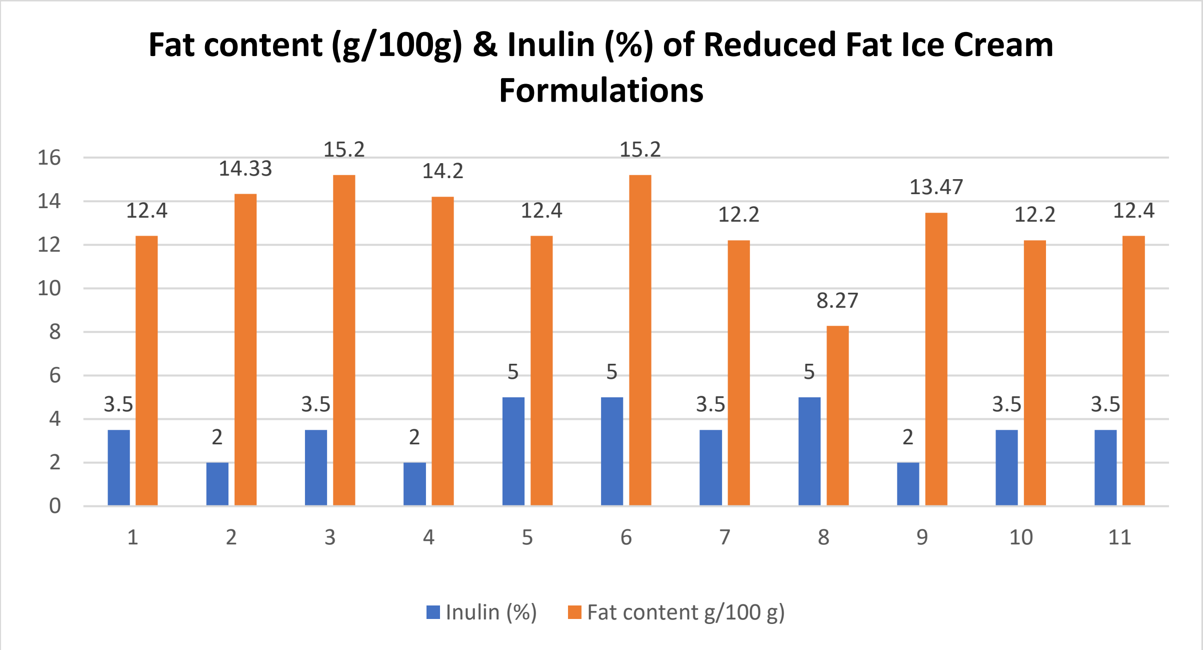


Figure 4.9. Fat content of the reduced fat ice cream formulations showing the level of inulin added (%) and fat content (g/100g) (adapted from data within Samakradhamrongthai *et al*., 2021).

A study on the development of an ice cream formulation with reduced sugar and fat levels through the incorporation of inulin, spirulina platensis or phycocyanin achieved a fat reduction across all formulations (da Silva Faresin et al., 2022). Results reported in this study, reveal that the formulation containing 50% reduced fat with added inulin had a greater fat reduction (2.90 ± 0.16, 56.8%) than the formulation containing 50% fat reduction alone (5.33 ± 0.25, 20.5%).. As presented in Table 4.7, the fat content of the ice cream formulations varied from 2.59g to 6.72 g/100g depending on the reduction of the level of cream added and with and without concentrations of emulsifier, inulin, phycocyanin and spirulina added.

Treatment	Inulin (%)	Fat content g/100 g)
IC1	0	6.72 ± 0.8^{c}
IC2	0	5.33 ± 0.25^{bc}
IC3	0	3.95 ± 0.15^{ab}
IC4	0	2.59 ± 0.21^{a}
IC5	2	2.90 ± 0.16^{a}
IC6	0	3.76 ± 0.43^{ab}
IC7	2	3.42 ± 0.12^{b}
IC8	0	4.29 ± 0.15^{ab}
IC9	2	3.12 ± 0.04^{a}
IC10	2	3.86 ± 0.09^{ab}
IC11	2	2.68 ± 0.09^{a}
IC12	2	3.51 ± 0.58^{a}

Table 4.6. Fat content of the reduced fat ice cream formulations showing the level of inulin added (%) and fat content (g/100g) (adapted from data within da Silva Faresin *et al*., 2022).

In a study conducted by Pintor, Escalona-Buendía and Totosaus, 2017, on the effect of inulin on functional properties of reduced fat and reduced sugar ice cream, inulin added at 3% achieved a butyric fat content reduction of 30% from 10% to 7% and an overall sugar reduction of 12%. Fat-reduced ice cream preparations were prepared to incorporate agave inulin at five different concentrations as a substitute for butyric fat and sugar in traditional ice cream recipes. While the functional characteristics of the ice cream samples were favorable, there was no sensory analysis conducted to evaluate the effect of inulin incorporation on perceived consumer acceptance.

The use of inulin as a fat replacer extends outside the scope of traditional ice cream to ice cream formulated with sheep milk. Kowalczyk, Znamirowska and Buniowska, 2021 assessed the effect of the addition of inulin and part substitution of the inulin with apple fibre on the physiochemical and sensory properties of ice cream made with sheep milk. The results report that inulin added at varying concentrations had no effect on the fat content of the inulin and apple fibre formulations ($p > 0.05$).

4.2.2 Effect on Inulin on the Physical and Textural Properties of Ice Cream

A study conducted by Akbari et al., 2016 on the effects of replacing fat with inulin in ice cream used varying levels of inulin added at 2, 3 and 4%. As can be seen from Figure 4.10 the weight of the melted control ice cream containing 10% fat was significantly lower than that of the other low-fat ice cream formulations with or without added inulin at all durations ($p < 0.05$). In this study it was observed that the inulin-free low-fat ice cream (2% fat) had a higher melting rate when compared to the control ice cream (10% fat).

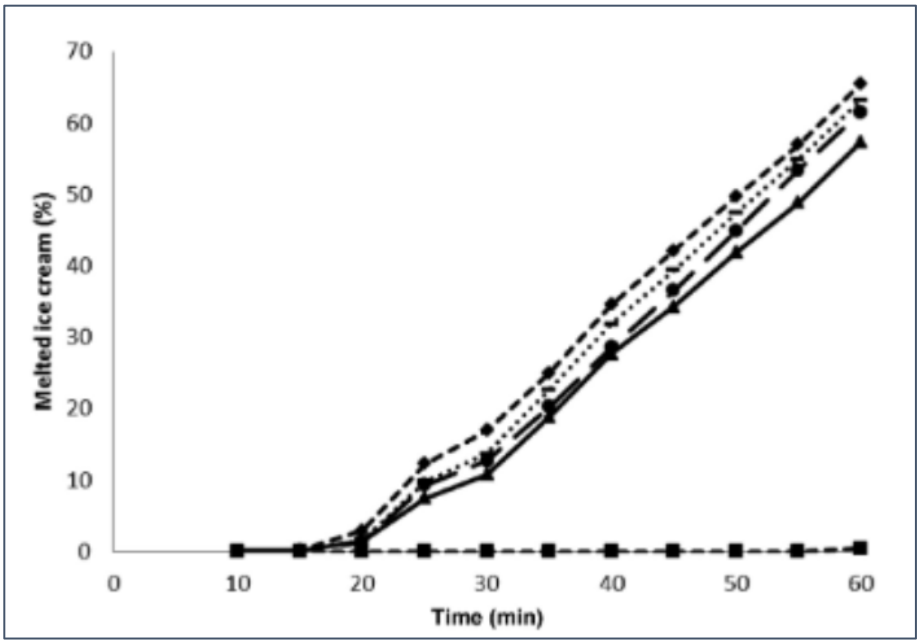


Figure 4.10. Weight percentage of the melted ice cream in the ice cream samples at different durations: ■, control ice cream; ▲, inulin-free low fat ice cream; ▬, low fat ice cream containing 2% inulin; ♦, low fat ice cream containing 3% inulin: ●, low fat ice cream containing 4% inulin. (Taken from (Akbari *et al.*, 2016)

This study also investigated the effect of inulin addition on ice cream hardness and adhesiveness and found that the low fat ice cream without inulin was had a significantly higher hardness level (1827 ± 150^a) than the control ice cream containing 10% fat (965 ± 35^c) ($p < 0.05$). Furthermore, as tabulated in Table 4.7 the hardness of the low-fat ice cream incorporated with inulin at addition levels 2%, 3% and 4% (1312 ± 68^b, 1300 ± 50^b, 1150 ± 100^b) was significantly lower than that of the inulin free ice cream (1827 ± 150^a) ($p < 0.05$). Similarly, the addition of inulin resulted in a reduced adhesiveness for the low-fat inulin containing ice creams (389 ± 25^c, 398 ± 30^c, 408 ± 10^c) in contrast to the inulin free ice cream (584 ± 21^c) however the adhesiveness of the low-fat ice cream formulations containing inulin was significantly higher (389 ± 25^c, 398 ± 30^c, 408 ± 10^c) than that of the control ice cream (342 ± 18^c) ($p < 0.05$).

Treatments	Control	LF-10	LF-12	LF13	LF-14
Hardness	965 ± 35^{c}	1827 ± 150^{a}	1312 ± 68^{b}	1300 ± 50^{b}	1150 ± 100^{b}
Adhesiveness	342 ± 18^{c}	584 ± 21^{c}	389 ± 25^{c}	398 ± 30^{c}	408 ± 10^{c}

Table 4.7. The hardness and adhesiveness of the frozen ice cream samples. Abbreviations are: LF-I0, inulin-free low fat ice cream; LF-I2, low fat ice cream containing 2% inulin; LF-I3, low fat ice cream containing 3% inulin; LF-I4, low fat ice cream containing 4% inulin. Values are the mean ± SD (n ¼ 3); different superscript letters show the significant differences ($p < 0.05$) in a row (Adapted from (Akbari *et al.*, 2016).

The physiochemical results of Samakradhamrongthai et al., 2021 study also showed that the addition of inulin positively influenced the ice-cream properties in added inulin recipes. The firmness of the inulin RFIC formulations ranged from $0.27–3.24 \times 10^3$ g.force, in comparison with the firmness of the inulin free ice cream at 0.57×10^3 g.force. The firmness of the low-fat ice cream was greater than that of reduced fat ice cream and significantly the optimized reduced fat ice cream showed an acceptable range of firmness, viscosity, melting rate and overrun of ice cream product (Samakradhamrongthai *et al.*, 2021).

4.2.3 Effect of Inulin on Sensory Properties of Ice Cream

In the study conducted by Samakradhamrongthai et al., 2021, the effect of inulin incorporation in the optimised reduced fat ice cream impacted most of the sensory attributes however appearance and colour attributes performed the best in the sensory rating scores compared to the control formulation. As shown in Figure 4.11 presenting the sensory attributes, milk flavour, melt in the mouth and viscosity received the lowest sensory rating scores of all the attributes. The overall liking of the optimised reduced fat ice cream formulation was rated in the range of like slightly to like moderately (6.9 – 7.2) (Samakradhamrongthai *et al.*, 2021).

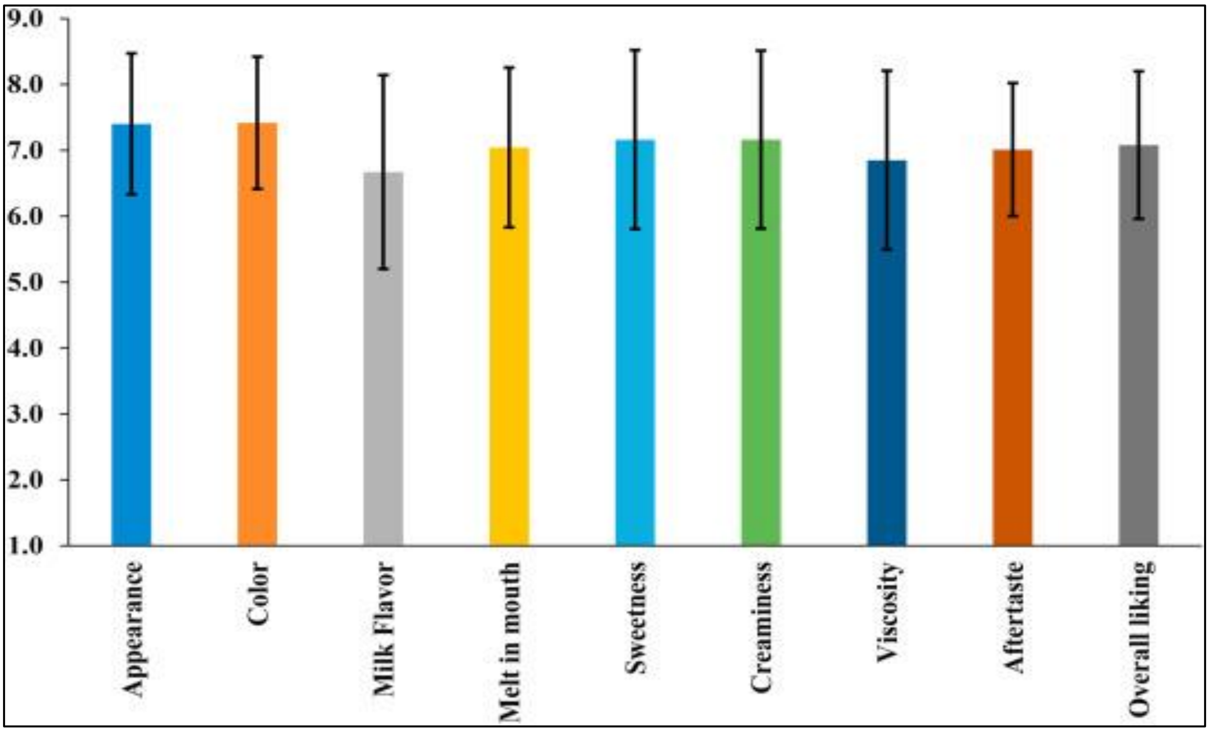


Figure 4.11. The sensory rating scores from consumer acceptance of the optimised RFIC using 9-point hedonic scale (n=400) (taken from Samakradhamrongthai et al., 2021).

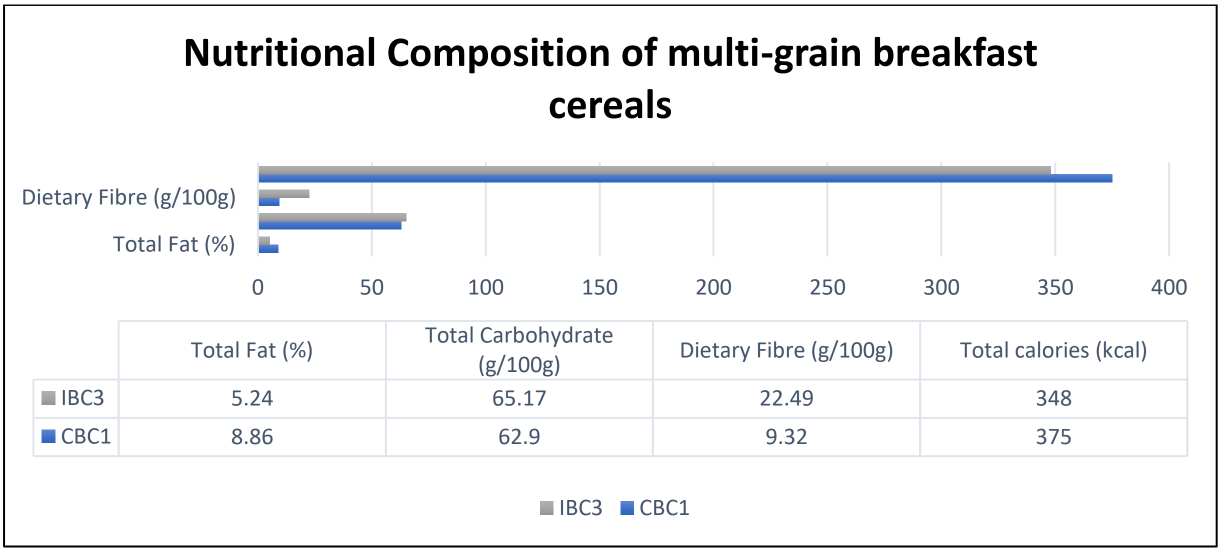
The sensory attributes of the different inulin containing formulations was considered in a study by da Silva Faresin et al., 2022. In the formulations containing reduced fat and sugar contents, through the incorporation of inulin and Spirulina, the sensory properties did not differ significantly from formulations prepared without these ingredients i.e. the control formulation and formulations containing 50% fat reduction and emulsifier (da Silva Faresin *et al*., 2022). Therefore, the sensory attributes of the inulin and Spirulina ice cream formulations were not negatively impacted.

4.3 Reformulation of Breakfast Cereals

4.3.1 Effect of Inulin on Nutritional Quality of RTE Breakfast Cereals

A limited number of studies have assessed the impact of incorporating inulin in breakfast cereal formulations on the nutritional properties. Kapoor and Haripriya, 2020 developed a high fibre and sugar free RTE breakfast cereal with differing levels of inulin to investigate the viability and acceptability of inulin incorporated RTE breakfast cereal. Nutritional analysis of the formulations as presented in Figure 4.12 showed that inulin added at 16% to replace 8% sugar significantly reduced the fat content by 40.8% (5.24 g/100g) when compared to the control formulation containing no inulin.

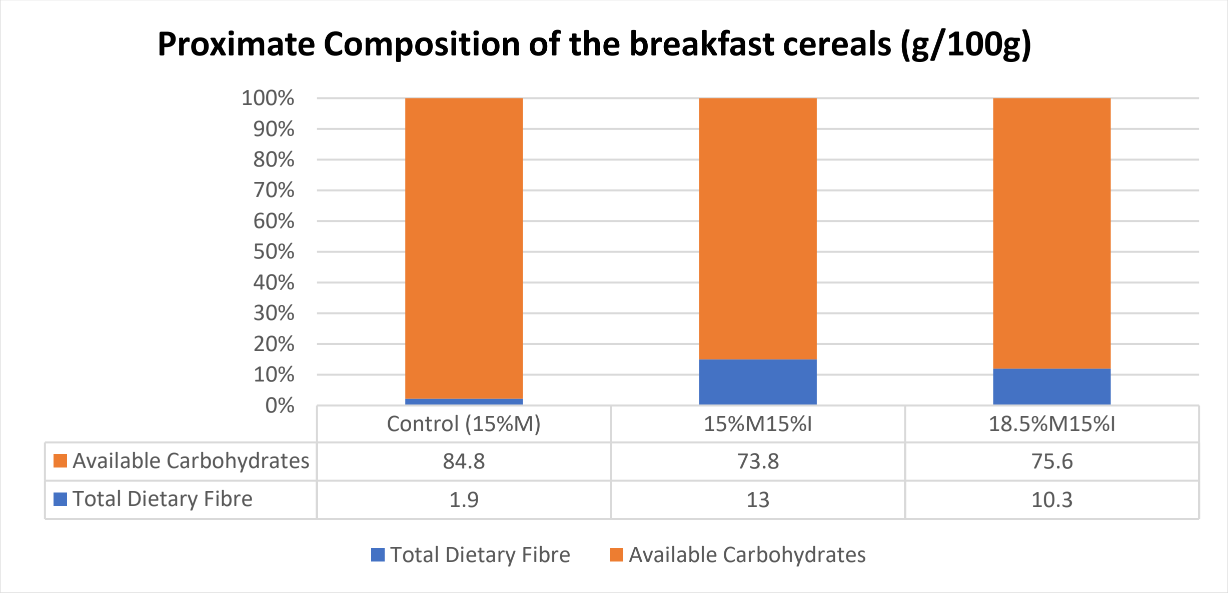
Dietary fibre analysis of the samples revealed a significant dietary fibre increase in the inulin containing sample compared to the control formulation. Furthermore, in analysing the nutrient composition of different foods it's important to consider the energy content of the food in the overall context of reformulation to ensure there is no significant negative increase. In this study, the total energy content of the control sample was 375 kcal, and the inulin preparation was 348 kcal. This decrease in energy content by 27 kcal is due to the addition of inulin in the 16g inulin enriched formulation as a replacement for table sugar which is typically added to breakfast cereals to contribute to sweetness and palatability.



	Total Fat (%)	Total Carbohydrate (g/100g)	Dietary Fibre (g/100g)	Total calories (kcal)
IBC3	5.24	65.17	22.49	348
CBC1	8.86	62.9	9.32	375

Figure 4.12. Nutritional composition of the multi-grain breakfast cereal for CBC1 (control sample) and IBC3 (breakfast cereal +16% inulin) (adapted from data within Kapoor and Haripriya, 2020).

Findings of a study by Ferreira, Capriles and Conti-Silva, 2021 found that the addition of 15% Orafti®GR inulin to breakfast cereal significantly increased the total dietary fibre content for the inulin samples by 5.4 fold compared to the control sample. While sugar reduction was not in scope for this study, there was a significant decrease in the available carbohydrates for the inulin containing breakfast cereals showing that inulin is effective in lowering carbohydrates.



	Control (15%M)	15%M15%I	18.5%M15%I
🟧 Available Carbohydrates	84.8	73.8	75.6
🟦 Total Dietary Fibre	1.9	13	10.3

Figure 4.13. Proximate composition of breakfast cereals (g/100g) for the control, 15% moisture 15% inulin, 18.5% moisture 15% inulin for available carbohydrates and total dietary fibre (adapted from data within Ferreira, Capriles and Conti-Silva, 2021)

An overview of the studies analysing the effect of inulin to extruded snacks including breakfast cereals and the nutrient composition outcome are presented in Table 4.8.

Study	Food Application	Inulin Type	Optimum Inulin %	Nutrient Composition Outcome
Ferreira, Capriles and Conti-Silva, 2021	Breakfast Cereals	Orafti®GR Inulin	15%	5.4-fold increase dietary Fibre 11% Carbohydrate reduction
Kapoor and Haripriya, 2020	Breakfast Cereals	Brand-Natures velvet Lifecare Inulin	16%	6.67% Fat reduction 141.3% Dietary Fibre increase 27 kcal reduction
Capriles, Conti-Silva and Gomes Arêas, 2021	Corn Snacks	Orafti® Synergy 1 Oligofructose enriched inulin	13.3%	7-fold increase dietary fibre Energy reduction of 40 kcal
Peressini et al., 2015	Extruded RTE snack product	Raftiline® HPX	5%	No nutritional analysis completed

Table 4.8. Overview of studies analysing the effect of inulin to extruded snacks including breakfast cereals and the improvement in nutrient profile

4.3.2 Effect of Inulin on Physical Properties of RTE breakfast cereals

It is important to assess the effects of adding inulin on the physical properties of breakfast cereals in the context of overall nutrition value and feasibility of the reformulated product. A review of the available studies evaluating the effects of inulin on breakfast cereals have looked at the expansion volume, hardness, cutting factor etc. incorporating different levels of inulin in the formulations to assess the overall influence of inulin on these attributes.

In a study conducted by Peressini et al., 2015 evaluating the effect of inulin incorporation on different properties of extruded snacks the use of two commercial inulin types was studied. Two types of inulin derived from chicory with different degree of polymerisation (DP) were used: Raftiline® HPX (inulin HPX, DP = 23) and Raftiline® GR (inulin GR, DP = 10). The results of the specific volume tests revealed no significant differences between the control sample (3.93 cm^3/g) and inulin HPX enriched samples at 2% (4.04 cm^3/g) and 5% (3.74 cm^3/g) addition levels. Inulin at 7% addition level slightly lowered the specific volume of the inulin HPX sample. Meanwhile, the inulin GR sample exhibited a higher expansion volume and hardness compared to the control sample.

Similar results were recorded by Ferreira, Capriles and Conti-Silva, 2021 in which the results of the physical properties are presented in Figure 4.14. There was no significant difference for the expansion volume and density of the three formulations. The cutting factor of extruded cereals is an important physical property, and this study revealed a significant reduction (22.1 N without milk and 6.5 N with milk) ($p \leq 0.05$) in the 15%M/15%I formulation versus the control sample (31.3 N without milk and 14.6 N with milk). Therefore, the effect of 15% inulin addition to the breakfast cereal formulation lowered the cutting force as the moisture content remained the same at 15%. There was no significant effect on the cutting force for the higher moisture formulation (27.2 without milk) versus the control sample (31.3 without milk) indicating that a higher moisture content counterbalances some of the cutting force loss when the same level of inulin is added.

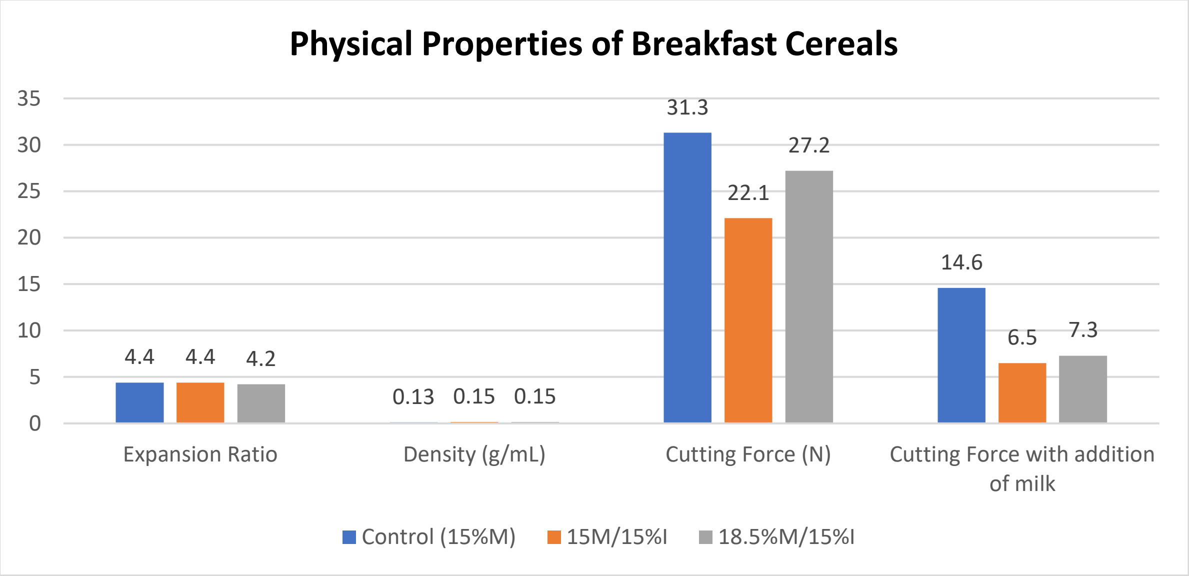
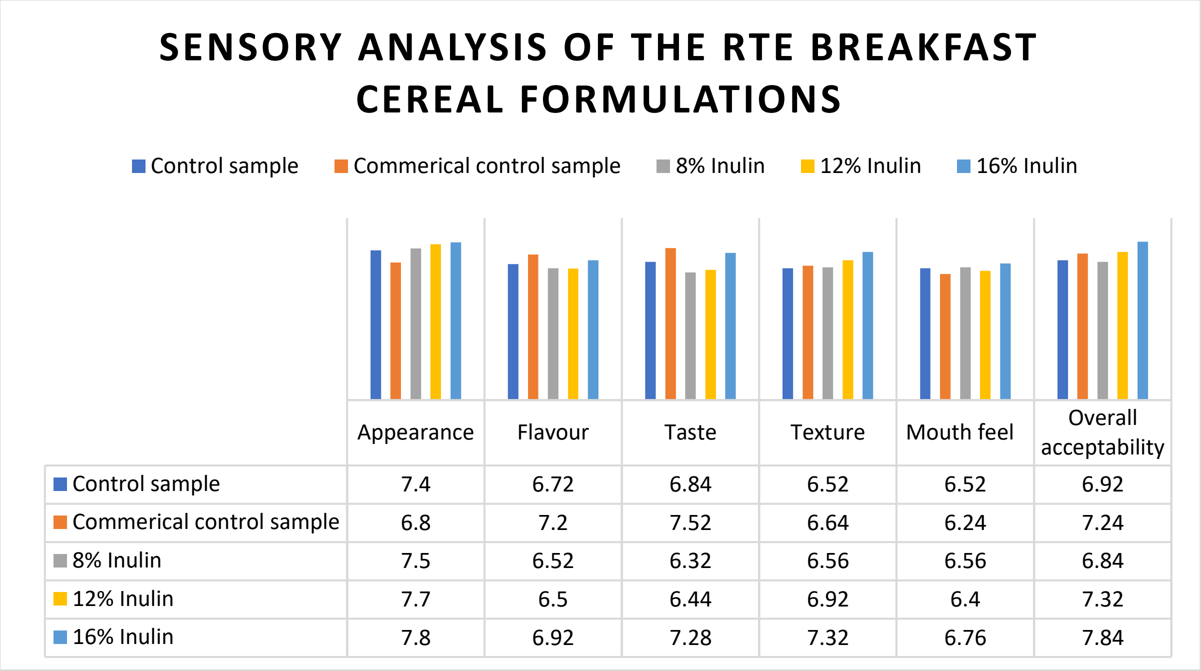


Figure 4.14. Physical properties of the breakfast cereals for control 15% moisture, 15% moisture 15% inulin and 18.5% moisture 15% inulin (adapted from data within Ferreira, Capriles and Conti-Silva, 2021).

4.2.3 Effect of Inulin on Sensory Properties of RTE breakfast cereals

Products perceived as healthier options can lead to negative annotations for some consumers which is why it's critical to ensure positive changes to the nutrient composition are well received in the sensory analysis results of studies. Based on an experimental study by Kapoor and Haripriya, 2020 on the formulation of high-fibre RTE breakfast cereals containing inulin, it can be concluded that the addition of 16% inulin was the most favorable of the formulations, receiving a significantly higher score (7.84 ± 0.06) for overall acceptability ($p < 0.05$), followed by 12% inulin with an overall acceptability score of 7.32 ± 0.02. The results of the sensory analysis as presented in Figure 4.15 showed that the addition of inulin resulted in higher sensory scores for appearance and texture compared to the control sample and commercial control sample ($p < 0.05$).



	Appearance	Flavour	Taste	Texture	Mouth feel	Overall acceptability
Control sample	7.4	6.72	6.84	6.52	6.52	6.92
Commerical control sample	6.8	7.2	7.52	6.64	6.24	7.24
8% Inulin	7.5	6.52	6.32	6.56	6.56	6.84
12% Inulin	7.7	6.5	6.44	6.92	6.4	7.32
16% Inulin	7.8	6.92	7.28	7.32	6.76	7.84

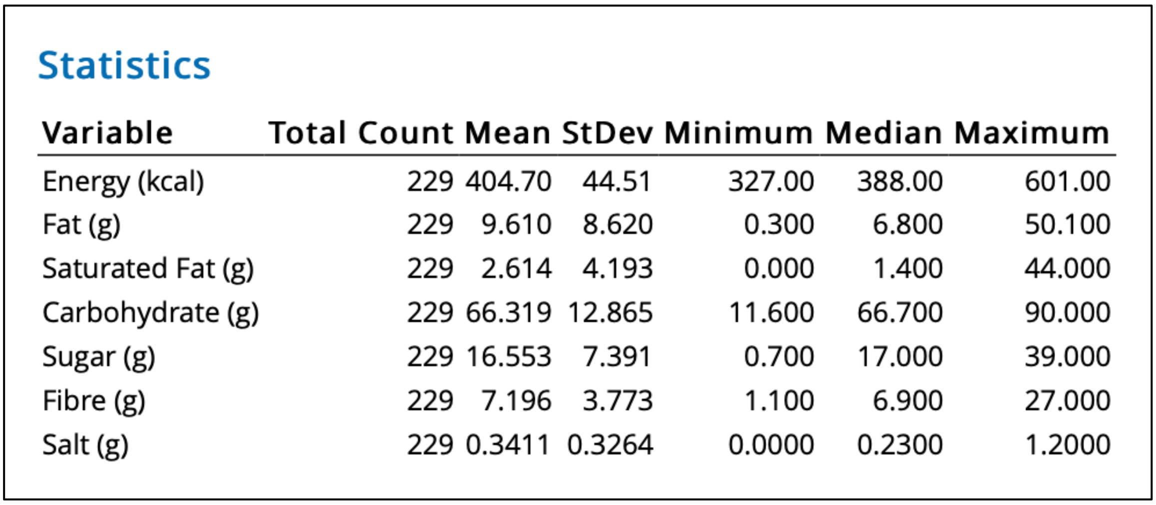
Figure 4.15. Sensory analysis of the formulations for control sample, commercial control sample, 8% added inulin, 12% added inulin and 16% added inulin (adapted from data within Kapoor and Haripriya, 2020)

Based on the results on the use of inulin in the sensory evaluation of breakfast cereals, Ferreira, Capriles and Conti-Silva, 2021 found that the formulations containing inulin had no significant influence on the aroma, texture and flavour attributes ($p > 0.05$). Furthermore, inulin had a positive influence on some sensory attributes receiving a higher score than the control sample ($p < 0.05$), with both inulin formulations received a higher degree of liking score (7.0 ± 1.6 and 7.1 ± 1.3) for flavour when milk was added in relation to the control sample (6.6 ± 1.5) ($p < 0.05$).

4.4 Potential for Reformulation with Dietary Fibre in Breakfast Cereals

4.4.1 Description of samples

Overall, 229 breakfast cereal products were surveyed across five retailers in the Irish market and were included for analysis. A total of 229 (100%) of products had complete data for all nutrients required to complete nutritional declaration comparison. This included breakfast cereals from the following categories: bran (7), children's cereal (38), flaked/puffed (37), granola & clusters (55), health & wellbeing (41), muesli (33) and wheat biscuits (18). Categories such as granola & clusters (24.0%), health & wellbeing (17.9%) and flaked/puffed (16.15%) accounted for the majority (58.05%) of products available on the market in February and March 2022. A summary of the descriptive statistics of study samples by nutrient is presented in Table 4.9. A further breakdown of descriptive statistics by category and nutrient is presented in Appendix 1a.



Statistics

Variable	Total Count	Mean	StDev	Minimum	Median	Maximum
Energy (kcal)	229	404.70	44.51	327.00	388.00	601.00
Fat (g)	229	9.610	8.620	0.300	6.800	50.100
Saturated Fat (g)	229	2.614	4.193	0.000	1.400	44.000
Carbohydrate (g)	229	66.319	12.865	11.600	66.700	90.000
Sugar (g)	229	16.553	7.391	0.700	17.000	39.000
Fibre (g)	229	7.196	3.773	1.100	6.900	27.000
Salt (g)	229	0.3411	0.3264	0.0000	0.2300	1.2000

Table 4.9. Descriptive analysis of the breakfast cereals (n = 229) nutritional data collected from retailer stores and websites

4.4.2 Summary of Nutrition Information for RTE Breakfast Cereals in Ireland

As can be seen in Table 4.9, there was high variability in the nutrient content of the cereals. The median energy content for the breakfast cereals was 327 kcal with the energy content ranging from 327 – 601 kcal. The highest energy density was recorded in the health & wellness category. The median total fat and saturated fat content for all breakfast cereals analysed was 6.8g and 1.4g per 100g respectively. Health & wellbeing were found to contain the highest fat (50.1g) and saturated fat content (44g). Children's cereal had the second highest fat content of 37g. Wheat biscuits contributed the least amount of fat (median 1.95g) while brans contained the lowest amount of saturated fat (0.4g) followed closely by wheat biscuits (0.6g).

Carbohydrate content ranged from 11.6g to 90g /100g with a median content of 66.7g with a difference of 19.42g between children's cereal, the highest in carbohydrate, to the lowest, granola & clusters. The median sugar content for all categories was 17g ranging from the lowest sugar content in wheat biscuits (0.7g) to the highest sugar content found in the muesli category (39g). The median amount of dietary fibre across all breakfast cereal categories was 6.9g/100g with the fibre content varying from 1.1 to 27 g/100g across all categories. The children's cereal category contained the least amount of fibre with a median fibre content of 3.85g g/100g. This category contributed the least amount of fibre of 1.1g with the highest fibre content reaching 16g for this category. Other breakfast cereal categories with similar fibre content to the children's cereal category were 'health & wellbeing' and flaked/puffed'. The health & wellbeing group had a median fibre content of 6.0 g/100g, ranging from 1.6 to 11.1 g/100g. The bran category contained the highest fibre content with an average fibre content of 17.3g varying from 11g to 27g for this category in the breakfast cereals analysed.

4.4.3 Nutritional Comparison of RTE Breakfast Cereals formulated with Chicory Root Fibre versus Standard Formulation

Statistical analysis of the nutrient content for products containing chicory root fibre versus breakfast cereals containing no chicory root fibre was conducted for nutrients in scope for reformulation: energy, fat, saturated fat, and sugar. The results of the analysis are outlined in Table 4.10. Products containing chicory root fibre had a significantly higher ($p < 0.05$) energy, fat, saturated fat, and fibre content compared to breakfast cereals containing no chicory root fibre. Breakfast cereal formulations containing chicory root had a significantly lower ($p < 0.05$) sugar content than products containing no chicory root fibre.

Nutrient Criteria	Without Chicory Root Fibre	With Chicory Root Fibre	*p*-Value
Energy (kcal)	387	449.5	0.000*
Fat (g)	6	18.5	0.000*
Saturated Fat (g)	1.3	4.15	0.001*
Sugar (g)	17.4	8.85	0.000*
Fibre (g)	6.90	10.85	0.000*

Table 4.10. Nutrient composition of breakfast cereals containing chicory root fibre (n = 12) and breakfast cereals without chicory root fibre (n = 211).

4.4.4 Fibre-related Claims on Ready to Eat Cereals – Are They Healthier?

The nutrient data of breakfast cereals containing fibre claims and without fibre claims from the sample set collected is reported in Table 4.11. A total of 229 breakfast cereals were included or analysis in this thesis and the fibre content was present in all nutrition declarations. In 204 products the fibre content exceeded 3g/100g that would permit a fibre-related claim to be made. Among the 195 products carrying a nutrition claim, 149 products carried a fibre claim (source of fibre: N = 39, high in fibre: N = 110). The number of fibre claims was marginally higher on retailer's own brand product labels than private brands (N=76 vs 75). Breakfast cereals with a 'High in Fibre' claim had a lower energy, carbohydrate, and salt content and higher dietary fibre content than breakfast cereals containing no fibre claim or 'source of fibre' claim.

		With Fibre Claim	
	No Fibre Claim	Source of Fibre	High in Fibre
Energy (kcal)	387	418	385.5
Total Fat (g /100g)	3.5	12.3	8
Saturated Fat (g /100g)	0.95	2.1	1.4
Total Carbohydrates (g / 100g)	70.05	71	64.95
Sugars (g /100g)	15.65	21.9	16
Fibre (g /100g)	4.5	5	8.5
Salt (g / 100g	0.49	0.5	0.135

Table 4.11. Nutritional quality of breakfast cereals containing a fibre claim and no fibre claim

Chapter 5: Discussion

The aim of this study was to evaluate the role and benefits of dietary fibre ingredients in supporting food reformulation strategies. Diet-attributable diseases present a huge concern for the health industries across the globe largely due to population's suboptimal diet quality and failure to meet national and international recommended dietary guidelines. Food reformulation strategies have been regarded as a public health intervention to tackle the spiralling rates of overweight and obesity by calling for action on the improvement of nutrient profiles of foods to improve populations nutrient intakes. The study expected, to establish the role that dietary fibre can play in achieving successful food reformulation strategies, by understanding the function of dietary fibre ingredients in improving the nutrient composition of three primary processed food groups.

The introductory chapter provided a background to the relationship between diet and disease and the scale of overweight and obesity rates across the globe and in Ireland and the EU to contextualise the need for urgent measures such as food reformulation. The data presented painted an overall picture of high incidences of overweight and obesity in these regions. Monteiro *et al.*, 2018 reported that high intakes of ultra-processed foods which are nutritionally inferior are contributing to the negative health consequences in these regions. It was clearly outlined that a poor-quality diet is associated with an increased risk of diet-related diseases.

NCDs are not just a global issue, they represent a huge problem for the whole island of Ireland. This was made even clearer by Pineda *et al.*, 2018 study which reported that Ireland was projected to experience the greatest obesity rates in Europe with 43% of the Irish population expected to be obese by 2025. This study was published in 2018 and the timeline is just a mere three years from now with little action undertaken to halt the spread of obesity among the Irish population. Background was also given to the impact of poor nutrition on NCD mortality and morbidity by Afshin et al., 2019 who effectively quantified the significant impact of high-sodium, low whole grain and low fruit diets on mortality rate and DALYS on a global scale. The statics reported by Afshin et al., 2019 show that 11 million deaths and 255 million DALYS are linked to dietary risk factors. This data was important to paint a clear depiction of the health consequences of imbalanced diets on health outcomes.

Concerning statistics were reported by *Overweight and obesity - BMI statistics*, 2022 regarding Ireland ranking as one of the highest European countries for obesity rates with 26% of the Irish adult population obese in 2019 with a further 56% of adults classified as overweight. The annual Healthy Ireland survey revealed that the Covid-19 pandemic has influenced adult's body weight with 29% of those surveyed admitting they have put on body weight since the start of the lockdown restrictions. Concrete facts like these put into the context the seriousness of health consequences attributable to poor quality diets.

To provide further context to the impact of diet on health in Ireland, data reported in the NANS was presented for survey years 2008 – 2010. Mean daily intake of nutrients, considered as unhealthy if consumed in excessive proportions, sugar and fat were above the recommended dietary values. Of particular interest relevant to the background of this thesis was the below par dietary intakes for dietary fibre with mean and median daily intakes reported of 19.2g and 18g for the Irish adult population aged 18 – 64 years which does not comply with the recommended intake of 25 – 30g. These values indicate that the Irish adult population is not getting adequate intakes of dietary fibre by up to 40%. These figures are noteworthy, and effort is needed to increase dietary fibre intakes among the Irish population.

In the second chapter, the literature review looked at the topic of food reformulation as a public health strategy. The topic of food reformulation was introduced including the concept and rationale of food reformulation. The definition was provided to the term food reformulation and its role in improving the nutrient composition of processed foods and making the product healthier than its traditional counterpart without negatively impacting product quality attributes. Food reformulation strategies are often steered towards the reduction of specific less healthy nutrients however the topic of positive reformulation was lightly touched on whereby the focus is on the addition of specific nutrients such as wholegrain, fibre or essential fatty acids. These initiatives are less researched however there are industry initiatives such as the Action on Fibre pledge which is aimed at increasing dietary fibre intakes to the recommended levels by increasing the fibre content of its member's range (Action on Fibre).

It's also important to note that reformulation in this way to add beneficial nutrients to the food formulation while maintaining product quality attributes is associated with NCD prevention (van Raaij, Hendriksen and Verhagen, 2008). When considering an improvement in overall health as the goal outcome then initiatives to introduce more beneficial macronutrients or micronutrients into the diet should be welcomed and have some weighting in the development of food manufacturer's food reformulation and nutrition strategies.

The approach that food reformulation must take in being undetectable in the consumer product by consumers was presented. The most effective reformulation strategies should adopt a silent reformulation approach to have the most positive influence on improving nutrient intakes and health and evidence of a successful silent reformulation method was discussed in detail (Gressier *et al.*, 2021).

Several studies were reviewed investigating the effectiveness of food reformulation strategies and all studies concluded an improvement in nutrient intakes as a result of intake of reformulated foods (Pigat *et al.*, 2018; Federici *et al.*, 2019; Gressier, Sassi and Frost, 2020). There is compelling evidence to show that reformulating processed foods provides a practical solution to achieving a positive impact on nutrient intakes and health status of the target population.

The scope of this thesis was concentrated on Ireland therefore it was important to discuss Ireland's newly launched Roadmap for Food Product Reformulation in Ireland set out by the Department of Health Ireland and Healthy Ireland (Department of Health, 2021). This Roadmap provides an important agenda and targets for voluntary reformulation of processed foods in Ireland. The Roadmap outlines the food and drink reformulation targets for Ireland for four key nutrients including five priority food groups. These targets provided the context for the nutrients focused on in this study, particularly sugar and fat reductions and some priority groups for focusing food reformulation efforts on.

Although dietary fibre is not a target nutrient for Ireland's Reformulation Roadmap, a review of the literature clearly highlights the abundance of evidence that exists for the health benefits of consuming dietary fibre in the diet (Grigor *et al.*, 2016; Barber *et al.*, 2020; Cronin *et al.*, 2021). These benefits include but are not limited to improved management of type 2 diabetes, weight management, normal laxation in adults etc. Data reviewed show that fibre intakes among the Irish population are sub adequate and little progress has been made in improving population intakes of dietary fibre since the last dietary survey conducted in 2010 in the Republic of Ireland.

In response to the impact of poor-quality diets on morbidity and mortality, dietary fibre presents an opportunity for food reformulation strategies to target increasing dietary fibre content in processed foods in the overall context of improving the nutrient profile and therefore nutrient intakes. Dietary fibre ingredients have many functions including their role in product reformulation. The use of dietary fibre to enhance the overall nutrient composition of processed foods is an important consideration for food reformulation strategies as the inclusion of dietary fibre in food formulations offers many benefits. From research, it has been established that dietary fibre ingredients have key properties, including functional properties and nutrition benefits.

Inulin, as a non-digestible carbohydrate, was discussed as a dietary source of dietary fibre found naturally in chicory root and other commonly consumed foods such as onion, asparagus etc. and can also be produced synthetically for commercial use. As outlined by Shoaib et al., 2016 inulin is added to processed foods as a sugar or fat replacer, providing only 25 to 35% of calories compared to digestible carbohydrates and a sweetness level of 10% compared to sucrose.

In this study, the role of dietary fibre was assessed to positively modify the nutrient composition of processed foods, either in isolation of a single nutrient or with simultaneous improvement of several nutrients. The two main nutrients focused on for reduction were sugar, and fat with an additional goal of increasing the dietary fibre content compared to the standard product. As sugar can be quite expansive, in the context of this thesis it includes total sugar, added sugars and sucrose.

Data from several studies combined, has clearly ascertained the role of inulin in improving the nutrient profile of select categories of processed foods (Doménech-Asensi *et al.*, 2016; Curti *et al.*, 2018; Majzoobi *et al.*, 2018; Kapoor and Haripriya, 2020; Paciulli *et al.*, 2020; Ferreira, Capriles and Conti-Silva, 2021; Ng *et al.*, 2021; Richardson *et al.*, 2021; Tsatsaragkou *et al.*, 2021).

With the goal of food reformulation of processed foods to improve the nutrient composition of processed foods and dietary intakes, experimental studies based on the use of inulin as a commercial ingredient were reviewed. These studies incorporated inulin with a combination of other ingredients such as Reb A, konjac, black beans, extra virgin olive oil etc. to assess the impact of partial replacement of traditional fat and sugar sources such as butter or sugar on the nutritional quality of the reformulated foods.

In the first food group reviewed of baked goods, several studies were reviewed, which focused specifically on the effect of inulin as a fat replacer and sugar replacer to improve the nutrient composition. Substituting fat with suitable replacers is a significant hurdle to overcome given the important role that fat plays in the textural and organoleptic properties of baked goods (Psimouli and Oreopoulou, 2013). Nutritional improvement of baked goods can be achieved by substituting saturated fats with unsaturated fats (Curti *et al.*, 2018; Pintado *et al.*, 2018).

The effect of fat replacement by incorporating inulin and unsaturated oil was investigated by Doménech-Asensi *et al*., 2016 and Paciulli *et al.*, 2020. Aligned data from these studies demonstrated that significant saturated fat reductions can be achieved up to 38% without impacting negatively on the physiochemical and sensory attributes of the cookies. Although the type and level of inulin differed in these studies using Orafti® HPX at a level of 19% w/w and Frutafit® IQ added in the range of 2.8% to 4.5%, both formulations had a positive influence on the nutritional quality of the cookies. As butter and margarine are key ingredients in cookies contributing to quality characteristics, the improved nutrient profile demonstrated in these studies provides potential for the reformulation of reduced saturated fat high fibre cookies. These results are supported by similar improvements in fat reduction observed for cookies where a total fat content was reduced by up to 46% and a saturated fat decrease of up to 87% in cookies (Giarnetti *et al.*, 2015). The inulin addition in Giarnetti *et al.*, 2015 study of 19% w/w correlates well with the results obtained for Paciulli *et al.*, 2020 suggesting that reformulating with this level of inulin could be a baseline to conduct additional reproducibility studies.

A novel use of an inulin and konjac muffin formulation produced reduced fat and higher dietary fibre muffins with fat reductions ranging from 3.3% to 9.72% and saturated fat reductions ranging from 1.24% to 3.61% (Ng *et al.*, 2021). Inulin konjac concentrations ranging from 30

– 75% were assessed on their impact on nutrient composition (Table 4.1). The experimental muffins were also shown to have a delayed starch retrogradation and lipid rancidity, with the formulation of up to 45% IK suspension showing the greatest potential in reduced fat muffins. Furthermore, the experimental muffins contained higher levels of dietary fibre which further contributes to the overall improvement of the nutrient profile. However, an increase in muffin hardness due to fat reduction and subsequent formation of strong gluten bonds was recorded during storage which would need to be reduced to maintain consumer acceptability. These findings suggest that reformulation of commercial muffins using inulin and konjac as two types of dietary fibre could be considered as a feasible reformulation strategy to produce higher nutritional quality muffins which are traditionally considered a high fat food.

Additional benefits of inulin application on muffins were recorded for an industrial scale experiment to specifically reformulate commercially available muffins which have a different composition to non-commercial baked goods due to the presence of preservatives and additives necessary to maintain the shelf life of the product. The benefits of sugar and fat replacement were seen with just a 10% replacement level with inulin and the addition of green banana flour as seen in Figure 4.2 with fat reductions ranging from 10 – 29% and sugar reductions ranging from 10 – 30% (Harastani *et al.*, 2021). Green banana flour is highly nutritious containing resistant starch up to 58.5% and a fibre content up to 15.5% in addition to phenolic acids and is being considered for commercial application (Sarawong *et al.*, 2014).

Using inulin alone to replace sugar and fat levels by 30% resulted in the muffins having a high-quality nutritional profile in comparison to the commercial muffins high in sugar and fat containing little to no fibre. However, negative results were seen for the texture properties firmness and springiness at the highest levels of fat and sugar substitution (30% fat and sugar replacement). These attributes were the least significantly impacted at substitution levels of 10% as shown in Figure 4.6. This was further supported by the sensory evaluation results in which the changes to the sensory properties were not negatively scored for the 10% reduced fat and 10% reduced sugar formulations containing inulin & GBF. The combined results of these nutritional, textural, and sensory analysis conclude that commercial muffins can be reformulated using 10% inulin to produce reduced fat and sugar muffins with higher dietary fibre content and have overall acceptance by consumers. Such findings provide clear guidance for a successful reformulation method to produce nutritionally superior muffins that are acceptable to consumers.

Based on the findings by Richardson et al., 2021, it can be concluded that inulin, Reb A and pureed black beans are a successful combination producing a simultaneous 50% fat reduction and 30% reduced sucrose sponge cake. This statement is based on the formulation SC30/50 (30% sucrose replacement and 50% fat replacement) which achieved the most favourable consumer acceptance containing 9.3% butter beans, 7.82% inulin and 0.2% Reb A. Sponge cakes containing 42% less fat and 28% less sucrose were achieved using 30% w/w inulin compared to the original formulation to produce a cake containing 7.5g total fat and 21.5g total sugar as presented in Table 4.2. Furthermore, a drastic improvement in the dietary fibre content up to 115% was seen as an additional benefit of the positive reformulation achieved. These results are further supported by a feasibility study in which Reb A and inulin were used to produce healthier cake samples with up to 50% less fat and sucrose compared to the control formulation with similar sensory and quality attributes to the control (Majzoobi *et al.*, 2018).

The replacement of fat and sugar at these levels did have an impact on the texture and colour with a significant increase in hardness recorded when sugar was reduced by 30%. A significantly lighter crust and crumb colour were also observed as presented in Figure 4.7. While these are important attributes in the eating quality of cakes, these changes did negatively affect the sensory scores as the 30% fat and 50% fat reduction had comparable sensory scores to the control sample. The strength of these results is very strong and clearly demonstrate that sponge cakes containing a significant reduction in sugar and fat can be achieved using natural ingredients reformulate commercial sponge cakes. To ensure overall acceptance further work is needed to reduce the impact to hardness and colour attributable to a 30% sugar replacement.

It's critical that caution must be given to such high levels of dietary fibre increases as seen in this study as daily dietary intakes for dietary fibre must fall in line with the recommended intakes. Increasing the dietary fibre drastically can crease gastrointestinal issues such as bloating, discomfort and pain therefore an increase in dietary fibre of 115% would not be consisted as acceptable for a reformulated food. There is a careful balance to strike between improving the nutrient composition of unhealthy nutrients and ensuring dietary fibre increases are progressive and tolerable to consumers without any negative health implications carefully considered.

An important consideration noted in this study was the determination of the minimum amount of both sugar and fat necessary to retain sensory acceptance comparable to the control sponge cake containing 28.9% sugar and 12.9% fat. The minimum sucrose and fat levels were quantified using sensory acceptance testing and/or optimised descriptive testing. Of the studies analysed on the effect of inulin on baked goods this was the only study to adopt this approach and based on the positive results of this trial, both SAT & ODP should be considerations for all reformulation studies to establish a baseline sugar and/or fat content necessary for reformulated products to be acceptable to consumers. Additional nutritional analysis or nutrient calculation at the methodology stage could be beneficial to establish the maximum level of change in dietary fibre from the non-reformulated food. This would ensure that any successful improvements in nutrients fat and sugar are not overcompensated for by a substantial increase in dietary fibre which would not be feasible to place on the market.

The combination of inulin and Reb A was also evaluated in the application of cakes to produce cakes containing up to 50% less fat and sucrose compared to the standard formulation containing high levels of fat and sugar (Majzoobi *et al.*, 2018). Sensory evaluation showed there was no significant difference for the physical properties including height, volume, crust colour and texture, of the 50% reduced fat and sugar formulations when compared to the full fat and sugar sample. Higher levels of fat and sucrose replacement (75% and 100%) negatively impacted these physical properties demonstrating that a minimum level of sugar and fat are important to the physical characteristics of cakes. Similar results were seen in older studies using combinations of inulin and Reb A to partially replace fat or sugar to produce cakes closely resembling the properties of the control (Zahn *et al.*, 2013; Rodríguez-García, Sahi and Hernando, 2014).

A fat and sucrose reduction of up to 50% would permit the food manufacturer to carry a ‘reduced fat’ or ‘reduced sugar’ claim on the label which may have a competitive advantage over silent reformulation for the manufacturer’s reformulation efforts if they wish to choose so.

Results from these studies consistently reported an improvement in the total fat or saturated fat content of the sample formulation compared to the traditional recipes. The significant saturated fat reduction observed in a study by Paciulli et al., 2020 showed reductions of up to 54% achieved when shortbread cookies were formulated with inulin and unsaturated oil to replace butter. Results from the physical properties analysis found that increasing amounts of EFG decreased the diameter and hardness of the cookies (Table 4.4) and affected the colour of the cookies. There was no significant difference recorded for the colour compared to the control when fat was reduced by 40% however hardness was affected. This would indicate that a more realistic fat reduction of 20% was achieved without being detrimental to the product characteristics. The decrease in diameter is to be expected given the important role that fat plays in cookie expansion during baking and has also been reported in previous studies evaluating the effect of inulin as a fat replacer on biscuits (Rodríguez-García *et al.*, 2013).

Cookies containing inulin had the most effect on yellowness with a reduction in yellowness observed as the level of inulin in the formulations increased. This is possibly due to the existence of inulin which provides reducing sugar and may speed up the Maillard reaction (Rodríguez-García *et al.*, 2013). Similar positive results were recorded using HOSO and inulin to reduce the fat content and total sugars and improving the overall nutrient composition (Doménech-Asensi *et al.*, 2016). Combined, these results strongly show the positive influence of inulin on the fat content of cookies and biscuits and show that inulin combined with other ingredients could be a feasible solution to reformulate this category of foods.

Based on two experimental studies on inulin in muffin formulations by Doménech-Asensi et al., 2016; Ng et al., 2021 it can be concluded that inulin is effective in reducing the fat content and noticeably improving the dietary fibre content. This presents an opportunity for food manufacturers to evaluate the use of inulin in reformulating commercial muffins and further assessing the performance of inulin on the physical and sensory properties during storage and the shelf life of the reformulated product.

A review of the literature shows that the incorporation of inulin to replace or reduce the sugar content only of baked goods has not been widely studied. However, the available studies show that inulin can be successful in reducing the sugar content of baked goods without negatively impacting on physical and sensory characteristics(Mieszkowska and Marzec, 2016; Richardson *et al.*, 2021; Tsatsaragkou *et al.*, 2021; Di Cairano *et al.*, 2022). Sugar is a particularly difficult nutrient to replace in baked products due to the important functionality that sugar provides including sugar crystallisation, shelf life protection, browning and retarding gluten formation (Sahin *et al.*, 2019).

The findings of a study conducted by Tsatsaragkou et al., 2021 found that replacement of sugar by 30% with inulin resulted in a 7% decrease in the sugar content of biscuits however hardness was affected resulting in a softer and less crunchy biscuit than the control biscuit containing 22% sugar. Despite the hardness of the biscuit being affected, the sensory results revealed there was no significant difference in sweetness detected for the biscuits formulated with Orafti®. The findings also found that most of the sensory attributed e.g., taste-flavour, mouthfeel and aftereffect had comparable results to the control biscuits containing 22% sugar. These findings are supported by Laguna et al., 2013 who found that inulin replaced the sugar content of short-dough cookies up to 25% without impacting negatively on the consumer overall acceptance however nutritional analysis was not completed as part of this study to directly compare the final sugar content of the biscuits. The findings of Richardson et al., 2021 which achieved a 28% sugar reduction as already outlined further supports the role of inulin in accomplishing an improved nutrient profile without being detrimental to other quality attributes.

These results are novel as they signify that sugar reduced biscuits with a lower sweetness level and less hard and crunchy biscuit were acceptable to the consumer. These findings strongly establish the role of inulin as a key ingredient in food reformulation studies. Higher levels of sugar reduction could be aimed for to assess the textural and sweetness impact on overall acceptance. A 7% - 28% sugar reduction in this category of foods is significant as biscuits have high consumption levels in Ireland as demonstrated by the last dietary survey carried out (The National Adult Nutrition Survey (NANS) (2008-2010) and therefore a sugar reduction in this range would greatly contribute to improved nutrient intakes of sugar.

Similar positive results were observed in the reformulation of commercial gluten-free biscuits. The findings by Di Cairano et al., 2022 as outlined in Figure found that modifying the commercial formulation to replace sugar with inulin at 30% and resistant starch led to a 19% total fat reduction, 60% saturated fat reduction and 32% sugar reduction. A substantial increase in the dietary fibre content of 559% was also recorded as the commercial sample contained just

2.73% of dietary fibre compared to the reformulated GF biscuit containing 18g of fibre. Results from the sensory evaluation scored the inulin reformulation as acceptable providing strength to the study as there was no significant impact on any textural or quality attribute detected. These improvements in the nutrient composition of the reformulated biscuits are tremendous and offer a far superior nutritional quality product than current GF products on the marketplace. Commercial GF biscuits can often be devoid of nutritional quality for individuals following a gluten-free diet. Commercial GF products usually contain a higher GI compared to gluten-containing bakery products (Pellegrini and Agostoni, 2015; Giuberti and Gallo, 2018; Romão *et al.*, 2021).

This was the first study investigating the reformulation of GF biscuits using inulin produced on an industrial level in a production plant therefore there are no comparable studies to critically evaluate the results against. These findings present a significant and practical opportunity for the gluten-free sector to produce nutritious and attractive gluten-free biscuits for coeliac consumers and consumers avoiding gluten in their diet. Manufacturers could also take advantage of the improvement in nutrition profile as the reduction in saturated fat and sugar nutrients and increase in dietary fibre exceeds the criteria for ‘reduced saturated fat’, ‘reduced sugar’ and ‘high fibre’ nutrition claims. As gluten free biscuits are typically nutritionally devoid these nutrition claims might attract interest from gluten-free consumers and contribute to a healthier diet.

Based on the analysis of these studies and taken together, the findings of these studies collectively establish the positive effect of inulin on the nutrient profile of baked goods such as muffins, cakes, and biscuits. This suggests that inulin could be considered as a promising ingredient in this food category as a fat and/or sugar replacer while maintaining acceptable textural and sensory properties to be acceptable to consumers. The results have shown that varying levels of inulin were used to develop formulations with similar characteristics close to the control which provides strength and novelty for its use in food reformulation methods. Different levels of inulin have been used in the studies analysed ranging from 2.8% upwards. For most studies, the results collectively show that the maximum levels of fat and sugar substitution had a negative impact on the physical and sensory properties showing that reformulation must be achieved in a progressive and controlled manner.

The second category of food products reviewed in this thesis was ice-cream selected due to its inclusion in Ireland's Roadmap for Food Reformulation falling under the category of dairy products and desserts. Ice cream is also in the scope of Public Health England's sugar reduction programme (PHE, 2020). To improve the nutrient profile of commonly consumed foods by the general population, we must consider commercially viable approaches to reformulate conventional ice cream products to achieve a fat reduction in line with product reformulation targets. The saturated fat reformulation target for Ireland 2015 – 2025 is a 10% reduction in the saturated fat content of processed foods that contribute most to saturated fat intakes among the Irish population (Department of Health, 2021) Therefore, we can evaluate the impact of inulin addition to conventional ice cream products though product reformulation methods to achieve a minimum saturated fat reduction of 10%.

Ice cream typically contains a fat level ranging from 10 – 16% from dairy cream and fat is a determinant factor in ice cream affecting several technological functions including melting resistance, dryness as well as quality attributes therefore it is critical to ensure these functionalities are not affected through the reduction of the fat content in ice cream (Akbari, Eskandari and Davoudi, 2019). The use of inulin as a fat replacer in ice cream formulations can mimic the technological properties of fat when fat is reduced in ice cream. Inulin is a unique compound with its ability to positively influence the rheological properties, thickness and hardness of foods while permitting changes in the sensory qualities such as texture and lowers the freezing point of desserts (da Silva Faresin *et al.*, 2022).

The studies reported on in this thesis have shown that fat levels can be reduced successfully in ice cream products through the incorporation of inulin and therefore can be considered for application in food reformulation strategies. Studies conducted by Shoaib *et al*., 2016, Kowalczyk, Znamirowska and Buniowska, 2021, Samakradhamrongthai *et al*., 2021, da Silva Faresin et al., 2022 with an overview provided in Table 4.8 prove that inulin has a role to play in improving the nutritional profile of ice cream.

The study on inulin application in a reduced fat ice-cream resulted in an optimised reduced fat formulation containing 13.87% with the inulin directly replacing the fat content by 2.30% (Samakradhamrongthai et al., 2021).Samakradhamrongthai et al., 2021 found that the addition of inulin at varying levels of 2-5% and varying the levels of cream and milk added as sources of sugar and fat had a positive impact on the fat content of the reduced fat ice cream formulation. The addition of inulin at the maximum level of 5% resulted in a reduced fat ice cream formulation containing 8.27% which was a significant reduction. The addition of inulin also positively influenced the ice-cream properties such as firmness with an improved firmness level observed (Samakradhamrongthai et al., 2021).

It should be noted that as the level of whipped cream was reduced in this formulation and the other formulations where the fat content was lower, it is difficult to measure the effect that inulin alone had on the improvement of the lipid profile. Nevertheless, as previous studies on reformulation of baked goods have highlighted (Majzoobi *et al.*, 2018; Richardson *et al.*, 2021) it is necessary for the reformulated product to retain some level of sugar and fat to maintain the product characteristics of ice cream. Consequently, the reduction of fat achieved is a successful outcome and has basis for further development to achieve a higher fat reduction with the potential of a higher level of inulin.

Akbari, Eskandari and Davoudi, 2019 concluded from a literature review of several studies, that reduced fat ice cream formulations containing carbohydrate-based fat replacer inulin has mixed results on ice cream melting properties. The conflicting results reported by several academics revealed that some low fat ice cream formulations containing differing levels of inulin had a significantly weaker melting behavior when compared with the control ice cream (Akbari *et al.*, 2016). In Akbari et al., 2016 study it was observed that the inulin-free low-fat ice cream with 2% fat had a faster melting rate than the control sample containing 10% fat. However, it’s important to note that there was no significant difference in the melting rate between the low-fat ice cream formulations ad the inulin free ice cream (Akbari *et al.*, 2016).

While positive results for a reduced fat formulation containing inulin was demonstrated in this study with positive rheological properties there was no analysis conducted to determine the fat content of the reduced fat ice creams with different inulin levels. This makes it difficult to directly compare the physical and textural properties to other similar studies when the fat content of the reduced-fat inulin containing ice cream formulations is unknown.

Overall, the analysis of these studies on the development and reformulation of reduced fat and full fat ice cream formulations with inulin show positive results. The outcomes from the above studies indicate that ice cream formulations, both full fat and reduced fat, incorporated with inulin can reduce fat and sugar content while delivering acceptable physical, textural properties and sensory acceptance. Further studies are needed in this category to assess the optimised level of inulin addition needed to maintain overall acceptance and contribute to feasibility studies for ice cream manufacturers looking for suitable ingredients to use in their reformulation strategies.

Breakfast cereals are a priority food group for food reformulation as set out in Ireland’s Roadmap for Food Reformulation. However few studies have evaluated the incorporation of inulin and oligofructose in breakfast cereal formulations for an improvement in nutritional quality indicating further research is needed in this area. Of the studies available, the impact on nutritional quality using inulin has been positive.

Kapoor and Haripriya, 2020 found a 16.67% decrease in the fat content of the breakfast cereal formulations by replacing 8% sugar with 16% inulin. In comparison to the other studies on inulin in baked goods, this study relied on a single ingredient of inulin alone to achieve a significant fat reduction. This study also found a dramatic increase (141%) in the dietary fibre content of the inulin containing formulation showing that inulin is effective in increasing the dietary fibre of breakfast cereals. This lower fat content represents a significant ($p < 0.05$) reduction of 16.67% in the fat content of the highest-level inulin sample compared to the control formulation. As previously outlined these studies should establish the maximum change in dietary fibre acceptable to consumers health to ensure that increases in dietary fibre are within a specified target range and do not compromise the successful improvement in nutrient composition that have the potential to improve dietary intakes.

The findings from Ferreira, Capriles and Conti-Silva, 2021 revealed a positive influence of inulin incorporation to breakfast cereal formulations. The addition of 15% inulin greatly improved the dietary fibre content by 5.4-fold which strongly demonstrates that inulin has a positive influence on improving the dietary fibre content of breakfast cereals. The experimental samples had total dietary fibre contents of 13% and 10.3% which can be classified as high in fibre since the total dietary fibre exceeds 6%. These improvements in the nutrient composition through dietary fibre are promising and show that food reformulation with inulin can be successful in improving nutrient intakes of popular RTE breakfast cereals. There was no other nutrient analysed relevant to the scope of this thesis to further discuss an overall improvement in nutrient composition.

The results of the cereal expansion and density results as shown in Figure 4.14 showed no significant difference between the control formulation and inulin samples suggesting that inulin was not detrimental to these physical properties (Ferreira, Capriles and Conti-Silva, 2021). Both expansion and density are fundamental to extruded products therefore these results show that the addition of inulin did not negatively impact these physical properties when added at 15% (Menis *et al.*, 2013).

Of particular interest were the sensory scores which revealed that the inulin samples had no negative effect on key sensory attribute's such as aroma, texture, and flavour. Furthermore, when milk was added the inulin formulations were ranked higher for flavour than the control sample. The positive sensory scores of this study correlate well with the findings of Kapoor and Haripriya, 2020 study who found that the 16% inulin formulation scored the highest in the overall acceptability tests and even improved the appearance and texture of the inulin formulation compared to both the control and commercial samples.

Peressini *et al.*, 2015 evaluated the effect of using two types of inulin with different degrees of polymerisation on physical characteristics of RTE breakfast cereals and this study has significance as it is the only study available in the literature sampled to assess and evaluate inulin with different DP on physical characteristics. In this context of this thesis, this study was analysed relevant to the potential implications of different inulin with different DP on product characteristics. No significant difference on specific volume tests was recorded for the inulin HPX samples (2% % 4& inulin) with a DP of 23 however the specific volume was lowered at the higher inulin level of 7%. The other inulin type with a DP of 10 did have an impact on the expansion volume and hardness with higher levels recorded (Peressini *et al.*, 2015).

The reformulation of foods with inulin and oligofructose as a replacement for glycaemic carbohydrates can offer several health and nutrition benefits including reducing postprandial blood glucose and contributing to reduced sugar intakes and increased fibre intakes among the population. This provides strength to the use of dietary fibre ingredients in food formulation strategies.

Although there are few studies in the literature on developing or reformulating breakfast cereals with inulin or oligofructose as a fat or sugar replacer, the limited studies analysed suggest that that inulin has a role to play in food reformulation strategies for this food category. Of the three food categories analysed breakfast cereals has most significance for food reformulation efforts given the high intakes of breakfast cereals in Ireland as proven by the increased sales of breakfast cereals over the last six years (Euromonitor International, 2021)

Consistent sales of RTE breakfast cereals in Ireland suggest that breakfast cereals remain a popular breakfast option for consumers in Ireland. Sales of healthy RTE breakfast cereals such as bran flakes, muesli and hot cereals have seen a boost in sales due to their perceived healthfulness, availability, and affordable pricing as well as innovations in flavour and formats (Euromonitor International, 2021). Category data obtained from Euromonitor International show sales volume of breakfast cereals in Ireland have grown by 14.1% in the period 2016 to 2021.

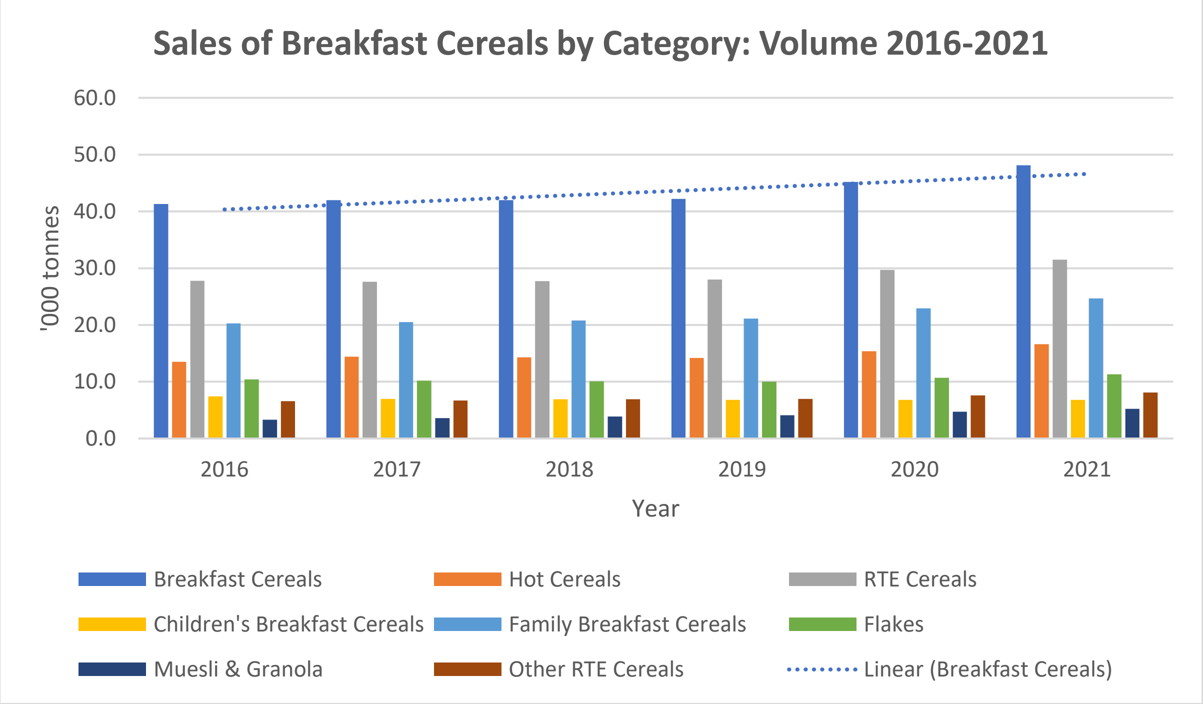


Figure 5.1. Sales of breakfast cereals by category: volume tonnes 2016 - 2021 (adapted from data within Breakfast Cereals in Ireland report from Euromonitor International, 2021).

A further breakdown of this data reveals that RTE cereals has grown by 11.7% in the same period. There has been significant growth in the family breakfast cereals, and muesli and granola categories which have seen a boost in sales of 17.8% and 36.5% respectively. These are strong growth figures for the category highlighting the important position of breakfast cereals in the diets of the Irish population. The only category which has seen a decline in volume sales has been in the children's breakfast cereals which has seen an overall decrease of 8.1%. In 2021 the breakfast cereal category in Ireland was valued at 279 million euros, an increase of 47 million euros in the category from 2016. The % volume growth 2016 - 2021 was estimated at 16.4%. This increasing growth in the breakfast cereal category is evidence that breakfast cereals are a staple food choice with significant opportunities to reformulate and make substantial improvements to nutrient intakes.

The nutritional comparison of breakfast cereals containing chicory root fibre and those without chicory root fibre was analysed for the nutrition data on 229 breakfast cereals collected. The results were of worth as products containing chicory root fibre were found to containing significantly higher levels of energy, fat, saturated fat, and fibre content in comparison to products containing chicory root. This is of interest as these results indicate that products chicory root fibre was not used to address fat reduction, only as a sugar replacer as evidence of the significantly lower sugar content recorded for the breakfast cereals containing chicory root fibre. However, the number of products containing chicory root fibre was a very small sample size of 12 products therefore these results do not have the required statistical power to make a true assessment. The lower sugar content of the breakfast cereals containing chicory root fibre is an encouraging result and provides strength to the feasibility of using inulin to reformulate breakfast cereals to reduce the sugar content and improve dietary intakes of sugars.

Analysis was caried out on the breakfast cereal data collected to assess if fibre claims on RTE breakfast cereals are nutritionally superior to products without a dietary fibre claim on the label or packaging. The results showed that a total of 204 products exceeded a fibre content of 3g/100g which would enable a fibre-related claim such as 'source of fibre' or high in fibre' to be made. 149 products surveyed had a fibre claim with no noticeable difference between private label products and own brand products. Results of the analysis showed that products carrying a ‘high in fibre’ claim had a lower energy intake and higher fibre content than breakfast cereals containing no fibre claim or source of fibre claim. Of significance relative to this thesis was that products containing a high fibre claim had higher amounts of fat, saturated fat and sugars than products containing no fibre claim suggesting that fibre claims are not reflective of the overall nutrition quality and are not a healthier option than products without a fibre claim.

Breakfast cereals containing nutrition claims should guide consumers in making informed food choices by providing information messages about certain nutrients in a simplified way e.g., high-fibre, low-fat etc. However, the literature shows there that the presence of nutrition claims on food packaging and labels highlighting specific “positive characteristics” of the food can often lead to positive interpretations about unrelated nutrients e.g., lower sugar content, reduced fat in what has been termed the “halo effect” (Apaolaza *et al.*, 2017; Fernan, Schuldt and Niederdeppe, 2018).

Findings carried out by Martini et al., 2021 examining 376 breakfast cereals to determine if products with fibre claims have a better nutrient composition than those without, showed that 109 products containing a ‘high in fibre’ claim had a higher protein and fat content but reduced carbohydrate, sugar and salt content compared to the 73 ‘source of fibre’ products and products without fibre claims. The results of this study are conflicting to the data analysis carried out in this study which showed that ‘high in fibre’ claiming products did not have a better nutrient profile than products with no fibre claim. Regarding this thesis, if nutrient claims are made on food products following food reformulation, a full assessment of the overall nutrient profile should be conducted to ensure there has been no negative influence on another nutrient that would jeopardise the goal of reformulation.

We can observe that, in most studies, inulin was used to improve the nutrient profile of processed foods to deliver a health benefit to the consumer and maintain the technological and sensory properties. Reformulation has an important role to play in fighting the spread of obesity and other diet-related diseases. While it is not a ‘silver bullet’ solution to the tackles faced, it is an intervention that has the potential to improve the nutrient profile of foods leading to improved dietary intakes at a population level without a shift in consumer behaviour.

Many reformulation studies on the incorporation of inulin and other dietary fiber ingredients in different food applications have focused mainly on the properties of the immediate finished product, few have evaluated the industrial performance of the reformulated food products to assess the physical and sensory characteristics during storage and the full product shelf life. It is essential to understand the performance of these ingredients in the product throughout the product shelf life and during storage to fully assess the viability of these ingredients for their use in food reformulation strategies. The literature surveyed has clearly demonstrated the positive influence that incorporating dietary fibre ingredients has on the nutritional quality of processed foods. This study has provided a baseline of a suitable ingredient across several different food applications for further review and study.

To make inulin suitable for commercial production, large scale suppliers for inulin need to be available in Ireland and other European countries. The price per kg of breakfast cereals containing inulin and oligofructose had a higher price range (€8.10 - €22.81 /kg) than products without these ingredients (€3.89 – €20.83 /kg) suggesting that inulin is more expensive indicated by the more premium price points. Price information for the commercial inulins used in these studies were not available to assess the real cost of producing products containing commercial dietary fibre ingredients. It is widely acknowledged that sugar is a very cheap commodity therefore breakfast cereals can be produced at a very low cost due to the inexpensive cost of sugar as a raw material that is added in high quantities in breakfast cereals. If inulin and similar commercial dietary fibre ingredients for reformulation strategies are to be used commercially, then the price will need to be discounted to remain commercially viable for the food manufacturer and encourage food manufacturers to reformulate their portfolio of products.

Further research on the optimization of inulin as a fat and sugar replacer should be investigated to find out the most suitable level of inulin to be added in the different food applications assessed during this study. Production feasibility and stability would need to be key considerations for use in successful food reformulation strategies and carefully designed into the study methodologies to account for a full assessment of inulin in reformulation.

The incorporation of inulin or oligofructose as a fibre ingredient into existing breakfast cereal formulations can offer a dual benefit of an increase in dietary fibre and reduction in sugar. These ingredients can be successful in food reformulation strategies as they offer a more balanced nutritional composition and acceptable organoleptic quality. Their use in breakfast cereals must be considered carefully so the inulin is not affected by the extrusion process and inulin degradation occurs. Inulin and oligofructose contribute to the crispness and expansion of extruded breakfast cereals and also increase the shelf life (Franck, 2002).

Analysis of the breakfast cereal data was conducted to determine current nutrient compositions as well as opportunities for reformulating these products with inulin using the results obtained from the studies critically analysed. There was a large variation in energy between product categories with some categories containing products with a very high energy density. Products in the health & wellness category are generally perceived to be healthier by consumers therefore the highest energy value in this category is not expected and reinforces the earlier message about the 'halo effect'.

Saturated fat is one of the target nutrients for reformulation in both the FSAI and PHE reformulation strategies therefore it is important to understand the current levels of fat and saturated fat in breakfast cereals as a priority group and determine if reformulation could achieve similar fat reductions achieved as the studies outlined in Table 4.8. Health & wellbeing and children's cereal were found to contain the highest levels of fat and saturated fat therefore fat reductions could be achieved in these categories as demonstrated in the improvement in fat contents (Kapoor and Haripriya, 2020; Capriles, Conti-Silva and Gomes Arêas, 2021; Ferreira, Capriles and Conti-Silva, 2021). The use of inulin to reformulate breakfast cereals in this category would substantially contribute to improved nutrient intakes of these nutrients while maintaining overall acceptability by consumers.

Wheat biscuits were naturally the lowest in sugar as they usually contain wheat ingredients with little to no added sugars. Muesli is often considered a high sugar food product and therefore as expected contributed the highest sugar content. Out of most interest in the sugar analysis were the sugar results for the children's cereal category. This category ranked the second highest for sugar content with a median sugar content of 20.95g /100g (*M*= 19.09, *SD* = 7.34, *Me*= 20.95). On average, just over one-fifth of children's cereals composition was sugar. The sugar content for children's cereals ranged significantly from 4.9g /100g which would be classified as low in sugar to the highest sugar content of 37g /100g. Both the average sugar content and maximum sugar content results are alarming considering that a child's recommendation of daily sugar is 25g/d. The high sugar level found in children's cereals represents an opportunity for food manufacturers to reformulate these products to achieve a sugar reduction in line with government recommendations and children's recommended intake for sugar. It is encouraging to see that the lowest sugar content recorded was less than 5g per 100g which would be classified as low in sugar, and this should be an example for food manufacturers to strive to achieve by adopting inulin in their product formulations. Considering breakfast cereals are a staple food for children these results highlight the significance of reformulating foods to urgently reduce the sugar content.

If a sugar reduction of 20% was achieved by food manufacturers and retailers producing children's cereals, there would be a vast improvement in the sugar content and therefore the sugar intake of children eating children's cereals. A 20% reduction level would see the average sugar content of children's cereals fall from 19.09g to 15.27g and an average reduction across all categories of 3.3g.

A higher fibre content for the health & wellbeing category would be expected as generally these products are perceived to be a healthier option by consumers and have a higher-than-average fibre content. In this case, the median fibre content for this category was considerably lower than the median fibre content for all breakfast cereal categories. Inulin was found to increase the fibre content by up to 7-fold therefore the use of inulin to increase fibre contents in breakfast cereals is encouraging. As previously suggested a maximum upper tolerance should be established through nutrient mathematical modelling to establish an acceptable dietary fibre increase. This would ensure increases in dietary fibre content to breakfast cereals are progressive and tolerable for consumers with no negative health consequence.

Chapter 6: Conclusion and Further Study

6.1 Conclusion

Fat and sugar represent two principal ingredients in many processed food formulations to define their physical and sensory characteristics. Over consumption of ultra-processed foods and unhealthy eating behaviours are accountable for the increasingly growing rates of obesity and overweight across the globe. Food reformulation has been viewed as one strategy to improve the nutritional composition of foods to achieve lower intakes of unhealthy nutrients in the population. However, what is lacking is concrete solutions for food manufacturers to achieve food reformulation guidelines and overcome the technological challenges of modifying the formulations of processed foods to achieve an improved nutritional value.

This thesis presented an overview of the role of a commercial dietary fibre ingredient inulin in improving the nutritional composition of processed foods. A simple reduction of fat and sugar in processed foods is not straightforward as the literature has demonstrated owing to the functions performed by these foods in different food applications. Therefore, careful consideration must be given to the effects of the replacement of sugar and fat on the quality and sensory attributes of products since these are crucial to the overall acceptance of reformulated products by consumers.

In conclusion, the role of dietary fibre to reduce the sugar and fat content and increase the dietary fibre content of processed foods was reviewed. Findings have established commercial inulin to be a suitable ingredient to reformulate processed foods in three key food categories to achieve a superior nutritional composition compared to the standard product formulation while maintaining product quality attributes comparable to the control formulation. In this way, reformulation would be successful by positively influencing the nutrient composition of processed foods and leading to improved nutrient intakes of the reformulated food which is the ultimate outcome of food reformulation strategies. Significant fat and sugar reductions were seen in the baked goods category when commercial inulin was incorporated at levels 2.5 to 10%. Higher levels of inulin substitution had negative impacts on product characteristics comparable to the control. Effects on product hardness and changes in colour would need to be mitigated if greater improvements in the nutrient profile are to be made to offer meaningful improvements to populations diets.

In formulations using inulin as a clean-label fat replacer in ice cream, fat reductions of up to 40% can be achieved with physiochemical and sensory tests confirming that the reduced fat ice cream has similar melting point, flavour, and creamy mouthful as the full-fat equivalent. While food reformulation is a strategy for food manufacturers to follow, it is not without its challenges and successful food reformulation techniques are needed to show manufacturers how different food groups can be reformulated without impacting on the physical and sensory properties of the product. Indulgence is key in ice cream products and consumers who purchase full fat and indulgent ice creams are not considering the fat content in their purchasing decisions, this is where silent reformulation will have more power than products carrying nutrition claims. By capitalising on the various studies on fat and sugar replacement, food manufacturers can deliver products that are reduced in sugar and fat while maintaining sensory acceptance and adding value by increasing the dietary fibre content through the incorporation of fibre ingredients such as inulin.

A valuable example of the type of industrial scale production that is required was outlined in two of the studies reviewed (Harastani et al., 2021 and (Di Cairano *et al.*, 2022) who reformulated commercially available products. Commercial cakes and other baked goods will differ significantly from control recipes using just traditional basic ingredients as they do not contain additives, preservatives etc. necessary for storage and shelf life. Findings of both studies showed a conclusively positive reformulation outcome with a nutritionally superior reformulated product and overall acceptance by the consumer. This is evidence to support the reproducibility of these studies at production scale to further assess the feasibility of inulin as solution to food reformulation in the categories reviewed.

The success of food reformulation strategies is dependent on consumers consuming these products to achieve the desired improvement in nutrient intakes at population level. While food reformulation strategies remain voluntary for Ireland at this current point in time, food companies must be incentivised to reformulate their products for the benefit of their customers, but this should not come at a financial loss. Prices for breakfast cereals were included in the sample collection however there was limited statistical power in analysing the cost of products containing inulin and those without since there was no information available on the cost of commercial inulin to fully evaluate and compare differences in prices. However, what is known is the inexpensive price of sugar which will make it very challenging for food manufacturers to compete with and be cost effective.

The analysis of the brekafast cereal nutriton data strongly shows there are opportunities to reformulate this category of foods with dietary fibre as demonstrated by the high variation of sugar, fat and fibre found. Analysis of breakfast cereals to predict changes in nutrients showed strong potential for the reduction of sugar in products.

To conclude, inulin and dietary fibre ingredients have a role to play in supporting the successful implementation of food reformulation strategies. The findings of this thesis are novel as for the first time the use of inulin as a sugar or fat replacer is applied in the context of food reformulation. Studies were selected and analysed to show how improvements in nutrient composition could be achieved to ensure comparable qualities to the control and non-reformulated samples. The scope of the studies predominantly focused on the development of new products lower in fat and sugar which would appeal to health-conscious consumers. Analysis of the studies in this thesis was carried out from a reformulation perspective to understand if inulin could improve the nutrient profile of products already on the marketplace with the view to proposing inulin as a suitable ingredient for food reformulation strategies.

6.2 Future Work

Inulin as a commercial dietary fibre ingredient was proven to be a suitable and successful ingredient for the three food applications studied. From the findings of this study, benefit could be achieved in assessing the impact these changes would have on nutrient intakes and health status. Further studies are required to assess the stability of inulin as an ingredient on product quality, texture, nutrition, and shelf life to ensure inulin is stable and maintains the same product qualities as found in the trial studies analysed.

Only one study surveyed investigated the effect of different inulin types with different DP and the findings showed that there were differences on the impact to physical characteristics observed. Future work should evaluate the use of different inulin types with different DP to assess the impact on product properties to select the inulin with the appropriate DP for specific food categories.

The results of the analysis of the breakfast cereals currently available on the market could be used for auditing purposes in the future by the FSAI to monitor the progress in nutrient reformulations over time. Currently there is no complete food product database of all food products in Ireland making it challenging to collect data on reformulated products to assess their contribution to improved nutrient intakes. Therefore, the data collected in this study could be used as a starting point for assessment of nutrient changes from March – April 2022 to determine if voluntary food reformulation is an effective strategy.

Chapter 7: References

Action on Fibre (no date) *The Food & Drink Federation*. Available at: https://www.fdf.org.uk/fdf/what-we-do/diet-and-health/action-on-fibre/ (Accessed: 20 March 2022).

Afshin, A. *et al.* (2019) 'Health effects of dietary risks in 195 countries, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017', *The Lancet*, 393(10184), pp. 1958–1972. doi:10.1016/S0140-6736(19)30041-8.

Aidoo, R.P., Afoakwa, E.O. and Dewettinck, K. (2015) 'Rheological properties, melting behaviours and physical quality characteristics of sugar-free chocolates processed using inulin/polydextrose bulking mixtures sweetened with stevia and thaumatin extracts', *LWT - Food Science and Technology*, 62(1), pp. 592–597. doi:10.1016/j.lwt.2014.08.043.

Akbari, M. *et al.* (2016) 'The effect of inulin on the physicochemical properties and sensory attributes of low-fat ice cream', *International Dairy Journal*, 57, pp. 52–55. doi:10.1016/j.idairyj.2016.02.040.

Akbari, M., Eskandari, M.H. and Davoudi, Z. (2019) 'Application and functions of fat replacers in low-fat ice cream: A review', *Trends in Food Science & Technology*, 86, pp. 34–40. doi:10.1016/j.tifs.2019.02.036.

Apaolaza, V. *et al.* (2017) 'Organic label's halo effect on sensory and hedonic experience of wine: A pilot study', *Journal of Sensory Studies*, 32(1), p. e12243. doi:10.1111/joss.12243.

Barber, T.M. *et al.* (2020) 'The Health Benefits of Dietary Fibre', *Nutrients*, 12(10), p. 3209. doi:10.3390/nu12103209.

Belc, N. *et al.* (2019) 'Reformulating foods to meet current scientific knowledge about salt, sugar and fats', *Trends in Food Science & Technology*, 84, pp. 25–28. doi:10.1016/J.TIFS.2018.11.002.

Briggs, A.D.M. *et al.* (2017) 'Health impact assessment of the UK soft drinks industry levy: a comparative risk assessment modelling study', *The Lancet Public Health*, 2(1), pp. e15–e22. doi:10.1016/S2468-2667(16)30037-8.

Buttriss, J.L. (2020a) 'Why food reformulation and innovation are key to a healthier and more sustainable diet', *Nutrition Bulletin*, 45(3), pp. 244–252. doi:10.1111/nbu.12455.

Buttriss, J.L. (2020b) 'Why food reformulation and innovation are key to a healthier and more sustainable diet', *Nutrition Bulletin*, 45(3), pp. 244–252. doi:10.1111/nbu.12455.

Capriles, V.D., Conti-Silva, A.C. and Gomes Arêas, J.A. (2021) 'Effects of oligofructose-enriched inulin addition before and after the extrusion process on the quality and postprandial glycemic response of corn-snacks', *Food Bioscience*, 43, p. 101263. doi:10.1016/j.fbio.2021.101263.

Croisier, E. *et al.* (2021) 'Back in Time for Breakfast: An Analysis of the Changing Breakfast Cereal Aisle', *Nutrients*, 13(2), p. 489. doi:10.3390/nu13020489.

Cronin, P. *et al.* (2021) 'Dietary Fibre Modulates the Gut Microbiota', *Nutrients*, 13(5), p. 1655. doi:10.3390/nu13051655.

Curti, E. *et al.* (2018) 'Structured emulsions as butter substitutes: effects on physicochemical and sensory attributes of shortbread cookies: Fibre-water-fat systems as butter substitutes in shortbread cookies', *Journal of the Science of Food and Agriculture*, 98(10), pp. 3836–3842. doi:10.1002/jsfa.8899.

Department of Health (2021) *A Roadmap for Food Product Reformulation in Ireland*.

Di Cairano, M. *et al.* (2022) ‘Formulation of gluten-free biscuits with reduced glycaemic index: Focus on in vitro glucose release, physical and sensory properties’, *LWT*, 154, p. 112654. doi:10.1016/j.lwt.2021.112654.

Doménech-Asensi, G. *et al.* (2016) ‘Influence of the reformulation of ingredients in bakery products on healthy characteristics and acceptability of consumers’, *International Journal of Food Sciences and Nutrition*, 67(1), pp. 74–82. doi:10.3109/09637486.2015.1126565.

Euromonitor International (2021) *Breakfast Cereals in Ireland*.

Federici, C. *et al.* (2019) ‘The impact of food reformulation on nutrient intakes and health, a systematic review of modelling studies’, *BMC Nutrition*, 5(1), p. 2. doi:10.1186/s40795-018-0263-6.

Fernan, C., Schuldt, J.P. and Niederdeppe, J. (2018) ‘Health Halo Effects from Product Titles and Nutrient Content Claims in the Context of “Protein” Bars’, *Health Communication*, 33(12), pp. 1425–1433. doi:10.1080/10410236.2017.1358240.

Ferreira, S.M., Capriles, V.D. and Conti-Silva, A.C. (2021) ‘Inulin as an ingredient for improvement of glycemic response and sensory acceptance of breakfast cereals’, *Food Hydrocolloids*, 114, p. 106582. doi:10.1016/j.foodhyd.2020.106582.

Foschia, M. *et al.* (2013) ‘The effects of dietary fibre addition on the quality of common cereal products’, *Journal of Cereal Science*, 58(2), pp. 216–227. doi:10.1016/j.jcs.2013.05.010.

Franck, A. (2002) ‘Technological functionality of inulin and oligofructose’, *British Journal of Nutrition*, 87(S2), pp. S287–S291. doi:10.1079/BJN/2002550.

Giarnetti, M. *et al.* (2015) ‘Fat replacement in shortbread cookies using an emulsion filled gel based on inulin and extra virgin olive oil’, *LWT - Food Science and Technology*, 63(1), pp. 339–345. doi:10.1016/j.lwt.2015.03.063.

Giuberti, G. and Gallo, A. (2018) ‘Reducing the glycaemic index and increasing the slowly digestible starch content in gluten-free cereal-based foods: a review’, *International Journal of Food Science & Technology*, 53(1), pp. 50–60. doi:10.1111/ijfs.13552.

Gressier, M. *et al.* (2021) ‘What is the impact of food reformulation on individuals’ behaviour, nutrient intakes and health status? A systematic review of empirical evidence’, *Obesity Reviews*, 22(2). doi:10.1111/obr.13139.

Gressier, M., Sassi, F. and Frost, G. (2020) ‘Healthy Foods and Healthy Diets. How Government Policies Can Steer Food Reformulation’, *Nutrients 2020, Vol. 12, Page 1992*, 12(7), pp. 1992–1992. doi:10.3390/NU12071992.

Grigor, J.M. *et al.* (2016) ‘The sensory acceptance of fibre-enriched cereal foods: a meta-analysis’, *International Journal of Food Science & Technology*, 51(1), pp. 3–13. doi:10.1111/ijfs.13005.

‘grocery-market-share-ireland’ (no date). Available at: https://www.statista.com/statistics/534106/grocery-market-share-ireland/ (Accessed: 23 April 2022).

Harastani, R. *et al.* (2021) ‘Reformulation of Muffins Using Inulin and Green Banana Flour: Physical, Sensory, Nutritional and Shelf-Life Properties’, *Foods*, 10(8), p. 1883. doi:10.3390/foods10081883.

Hashem, K.M., He, F.J. and MacGregor, G.A. (2019) ‘Effects of product reformulation on sugar intake and health—a systematic review and meta-analysis’, *Nutrition Reviews*, 77(3), pp. 181–196. doi:10.1093/nutrit/nuy015.

Healthy Ireland (no date) *Healthy Ireland Survey 2021 Summary Report*.

Jensen, J.D. and Sommer, I. (2017) ‘Reducing calorie sales from supermarkets – “silent” reformulation of retailer-brand food products’, *International Journal of Behavioral Nutrition and Physical Activity*, 14(1), p. 104. doi:10.1186/s12966-017-0559-y.

Kaldor, J.C. (2018) ‘Food Reformulation for NCD-Prevention: Regulatory Options and Potential Barriers’, *QUT Law Review*, 18(1), pp. 76-76–95.

Kapoor, T. and Haripriya, A. (2020) ‘Formulation and Evaluation of Functional, Nutritional and Sensory Properties of Inulin Incorporated Ready to Eat Multi-grain Breakfast Cereal’, *Indian Journal of Nutrition & Dietetics*, 57(4), pp. 422–438.

Kowalczyk, M., Znamirowska, A. and Buniowska, M. (2021) ‘Probiotic Sheep Milk Ice Cream with Inulin and Apple Fiber’, *Foods*, 10(3), p. 678. doi:10.3390/foods10030678.

Krasaekoopt, W. and Watcharapoka, S. (2014) ‘Effect of addition of inulin and galactooligosaccharide on the survival of microencapsulated probiotics in alginate beads coated with chitosan in simulated digestive system, yogurt and fruit juice’, *LWT - Food Science and Technology*, 57(2), pp. 761–766. doi:10.1016/j.lwt.2014.01.037.

Laguna, L. *et al.* (2013) ‘Inulin and Erythritol As Sucrose Replacers in Short-dough Cookies: Sensory, Fracture, and Acoustic Properties: Sucrose replacers in short-dough cookie…’, *Journal of Food Science*, 78(5), pp. S777–S784. doi:10.1111/1750-3841.12119.

Lightowler, H. *et al.* (2018) ‘Replacement of glycaemic carbohydrates by inulin-type fructans from chicory (oligofructose, inulin) reduces the postprandial blood glucose and insulin response to foods: report of two double-blind, randomized, controlled trials’, *European Journal of Nutrition*, 57(3), pp. 1259–1268. doi:10.1007/s00394-017-1409-z.

Maillot, M., Privet, L. and Masset, G. (2020) ‘Modeled industry-wide food and beverage reformulations reduce the gap between current and nutritionally adequate dietary intakes among French adults’, *European Journal of Nutrition*, 59(3), pp. 1123–1134. doi:10.1007/s00394-019-01973-y.

Majzoobi, M. *et al.* (2018) ‘Feasibility study of sucrose and fat replacement using inulin and rebaudioside A in cake formulations’, *Journal of Texture Studies*, 49(5), pp. 468–475. doi:10.1111/jtxs.12330.

Makki, K. *et al.* (2018) ‘The Impact of Dietary Fiber on Gut Microbiota in Host Health and Disease’, *Cell Host & Microbe*, 23(6), pp. 705–715. doi:10.1016/j.chom.2018.05.012.

Martini, D. *et al.* (2021) ‘Breakfast Cereals Carrying Fibre-Related Claims: Do They Have a Better Nutritional Composition Than Those without Such Claims? Results from the Food Labelling of Italian Products (FLIP) Study’, *Foods*, 10(9), p. 2225. doi:10.3390/foods10092225.

McMenemy, D., Kelly, F. and Sweeney, M.R. (2020) ‘An exploration of food industry led reformulation on fortified food staples in Ireland’, *Journal of Public Health* [Preprint]. doi:10.1093/pubmed/fdaa223.

Menis, M.E.C. *et al.* (2013) ‘Extrusion of flavored corn grits: Structural characteristics, volatile compounds retention and sensory acceptability’, *LWT - Food Science and Technology*, 54(2), pp. 434–439. doi:10.1016/j.lwt.2013.06.021.

Meyer, D. *et al.* (2011) ‘Inulin as texture modifier in dairy products’, *Food Hydrocolloids*, 25(8), pp. 1881–1890. doi:10.1016/j.foodhyd.2011.04.012.

Mieszkowska, A. and Marzec, A. (2016) ‘Effect of polydextrose and inulin on texture and consumer preference of short-dough biscuits with chickpea flour’, *LWT*, 73, pp. 60–66. doi:10.1016/j.lwt.2016.05.036.

Monteiro, C.A. *et al.* (2018) ‘Household availability of ultra-processed foods and obesity in nineteen European countries’, *Public Health Nutrition*, 21(1), pp. 18–26. doi:10.1017/S1368980017001379.

Narala, V.R. *et al.* (2022) ‘Inulin as a fat replacer in pea protein vegan ice cream and its influence on textural properties and sensory attributes’, *Applied Food Research*, 2(1), p. 100066. doi:10.1016/j.afres.2022.100066.

Ng, F.S.K. *et al.* (2021) ‘Influence of inulin–konjac suspension as a fat replacer in baked muffins and its impact on textural and oxidative stability upon storage’, *Journal of Food Processing and Preservation*, 45(10). doi:10.1111/jfpp.15769.

Nieto-Nieto, T.V. *et al.* (2015) ‘Inulin at low concentrations significantly improves the gelling properties of oat protein – A molecular mechanism study’, *Food Hydrocolloids*, 50, pp. 116–127. doi:10.1016/j.foodhyd.2015.03.031.

Nourbehesht, N., Shekarchizadeh, H. and Soltanizadeh, N. (2018) ‘Investigation of stability, consistency, and oil oxidation of emulsion filled gel prepared by inulin and rice bran oil using ultrasonic radiation’, *Ultrasonics Sonochemistry*, 42, pp. 585–593. doi:10.1016/j.ultsonch.2017.12.029.

Obesity and overweight (no date a). Available at: https://www.who.int/news-room/fact-sheets/detail/obesity-and-overweight (Accessed: 6 December 2021).

Obesity and overweight (no date b). Available at: https://www.who.int/news-room/fact-sheets/detail/obesity-and-overweight (Accessed: 12 February 2022).

Overweight and obesity - BMI statistics (no date). Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Overweight_and_obesity_-_BMI_statistics (Accessed: 20 March 2022).

Paciulli, M. *et al.* (2020) ‘Inulin-based emulsion filled gel as fat replacer in shortbread cookies: Effects during storage’, *LWT*, 133, p. 109888. doi:10.1016/j.lwt.2020.109888.

Pellegrini, N. and Agostoni, C. (2015) ‘Nutritional aspects of gluten-free products: Nutritional aspects of gluten-free products’, *Journal of the Science of Food and Agriculture*, 95(12), pp. 2380–2385. doi:10.1002/jsfa.7101.

Peressini, D. *et al.* (2015) ‘Impact of soluble dietary fibre on the characteristics of extruded snacks’, *Food Hydrocolloids*, 43, pp. 73–81. doi:10.1016/j.foodhyd.2014.04.036.

Pigat, S. *et al.* (2018) ‘A probabilistic intake model to estimate the impact of reformulation by the food industry among Irish consumers’, *International Journal of Food Sciences and Nutrition*, 69(8), pp. 938–945. doi:10.1080/09637486.2018.1438375.

Pineda, E. *et al.* (2018) ‘Forecasting Future Trends in Obesity across Europe: The Value of Improving Surveillance’, *Obesity Facts*, 11(5), pp. 360–371. doi:10.1159/000492115.

Pintado, T. *et al.* (2018) ‘Chia and oat emulsion gels as new animal fat replacers and healthy bioactive sources in fresh sausage formulation’, *Meat Science*, 135, pp. 6–13. doi:10.1016/j.meatsci.2017.08.004.

Pintor, A., Escalona-Buendía, H.B. and Totosaus, A. (2017) ‘Effect of inulin on melting and textural properties of low-fat and sugarreduced ice cream: optimization via a response surface methodology.’, *International Food Research Journal*, 24(4), pp. 1728-1728–1734.

Prada, M. *et al.* (2021) ‘Examining the Relationship between Sugar Content, Packaging Features, and Food Claims of Breakfast Cereals’, *Nutrients*, 13(6), p. 1841. doi:10.3390/nu13061841.

Psimouli, V. and Oreopoulou, V. (2013) ‘The Effect of Fat Replacers on Batter and Cake Properties: Fat Replacers in Cake…’, *Journal of Food Science*, 78(10), pp. C1495–C1502. doi:10.1111/1750-3841.12235.

van Raaij, J., Hendriksen, M. and Verhagen, H. (2008) ‘Potential for improvement of population diet through reformulation of commonly eaten foods’, *Public Health Nutrition*, p. 1. doi:10.1017/S1368980008003376.

Richardson, A.M. *et al.* (2021) ‘The Application of Pureed Butter Beans and a Combination of Inulin and Rebaudioside A for the Replacement of Fat and Sucrose in Sponge Cake: Sensory and Physicochemical Analysis’, *Foods*, 10(2), p. 254. doi:10.3390/foods10020254.

Robin, F., Schuchmann, H.P. and Palzer, S. (2012) ‘Dietary fiber in extruded cereals: Limitations and opportunities’, *Trends in Food Science & Technology*, 28(1), pp. 23–32. doi:10.1016/j.tifs.2012.06.008.

Rodríguez-García, J. *et al.* (2013) ‘Effect of Fat Replacement by Inulin on Textural and Structural Properties of Short Dough Biscuits’, *Food and Bioprocess Technology*, 6(10), pp. 2739–2750. doi:10.1007/s11947-012-0919-1.

Rodríguez-García, J., Sahi, S.S. and Hernando, I. (2014) ‘Functionality of lipase and emulsifiers in low-fat cakes with inulin’, *LWT - Food Science and Technology*, 58(1), pp. 173–182. doi:10.1016/j.lwt.2014.02.012.

Romão, B. *et al.* (2021) ‘Glycemic Index of Gluten-Free Bread and Their Main Ingredients: A Systematic Review and Meta-Analysis’, *Foods*, 10(3), p. 506. doi:10.3390/foods10030506.

Sahin, A.W. *et al.* (2019) ‘Sugar reduction in bakery products: Current strategies and sourdough technology as a potential novel approach’, *Food Research International*, 126, pp. 108583–108583. doi:10.1016/j.foodres.2019.108583.

Samakradhamrongthai, R.S. *et al.* (2021) ‘Inulin application on the optimization of reduced-fat ice cream using response surface methodology’, *Food Hydrocolloids*, 119, p. 106873. doi:10.1016/j.foodhyd.2021.106873.

Sarawong, C. *et al.* (2014) ‘Effect of extrusion cooking on the physicochemical properties, resistant starch, phenolic content and antioxidant capacities of green banana flour’, *Food Chemistry*, 143, pp. 33–39. doi:10.1016/j.foodchem.2013.07.081.

Shoaib, M. *et al.* (2016) ‘Inulin: Properties, health benefits and food applications’, *Carbohydrate Polymers*, 147, pp. 444–454. doi:10.1016/j.carbpol.2016.04.020.

da Silva Faresin, L. *et al.* (2022) ‘Development of ice cream with reduction of sugar and fat by the addition of inulin, Spirulina platensis or phycocyanin’, *International Journal of Gastronomy and Food Science*, 27, p. 100445. doi:10.1016/j.ijgfs.2021.100445.

Stephen, A.M. *et al.* (2017) ‘Dietary fibre in Europe: current state of knowledge on definitions, sources, recommendations, intakes and relationships to health’, *Nutrition Research Reviews*, 30(2), pp. 149–190. doi:10.1017/S095442241700004X.

Sugar reduction and wider reformulation - GOV.UK (no date). Available at: https://www.gov.uk/government/collections/sugar-reduction (Accessed: 20 March 2022).

‘The National Adult Nutrition Survey (NANS) (2008-2010).pdf’ (no date). Available at: https://irp-cdn.multiscreensite.com/46a7ad27/files/uploaded/The%20National%20Adult%20Nutrition%20Survey%20%28NANS%29%20%282008-2010%29.pdf (Accessed: 13 February 2022).

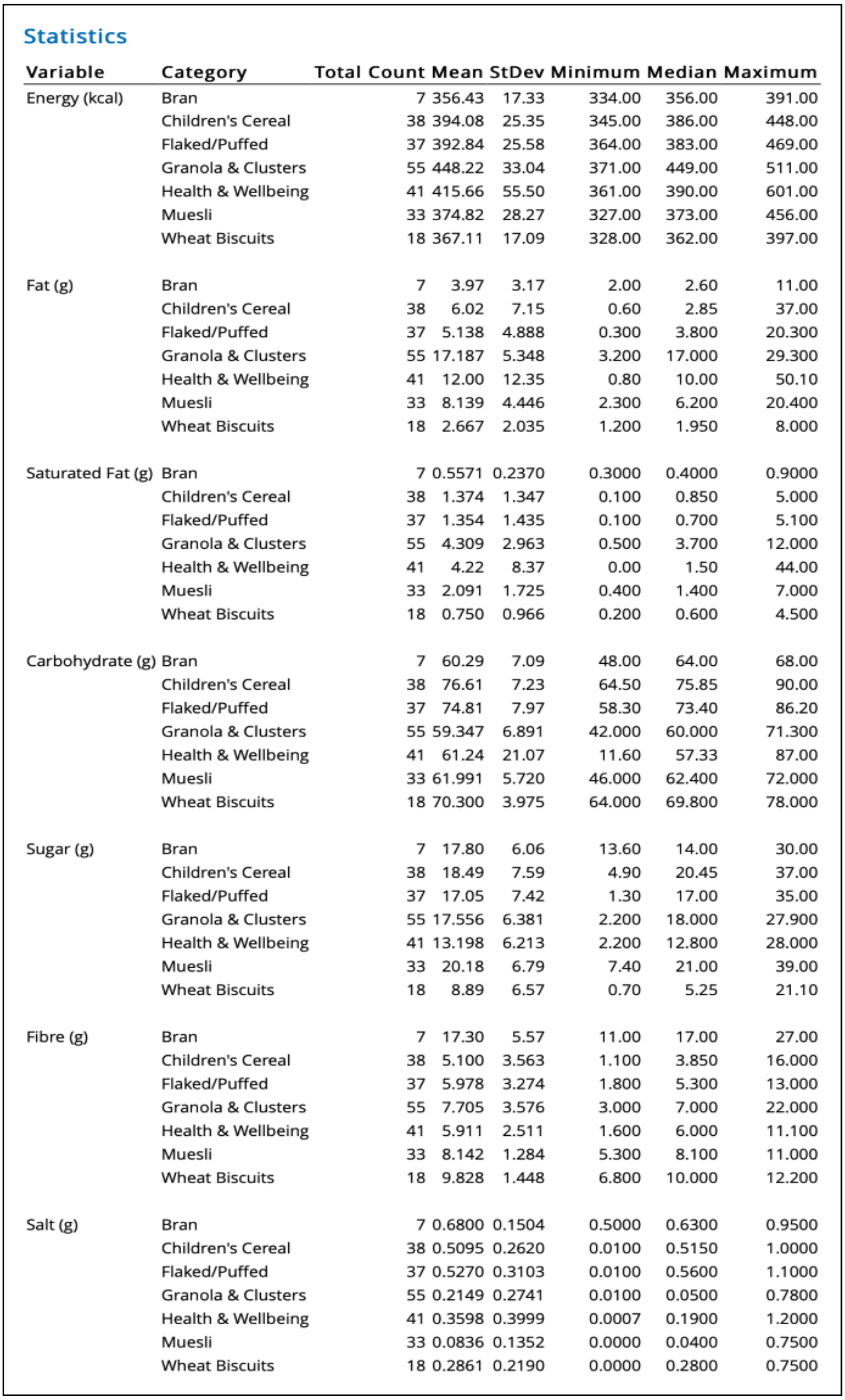
Tsatsaragkou, K. *et al.* (2021) ‘The Functionality of Inulin as a Sugar Replacer in Cakes and Biscuits; Highlighting the Influence of Differences in Degree of Polymerisation on the Properties of Cake Batter and Product’, *Foods*, 10(5), p. 951. doi:10.3390/foods10050951.

Yeung, C.H.C. *et al.* (2017) ‘Modelling of the impact of universal added sugar reduction through food reformulation’, *Scientific Reports*, 7(1), p. 17392. doi:10.1038/s41598-017-17417-8.

Zahn, S. *et al.* (2013) ‘Combined use of rebaudioside A and fibres for partial sucrose replacement in muffins’, *LWT - Food Science and Technology*, 50(2), pp. 695–701. doi:10.1016/j.lwt.2012.07.026.

Appendix 1: Additional Tables

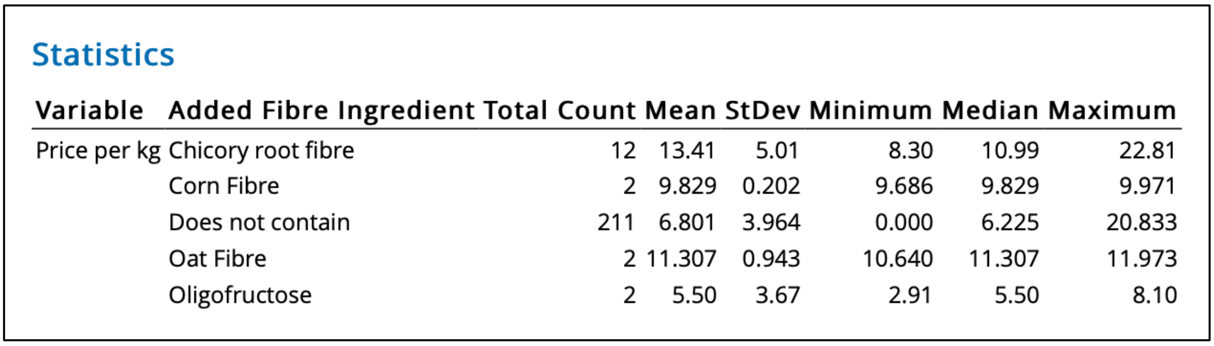
Appendix 1a: Descriptive Statistics of Breakfast Cereals Nutrition Data by Category



Statistics

Variable	Category	Total Count	Mean	StDev	Minimum	Median	Maximum
Energy (kcal)	Bran	7	356.43	17.33	334.00	356.00	391.00
	Children's Cereal	38	394.08	25.35	345.00	386.00	448.00
	Flaked/Puffed	37	392.84	25.58	364.00	383.00	469.00
	Granola & Clusters	55	448.22	33.04	371.00	449.00	511.00
	Health & Wellbeing	41	415.66	55.50	361.00	390.00	601.00
	Muesli	33	374.82	28.27	327.00	373.00	456.00
	Wheat Biscuits	18	367.11	17.09	328.00	362.00	397.00
Fat (g)	Bran	7	3.97	3.17	2.00	2.60	11.00
	Children's Cereal	38	6.02	7.15	0.60	2.85	37.00
	Flaked/Puffed	37	5.138	4.888	0.300	3.800	20.300
	Granola & Clusters	55	17.187	5.348	3.200	17.000	29.300
	Health & Wellbeing	41	12.00	12.35	0.80	10.00	50.10
	Muesli	33	8.139	4.446	2.300	6.200	20.400
	Wheat Biscuits	18	2.667	2.035	1.200	1.950	8.000
Saturated Fat (g)	Bran	7	0.5571	0.2370	0.3000	0.4000	0.9000
	Children's Cereal	38	1.374	1.347	0.100	0.850	5.000
	Flaked/Puffed	37	1.354	1.435	0.100	0.700	5.100
	Granola & Clusters	55	4.309	2.963	0.500	3.700	12.000
	Health & Wellbeing	41	4.22	8.37	0.00	1.50	44.00
	Muesli	33	2.091	1.725	0.400	1.400	7.000
	Wheat Biscuits	18	0.750	0.966	0.200	0.600	4.500
Carbohydrate (g)	Bran	7	60.29	7.09	48.00	64.00	68.00
	Children's Cereal	38	76.61	7.23	64.50	75.85	90.00
	Flaked/Puffed	37	74.81	7.97	58.30	73.40	86.20
	Granola & Clusters	55	59.347	6.891	42.000	60.000	71.300
	Health & Wellbeing	41	61.24	21.07	11.60	57.33	87.00
	Muesli	33	61.991	5.720	46.000	62.400	72.000
	Wheat Biscuits	18	70.300	3.975	64.000	69.800	78.000
Sugar (g)	Bran	7	17.80	6.06	13.60	14.00	30.00
	Children's Cereal	38	18.49	7.59	4.90	20.45	37.00
	Flaked/Puffed	37	17.05	7.42	1.30	17.00	35.00
	Granola & Clusters	55	17.556	6.381	2.200	18.000	27.900
	Health & Wellbeing	41	13.198	6.213	2.200	12.800	28.000
	Muesli	33	20.18	6.79	7.40	21.00	39.00
	Wheat Biscuits	18	8.89	6.57	0.70	5.25	21.10
Fibre (g)	Bran	7	17.30	5.57	11.00	17.00	27.00
	Children's Cereal	38	5.100	3.563	1.100	3.850	16.000
	Flaked/Puffed	37	5.978	3.274	1.800	5.300	13.000
	Granola & Clusters	55	7.705	3.576	3.000	7.000	22.000
	Health & Wellbeing	41	5.911	2.511	1.600	6.000	11.100
	Muesli	33	8.142	1.284	5.300	8.100	11.000
	Wheat Biscuits	18	9.828	1.448	6.800	10.000	12.200
Salt (g)	Bran	7	0.6800	0.1504	0.5000	0.6300	0.9500
	Children's Cereal	38	0.5095	0.2620	0.0100	0.5150	1.0000
	Flaked/Puffed	37	0.5270	0.3103	0.0100	0.5600	1.1000
	Granola & Clusters	55	0.2149	0.2741	0.0100	0.0500	0.7800
	Health & Wellbeing	41	0.3598	0.3999	0.0007	0.1900	1.2000
	Muesli	33	0.0836	0.1352	0.0000	0.0400	0.7500
	Wheat Biscuits	18	0.2861	0.2190	0.0000	0.2800	0.7500

Appendix 1b: Descriptive Statistics of Breakfast Cereals Price per kg by Dietary Fibre Ingredient



Statistics

Variable	Added Fibre Ingredient	Total Count	Mean	StDev	Minimum	Median	Maximum
Price per kg	Chicory root fibre	12	13.41	5.01	8.30	10.99	22.81
	Corn Fibre	2	9.829	0.202	9.686	9.829	9.971
	Does not contain	211	6.801	3.964	0.000	6.225	20.833
	Oat Fibre	2	11.307	0.943	10.640	11.307	11.973
	Oligofructose	2	5.50	3.67	2.91	5.50	8.10