Reformulation of Foods for Weight Loss: a Focus on Carbohydrates and Fats

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Abstract

The Health Survey for England 2016 shows that the prevalence of overweight and obesity is increasing with 27% of adults being obese and 40% of men and 30% of women were overweight. As half of the UK population is expected to be obese by 2050, reformulation of food products can play a significant role in production of healthier foods with low energy density that can increase satiety and reduce food intake. Fat is the most energy dense nutrient, hence is a key area of reformulation for weight loss. The focus for reformulation in terms of fat is often on reducing saturated fat, but for weight loss overall fat reduction is most important. This can be achieved through fat replacement products or altering the type of fats added to products to make them more satiating. Food reformulation in carbohydrate foods mainly involves reducing sugar and increasing fibre content. Considering that the current UK population has a high intake of sugars and low intake of fibre, reformulation strategies using bulk and intense sweeteners (IS) as well as various dietary fibre ingredients, are a viable way to have a positive influence on public health. The current chapter focuses on how carbohydrate and fat in food products can be reformulated to promote satiety and weight loss.

Keywords: body weight, lipid, sugar, fibre, fatty acid

1. Introduction

Overweight and obesity has been a problem worldwide for the past few decades, caused by changes in patterns of energy intake, physical activity as well as various genetic and environmental factors (Wilding, 2012; Frayling, 2012). Currently, maintaining a healthy body mass index (BMI) and body composition is more important than ever in order to reduce the prevalence of various chronic diseases such as cardiovascular diseases, type 2 diabetes, some types of cancers and many other chronic diseases (Dee et al., 2014). Dietary strategies to achieve this goal include reducing the consumption of sugars and fats as well as increasing the intake of fibre and protein (Howarth et al., 2001; Leidy et al., 2015; Morenga et al., 2013). Irrespective of the choice of strategy, the end goal for the consumer should be not just to lose weight, but also to maintain the weight loss in a sustainable way and prevent the yo-yo effect that leads to subsequent weight gain.

The amount of the British household income currently spent on food and soft drinks is just 15% – less than half of what was spent 50 years ago (Office for National Statistics, 2015). In the 1960s, having sufficient nutritious food was a real problem. Today, however, malnutrition still exists but in the form of obesity, the current major public health concern. The Health Survey for England 2016 (NatCen Social Research and UCL, 2017) shows that the prevalence of overweight and obesity is increasing, with 27% of adults being obese and 40% of men and 30% of women were overweight. Based on previous trends it is predicted that by 2030 the prevalence of obesity will rise to from 26% to 41-48% in men, and from 26% to 35-43% in women (Wang et al, 2011). Consumers seek affordable, convenient and palatable foods and though health is an important factor for many in choosing foods, it is not at the top of consumer priorities (Lappalainenab et al, 1998). Food companies are under increasing pressure to develop healthier foods both by consumers and by Governments. In 2012, many food firms, supermarkets and high street chains agreed a series of voluntary pledges with the Department of Health called The Responsibility Deal, in which they committed to playing their part in trying to ensure that Britons consume five billion fewer calories a day (Public Health England, 2017). Reformulation of food products can play a significant role in production of healthier foods (Tedstone, 2016).

2. Reformulation of Carbohydrates

Previous research has investigated the impact of sugar-sweetened beverage (SSB) consumption on increased prevalence of obesity in both children and adults (Hu, 2013; Malik et al., 2013) as well as the incidence of chronic diseases (Chen et al., 2009; Dhingra et al., 2007; Dubois et al., 2007; Fung et al., 2009; Malik et al., 2006. However, there has also been much debate on the role of natural fruit sugars such as fructose on weight gain and related co-morbidities (van Buul et al., 2014). The recommendations often focus around reducing 'free sugar' consumption which is not only naturally present in honey, syrup, fruit juices and fruit juice concentrates, but also added by the consumer, cook or manufacturer to various products (World Health Organisation, 2015). Previously, free sugars were included under the category 'Non-milk extrinsic sugars' (NMES), which also included half of the fruit sugars from dried, stewed or canned fruit (Public Health England, 2015a). Another terminology that was used before the emergence of the term 'free sugars' was 'added sugars', which did not include natural sugars in fruits, vegetables, their juices or purees and dairy products (Mela and Woolner, 2018).

Current UK data shows intake of free sugars at 11.1 % and 11.2% in adult men and women aged 19 to 64 years respectively (National diet and nutrition survey, 2018). This is more than double the recommended amount of no more than 5% of daily energy intake from free sugars in individuals over 2 years of age (SACN, 2015). Children aged 1.5 to 3 years had similar intake levels at 11.3 %. But, the data for free sugars in girls aged 11-18 years is even higher at 14.4% total daily energy intake (National diet and nutrition survey,2018). The mean fibre intake (using the Association of Official Agricultural Chemists (AOAC) method) in adults from 19 to 64 years was 19%, considerably lower than the recommended 30 g/day by the Scientific Advisory Committee on Nutrition (SACN, 2015). Children of all age groups had significantly lower AOAC fibre intake levels compared to previous years. Moreover, only 2% of 11-18 year old girls met the AOAC fibre recommendations (National diet and nutrition survey, 2018). According to Hashem et al. (2016), results from diet and nutrition surveys may underestimate a population's free or added sugar consumption as consumers are not able to distinguish between free and total sugars in their diet. Moreover, this effect can be exacerbated by the inherent problem of underreporting commonly referred to in surveys.

Added sugars, especially in SSBs are known to contribute to increasing obesity levels in not only the UK, but also in American, Brazilian and Australian populations (Hu, 2013; Jeong et al., 2014; Lei et al., 2016). Public Health England advocates dietary sugar reduction to improve the health status of individuals, as well as to achieve annual savings on the National Health Service (NHS) spending on various diseases/conditions resulting from the overconsumption of SSBs and sugary foods (Public Health England, 2015). These recommendations along with fiscal policies such as the implementation of sugar tax have motivated food manufacturers to reformulate sugary foods and beverages by using non-nutritive sweeteners (NNS). As indicated by the name, NNS provide sweetness to foods with very little or no addition of energy or calories (Sylvetsky and Rother., 2018).

Popular weight loss strategies often recommend reducing the consumption of sugar and increasing the consumption of fibre or replacing carbohydrate intake in daily diet with other macronutrients such as protein (SACN, 2015). Another viable strategy is to consume reformulated foods with low sugar content (van Raaij et al., 2009). Starch and sugar-rich foods could be made less energy dense by including low- or no-calorie sweeteners or dietary fibre from various natural or synthetic sources. Previous research on low-calorie sweeteners (LCS) has produced mixed results on weight loss (Foreyt et al., 2012; Stellman and Garffinkel, 1986; Blundell and Hill, 1986; Mattes and Popkin, 2009; Piernas et al., 2013). Whilst they are well known to maintain the sweetness and palatability of the products by decreasing energy density during reformulation, some studies have reported an increase in energy intake and weight gain following consumption of LCS (Stellman and Garffinkel, 1986; Blundell and Hill, 1986). The mechanisms behind this effect indicate their inability to induce satiety mediated by hormones as well as cause undesirable side effects and taste alterations resulting from various doses of the LCS used (Stellman and Garffinkel, 1986; Blundell and Hill, 1986).

This section aims to explore the various ingredients and strategies used in carbohydrate reformulation of foods and beverages and their effectiveness in achieving weight loss in adult participants. Due to the broad nature of the topic, it has not been possible to include research related to reformulation of all types of carbohydrates. Therefore, the studies presented are from year 2000 onwards, relating

to the use of sweeteners to replace sucrose (table sugar). The impact of using fibre ingredients for the replacement of starch in food products is also included. However, those studies where carbohydrates are not used for reformulation, but, given as *supplements for weight loss* are beyond the scope of this chapter.

2.1 Strategies for Carbohydrate Reformulation

Carbohydrate reformulation involves multiple strategies using alternative sweeteners, sugar alcohols, starch, fibre etc to replace sucrose and starch in foods and beverages, resulting in reduction of energy content to varying levels. Sometimes, in savoury foods, if sugar is added for functions other than sweetness, it does not have to be replaced (Markey et al., 2015). Alterative sweeteners can be classified as bulk sweeteners (BS) or intense sweeteners (IS). As the name implies, IS have very strong sweetness and hence, are needed in only small quantities to replace large amounts of sugar with no increase in calorie content. On the other hand, most of the BS contribute to less sweetness and energy content than sucrose, but provide bulking effect and are non-cariogenic (Kroger at al., 2006; Mortensen, 2006; Grembecka, 2015). Furthermore, sometimes both BS and IS are used together making it difficult to decipher their individual effects on food product characteristics and their resultant health effects. Due to the chemical origin of many IS, they are also referred to as artificial sweeteners (AS) (Mortensen, 2006). However, more recently, food manufacturers and consumers have become more interested in plant-based IS such as steviol glycosides. Table 1 lists the LCS commonly used in food products.

Table 1: Commonly used intense and bulk sweeteners in sugar reformulation

Intense sweeteners	**Bulk sweeteners**
Acesulfame potassium	Erythritol
Aspartame	Hydrogenated starch hydrolysates
Luo han guo extract	Isomalt
Neotame	Lactitol
Saccharin	Maltitol
Steviol glycosides	Mannitol
Sucralose	Sorbitol
Cyclamate	Xylitol

Thaumatin Neohesperidin dihydrochalcone Alitame	Polyglycitol syrup

References: Miller and Perez, 2014; Bruyere et al., 2015; Mortensen, 2006; Grembecka, 2015

2.1.1 Sugar reformulation using intense sweeteners

Intense sweeteners (IS) are either plant based or produced by chemical synthesis (Bruyere et al., 2015). They are used as single ingredients, a blend or in combination with sugar based on the required flavour for the product in which they are incorporated (Gardner et al., 2012). One of the most commonly used IS is aspartame, which is a couple of hundred times sweeter than sucrose (Benton, 2005). However, the first sweetener to be used in foods was saccharin, which is about 300 times sweeter compared to sucrose. A third sweetener called cyclamate has also been used in foods in combination with other sweeteners because it is only thirty times as sweet as sucrose (Benton, 2005). Some of the second generation AS such as acesulfame–K can result in bitter taste characteristics in foods, while others such as sucralose can result in reformulated products with significantly higher sweetness compared to their regular counterparts (Markey et al., 2015). Acesulfame and sucralose are approximately 200 and 600 times sweeter than sucrose respectively, whereas other recently developed sweeteners such as alitame and neotame could impart several thousand times sweetness than sucrose (Benton, 2005).

Stevioside is an IS (200-300 times as sweet as sucrose) extracted from the leaves of the plant *Stevia rebaudiana* Bertoni (Mortensen, 2006). An extract containing 95% or more of the sweet compounds steviol glycosides, qualify as a sweetener to be used in foods and beverages. There are 11 steviol glycosides, of which, the most abundant types in the commercial extracts are Rebaudioside A and Stevioside (Ashwell, 2015). Stevia has got generally recognized as safe (GRAS) status from the United States Food and Drug Administration (FDA) (Anton et al., 2010) and has been approved by the Food and Agriculture Organization (FAO) and the World Health Organization (WHO) as a sweetener (FAO/WHO, 2005). Furthermore, the European Food Safety Authority (EFSA) approved the use of steviol glycosides as a food additive in 2010 (EFSA, 2010a). Yet, there is a lack of human studies investigating the effect of

reformulated foods with stevia extracts on appetite, energy intake or weight loss. Nonetheless, considering the increasing awareness in recent years among consumers to choose healthier foods, there are even higher chances for sugar reformulated products to appeal to the general public with the help of the claims given below (Burgos et al., 2016):

Low sugar	Only used if the product contains no more than 5 g of sugars in 100 g solids and 2.5 g sugars in 100 ml liquids
Sugar-free	The product must contain 0.5 g or less sugars in 100 g or 100 ml of solids and liquids respectively
No added sugar	Can be used only of no sugars are added to the food
Energy reduced	Can be used only if the product is reduced in energy content by at least 30%

By reducing the calorie content of the foods/beverages in which the ISs are incorporated, an effect on weight loss and/or weight management is anticipated. Yet, there are no EFSA approved health claims approved for these sweeteners in relation with the above effects (Bruyere et al., 2015). This may be partly because our human body can adjust the energy intake and expenditure based on the available calorie content of the foods consumed and therefore, we tend to compensate for the reduced energy intake after consuming sugar-reformulated products. In order to fully understand this phenomenon, it is important to explore the effects of ISs on satiation, satiety, energy compensation, the amount and type of macronutrients consumed during compensation as well as the short- and long-term effects of ISs (Benton, 2005).

2.1.2. Bulk sweeteners to replace sucrose

As seen in Table 1, BS are mostly sugar alcohols (polyols) present naturally in fruits, some vegetables and mushrooms, or produced by enzymatic methods of carbohydrate hydrogenation for commercial use (Grembecka, 2015). The sweetness index of BS is either the same or lower than sucrose. For e.g. polyols such as xylitol and maltitol are as sweet as sucrose, whereas, lactitol and isomalt have only 50% of the sweetness of sucrose. Other BSs such as erythritol, sorbitol and mannitol have a range of sweetness from 50 to 100% in comparison with sucrose (Mortensen, 2006).

Generally, BSs affect the physical properties of foods such as their freezing point and susceptibility to browning reaction. The polyols are also called nutritive sweeteners due to their slow or partial absorption in the intestine contributing to a laxative effect and a lower caloric value ranging from 0.2 to 2.7 kcal/g (Grembecka, 2015). Moreover, they do not stimulate insulin production and may also provide a prebiotic effect by stimulating the growth of good gut bacteria (Grembecka., 2015; Mortensen., 2006).

In addition to providing sweetness, polyols also act as flavour enhancers, stabilisers, humectants, bulking agents, anticaking agents, glazing agents, thickeners, emulsifiers and sequestrants (Grembecka., 2015). Polyols such as maltitol can give a cooling effect and change the rheological properties and thereby quality, when used to replace sugar in some products (Markey et al., 2015). Despite the above properties, if consumed in excess, polyols can cause undesirable gastrointestinal side-effects such as flatulence and bloating. This is due to their fermentation in the large intestine resulting in the production of short chain fatty acids and gases (Livesey., 2003; Grabitske and Slavin., 2008).

2.2 Dietary fibre to replace starch and sucrose

Dietary fibre is an integral part of plant-based foods, which have been shown to provide various health benefits including reducing the risk of chronic diseases such as type 2 diabetes, cardiovascular diseases and some types of cancers (Brownlee et al., 2017). Foods high in fibre as well as the isolated and extracted fibre ingredients have low energy density and therefore reduce energy intake and energy absorption. In some instances, fibre has also been shown to increase energy expenditure (by influencing the secretion of hormones and ileal brake) as well as promote energy excretion in the form of fats and bile acids (Weickert and Pfeiffer., 2008). Moreover, dietary fibre is also linked to laxative effects resulting from stool bulking and reduced gut transit time, albeit the impact is not apparently the same for different fibre sources (de Vries et al., 2016).

In a recent review, Brownlee et al (2017) have highlighted that although plant-based foods are recommended for weight loss and weight management, neither observational nor interventional studies have been successful in demonstrating their effectiveness in showing a biologically meaningful effect on weight loss parameters

such as body weight, BMI, body fat and waist circumference. The studies included were considering the intake of whole grains, fruits and vegetables using various research designs, doses of test foods and study duration, which may be some of the reasons for the lack of effect (Brownlee et al., 2017). On the contrary, long-term studies using vegetarian, vegan and Mediterranean diets have demonstrated significant effects on weight loss proving that an increase in fibre intake is an important contributing factor for the results (Barnard et al., 2005; Esposito et al., 2004; Reidlinger et al., 2015). Polydextrose, Resistant starch, inulin, beta-glucan and glucomannan are some of the commonly used polysaccharides to reduce energy density of carbohydrate foods and thereby potentially contribute to weight loss (Ibarra et al., 2016; Higgins., 2014; Liber and Szajewska., 2013; Yeung et al., 2018; Clegg and Thondre., 2014).

Polydextrose is a glucose polymer that resembles sucrose providing only 25% of its energy content. It acts as a soluble fibre without undergoing complete digestion in the intestine and thereby being subjected to fermentation in the colon by the gut bacteria. Due to its versatility as a neutral, low calorie ingredient with non-viscous, yet bulking properties, polydextrose has been used in many foods (Do Carmo., et al 2016).
Resistant starch (RS) can be defined as the type of starch or products of starch digestion that are not digested and absorbed in the small intestine, and therefore reaches the large intestine where they undergo fermentation (Higgins., 2014). There are four types of RS - physically inaccessible RS1 present in seeds and grains, enzymatically inaccessible RS2 which differs in the starch component ratio of amylose and amylopectin, RS3, formed by retrogradation of starch following cooking and cooling and finally, chemically altered RS4 (Englyst and Englyst., 2007).

Konjac glucomannan is a soluble dietary fibre from the plant *Amorphophallus konjac,* which has been part of many traditional Asian recipes such as noodles. It is versatile as an ingredient due to its neutral taste and gel-like consistency (Keithley et al., 2013). Inulin and oligofructose are soluble fibre ingredients commonly found in small quantities in many vegetables and fruits such as onion, garlic, artichoke and banana. Commercially, they are extracted from chicory (*Cichorium intybus*) roots to be used in product development by replacing sucrose, starch or fat (Liber and Szajewska., 2013). They have been successfully used to replace sucrose in products such as yogurt

drinks and fruit jellies without compromising their sensory properties (Lightowler et al 2018). Physicochemical and sensory characteristics of many different foods or beverages have been determined in reformulated foods with inulin and oligofructose (Laguna et al., 2013; Morais et al., 2014).

Beta glucan is a soluble fibre present in oats and barley that contributes to a thicker and creamier texture in foods. When solubilised with water, beta glucan results in increased viscosity and thereby provides a number of physiological responses such as attenuated gastric emptying, production of satiety hormones, and promotion of ileal brake mechanism (Rebello et al., 2016; Vitaglione et al., 2010).

2.3. Effect of Reformulated Foods with Sweeteners on Weight Loss

The discovery of ISs was a landmark in the history of food and nutrition research. But, ever since they were approved for food use, various surveys, large scale studies, prospective cohort studies and randomised controlled trials (RCTs) have investigated their effects on obesity and metabolism. In adults, the use of IS have been associated with weight gain, increase in waist circumference, high blood pressure, high blood glucose, increased insulin resistance, higher incidence of metabolic syndrome and type 2 diabetes in majority of the studies (Fowler et al., 2008; Tellman and Garfinkel., 1986; Colditz et al., 1990; Duffey and Popkin., 2006; Lutsey et al., 2008; Dhingra et al., 2007; Winkelmayer et al., 2005; Nettleton et al., 2009; McNaughton et al., 2008). On the contrary, several RCTs and some cohort studies have shown the effect of ISs on controlling weight gain or promoting weight stability (Schulze et al., 2008; Blackburn et al., 1997; Tordoff and Alleva., 1990; Raben et al., 2002). No effect of IS intake on glucose homesostasis has also been reported in a few studies (Palmer et al., 2008; Grotz et al., 2003). However, due to the lack of a convincing cause and effect relation between IS intake and obesity, it is not clear whether the use of ISs will increase or decrease the risk of weight gain in consumers (Swithers et al., 2010). Nevertheless, due to the recent implementation of sugar tax in the UK and other countries as well as the public health recommendations worldwide to reduce sugar intake, reformulation of sugary products by replacing with ISs is re-emerging as a trend within the food industry.

In overweight subjects, a ten-week study comparing sucrose and sweetener supplementation found a significant decrease in body weight (average 1.0 kg) and fat mass (average 0.3 kg) in the sweetener group. On the parallel arm, the participants in the sucrose group had a significant increase in body weight of average 1.6 kg and fat mass of 1.3 kg (Raben et al., 2002). This study also found favourable effects on blood pressure as well. Sucrose or sweeteners (aspartame, cyclamate, acesulfame K, and saccharin, in the order of decreasing amounts) were included in soft drinks, fruit juices, yogurts, marmalade, ice-cream and stewed fruits. The results were attributed to the reduced sucrose intake and energy density in those who had sweetener supplementation compared to those in the sucrose group who increased their energy intake by 1.5 MJ/day mainly due to increased consumption of sucrose, from beverages. The above study was one of the first investigations that reported the differences in satiating effects of liquid and solid calories, leading to overconsumption following sugary drinks (Raben et al., 2002). The authors further explored the mechanisms in this study design which showed that the decrease in body weight and fat percentage in the sweetener group at the end of the study was due to changes in energy intake rather than energy expenditure (Sorensen et al., 2014). Another sub-study was conducted but, could not link the effect of sweeteners used in the study to any of the satiety hormones measured, thus failing to demonstrate a physiological mechanism over and above uncontrolled eating behaviour in the participants who were in the sucrose group (Raben et al., 2011).

When beverages containing sucrose were replaced with AS, young healthy adults were reported to consume less energy over a two-day period (Van Wymelbeke et al., 2004), showing no evidence of energy compensation following the intake of ASs. But, the participants in either group did not gain weight during the ten-week testing period, probably because of increased energy expenditure which was not measured in this study. Although the palatability of the drinks with ASs was rated poorly compared to SSBs, the different flavours (orange and raspberry) used for either type of drink did not affect the energy intake of the participants (Van Wymelbeke et al., 2004). The issues related to palatability could be overcome with the use of innovative products such as cocoa beverages used in a 6 week study in overweight participants (Njike et al., 2011). The main aim of the study was not to compare the effect of sugars and sweeteners on weight loss, but to test the role of cocoa flavanols on endothelial

function. However, the sugar free version on the cocoa drink with aspartame and Acesulfame-K further enhanced the resultant effects of flavanols on body weight.

The REFORM study aimed at a minimum reduction of 32 g/day of NMES from the participants' diet (Markey et al., 2016). Although energy intake from NMES was theoretically calculated to reduce by at least 7%, the results showed a mean reduction of 8.3% contributed by a significant reduction in intake of carbohydrate, total sugars and NMES. However, the participants in the study compensated by significantly increasing their fat and protein intake as well as by lowering their physical activity levels when some of the commonly consumed food sources were replaced with sugar reformulated products for 8 weeks. Whilst artificial sweeteners are useful in maintaining palatability of food products during reformulation, they are also known to induce energy compensation in participants (Gardner et al., 2012). The authors acknowledged the limitations of relying on self-reported energy intake using food diaries as reported extensively in the literature (Dhurandhar et al., 2014).

When the polyol, isomalt was added to a range of foods (marmalade, junket, yoghurt, biscuits, chocolate, puddings and candies), and given to twenty healthy volunteers, there was no difference noted in body weight after four weeks of intervention (Gostner et al., 2005). However, it may be noted that the main objective of this study was to measure a range of metabolic parameters such as blood lipids, leptin, fructosamine etc. So, the diet was controlled and both the control and isomalt periods resulted in a small weight loss.

A modelling study based on the Australian National Nutrition survey data showed that reduction in added sugars by 25% will result in an energy deficit of 114 kJ/day for the population aged 2-16 years, which is very modest at an individual level (Yeung et al., 2017). However, a cumulative effect over many years at population level is expected to prevent obesity-related diseases in the above population during adulthood. This model also predicted a daily reduction in added sugars by 11.73 g along with 0.23 g and 1.73 g increase in fat and fibre respectively in the same age group. The results may have been affected by the high consumption of sugars in the older age groups of children (14-16 years) compared to younger children in the survey. Although this chapter excludes studies in children, this particular research was included as a

theoretical study. But, one of the main drawbacks is that consumer behaviour and related changes in dietary choices following reformulation have not been explored. The authors acknowledge this as a limitation which could be overcome by sensory evaluation of the reformulated products as shown by Markey et al (2015).

Tate et al (2017) investigated the effects of substituting caloric beverages with water or diet beverages for six months in overweight and obese adults. This study resulted in a remarkable average weight loss of 2 to 2.5 % from the baseline due to reduced calorie intake by 225 kcal/day. The study design in this experiment was unique in that all the three intervention groups were given positive strategies to improve their energy intake and body weight. Whilst the water and diet beverage groups received supply of beverages, the control group just received instructions for weight loss without any mention of beverages (Tate et al., 2017). This showed how weight loss could be twice as likely to happen with the provision of reformulated beverages or water rather than advice alone. Contrary to the above, in a similar six months' parallel study, when overweight subjects were given sucrose or aspartame sweetened cola (1L per day), no difference was observed in body weight in either group (Maersk et al., 2012). The main finding in this study was the significant increase in visceral fat (average 13%) in the participants who consumed sucrose sweetened cola. Despite the small sample size (10-12 per group) and the lack of any positive health effects from the consumption of aspartame, the results of this study indicate the harmful effects of excessive sugar consumption.

The results from studies using ISs such as aspartame have yielded mixed results (Mattes and Popkin., 2009) on satiety and weight gain. As a result, natural botanical compounds such as Stevia have also been tested as replacement for sucrose. In a study with lean and obese men, preloads containing sucrose, aspartame and stevia were used before lunch and dinner to test their effects on food intake and satiety (Anton et al., 2010). Energy intake was significantly reduced by 300 -340 kcal when the stevia and aspartame preloads were consumed, but this did not contribute any differences in food intake at the lunch or dinner meals. The remarkable result from this study is that the participants did not have differences in their hunger and satiety feelings following any of the preloads. Neither did they compensate by eating more following the low energy preloads (which were 203 kcal less than sucrose preloads)

containing aspartame and stevia. Participants in this study rated aspartame-containing preloads better than sucrose and stevia-preloads demonstrating the superior effect of synthetic sweeteners over natural ones on palatability of the foods.

Although Anton et al (2010) tested both lean and obese individuals; it is not certain why the results were presented for the entire group rather than separately for the lean and obese individuals. Considering the apparent differences in satiety hormones and subjective and emotional feelings of satiety between lean and obese individuals (Van Strein et al., 2009), one would have expected the results to be skewed when both groups' data were used together. Furthermore, lack of a control group and the inability to collect long-term data were some of the identified limitations of the above study. This is further confirmed by the non- significant effect on body weight of overweight/obese diabetic participants in a 16-week study following a daily consumption of 1 g Rebaudioside A compared to a placebo (Maki et al., 2008). As Rebaudioside was provided as a supplement, this research does not pertain to reformulation.

Long-term studies using sucrose and sweetener -based drinks in normal weight and overweight participants have shown similar results, when the study design was replicated (Reid et al., 2007; Reid et al., 2010). Reid et al (2007) found no significant effect of sucrose supplementation on BMI over four weeks in normal weight participants when compared with aspartame supplementation. The participants in the sucrose group increased their carbohydrate intake while compensating by decreasing fat and protein intake. This change resulted in a marginal increase in weight of less than 2 kg, showing a tendency for weight gain in the sucrose group. When the same test beverages were given to overweight women, the results were replicated, but with no effect on macronutrient intake due to compensation for energy intake (Reid et al., 2010). This shows that sucrose given in a blinded product will not increase weight gain in the short-term in normal or overweight individuals. That said, the results may be different in the long-term when people consume sugary beverages in large doses.

A meta-analysis published more than a decade ago concluded that the consumption of foods and beverages in which sucrose is substituted with the AS Aspartame, could potentially results in a weight loss rate of 0.2 kg/week (De la Hunty et al., 2006). This

is a positive result considering that in the reviewed studies, the participants compensated for only 30% of the energy reduced by reformulation in solid foods and 15% of the energy replaced in beverages. This disproves the finding from many studies that concluded that LCSs are not effective in promoting weight loss due to their inability to evoke the same physiological satiety responses caused by sugar, despite providing the same sensory perception of sweetness (Nettleton et al., 2009; Blundell and Hill., 1986; Blundell et al., 1988; Rogers and Blundell., 1989; Rogers and Blundell., 1993; Rogers et al., 1988). One of the main reasons for this is the lack of energy in LCS, and therefore, prolonged consumption of LCS containing foods may lead to overconsumption of energy from other meals, thereby promoting weight gain.

Another recent finding mainly from rodent studies is related to the change in gut microbiota resulting from the use of NNS that might trigger changes in our body weight and metabolic profile (Sylvetsky and Rother., 2018). It is well known that the gut microbiota changes as an individual loses or gains weight. Therefore, this emerging area of research needs to be further explored to have a clear idea of the mechanisms involved. Other animal studies have also indicated a link between maternal consumption of NNS and increased prevalence of childhood obesity in their offspring (Zhang et al., 2011), which is another long-term effect of reformulation that requires further research. Table 2 and Table 3 summarise the results from observational studies and RCTs investigating the effect of reformulated foods and beverages with sweeteners on satiety, energy intake and weight loss.

2.4. Effect of Reformulated Foods with Dietary Fibre on Weight Loss

Polydextrose, when provided in a mid-morning preload, has resulted in a dose-dependent reduction in energy intake by overall 12.5% at a subsequent meal, demonstrating its ability to behave as a soluble fibre (Ibarra et al., 2015). A further systematic review and meta-analysis also confirmed the ability of polydextrose to reduce subjective feelings of appetite during the satiation period (Ibarra et al., 2016). However, these effects on appetite and energy intake have not yet been translated to meaningful effects on weight loss or management in human participants.

When 16.5 g RS4 was incorporated in scones, there were no differences in fullness or prospective food consumption ratings in healthy participants for the fibre rich scone in comparison with the control scone (Stewart et al., 2018). However, subjective

519 feelings of hunger and desire to eat were reported to be significantly different between
520 the two scones demonstrating that replacing starch with fibre may be effective in
521 reducing energy intake, although the mechanisms were not clear. However, this study
522 did not measure food intake and other studies that tested different types of RS4 (dose
523 ranging from 10 g to 40 g) in solid and liquid foods also were not successful in
524 demonstrating increased satiety (Karalus et al., 2012; Haub et al., 2012; Gentile et al.,
525 2015). These results combined with the lack of long-term studies on energy intake
526 using RS4 warrants further research to investigate its role in weight loss.
527
528 Complete and partial substitution of high carbohydrate noodles with Konjac
529 glucomannan in an RCT resulted in no difference in energy intake at a subsequent
530 meal. But, there was an overall reduction of 47% and 23% respectively in cumulative
531 energy intake during the test session due to the high fibre content of the meals, which
532 contributed to low energy density without affecting the meal's palatability (Yeung et
533 al., 2018). Most of the studies in overweight and obese adults and children
534 investigating weight loss effects were using supplements of glucomannan and
535 therefore, does not come under reformulation (Kaats et al., 2015; Zalewski et al., 2015;
536 Keithley et al., 2013). Similarly, almost all the satiety and weight loss studies published
537 so far have used inulin and oligofructose as supplements with a range of doses rather
538 than including them in reformulated foods (Liber and Szajewska., 2014).
539
540 Enrichment of solid and liquid foods with 4 and 8 g of oat beta glucan resulted in
541 increased feelings of fullness and satiety in healthy females (Pentikainen et al., 2014).
542 The perceived effect was attributed to increased viscosity effect of the bolus, which
543 was higher for the juice than the biscuits. The authors demonstrated the importance
544 of choosing the appropriate food matrix for reformulation when including soluble fibre
545 such as beta glucan. However, the test products were rated low for palatability, which
546 could be another potential reason for the results on satiety (Rebello et al., 2016). On
547 the contrary, when 3 g of barley beta glucan with different molecular weight were used
548 in soups, there was no effect on satiety feelings in healthy male participants (Clegg
549 and Thondre., 2014). Despite an increased viscosity in the test soups compared with
550 the control no significant difference was noted in subsequent energy intake following
551 consumption of beta glucan. This demonstrates the challenges involved in developing

552 reformulated products with the accurate dose of the dietary fibre and without
553 compromising on palatability.
554
555 When barley beta glucan enriched biscuits (5.2 %) were given to healthy participants,
556 there was no effect on energy intake at a subsequent meal despite an increase in
557 fullness ratings during the test session (Vitaglione et al., 2010). Other research has
558 shown a positive correlation between beta glucan dose in cereals and the satiety
559 hormone Peptide YY (PYY) in overweight adults (Beck et al., 2009). PYY is known to
560 prolong satiety effects resulting from undigested food remaining in the intestine for a
561 longer period due to the viscosity effect caused by beta glucan. In a long-term study
562 using overweight participants, Beck et al (2010) reformulated various foods (ready to
563 eat cereal, porridge, muesli bars and cereal snack packs) with two different doses of
564 beta glucan and compared with a control diet with no beta glucan. In spite of achieving
565 weight loss in all the participant groups, beta glucan did not seem to have contributed
566 to an enhancing effect, potentially because all the three diets contributed to energy
567 deficit. Similar to their earlier study (Beck et al., 2009), there was an increase in PYY
568 levels following beta glucan intake, but the results were not significant and did not
569 show a dose-dependent response. Table 4 summarises the results from RCTs
570 investigating the effect of reformulated foods with dietary fibre on satiety, energy intake
571 and weight loss.
572
573 **2.5. Limitations in Carbohydrate Reformulation**
574 One of the biggest challenges involved in developing reformulated products is to
575 match the sensory properties to the original versions with sucrose. Failing in this can
576 result in energy compensation as reported by Markey et al (2016). Great care was
577 taken by the researchers in the above study in hiding the brands, labels etc by
578 repackaging the food products, yet the participants were able to recognise between
579 the regular and sugar-reduced products, apparently due to differences in palatability
580 (Markey et al., 2016). Sugar replacement in products can affect their sensory attributes
581 negatively (Markey et al., 2015). Markey et al (2015) found significant differences in
582 appearance, flavour and texture attributes between the regular and reformulated
583 products tested ($P<0.0001$). Interestingly, none of the reformulated products scored
584 the threshold values required to qualify for consumer acceptance, which could also be
585 partially attributed to the lack of brand, labelling and nutrition information on the

products. In the case of some products, ingredients such as salt can interfere when sugar is removed or replaced by sweeteners, whereas some sweeteners can also alter the texture and mouthfeel of the products (Markey et al., 2015). Therefore, small amounts of sugar reduction without using any artificial sweeteners may be a more viable strategy to maintain sensory properties of some products. Markey et al (2015) demonstrated this in a reformulated strawberry jam product which had only 28% reduction in NMES compared to its regular counterpart. Nevertheless, the reformulated jam performed the best in terms of consumer preference, in comparison with products containing AS. On the other hand, a reduced sugar baked beans product performed poorly on sensory attributes, even though it had only 32% less NMES compared to the regular baked beans. The results may have been influenced by various factors such as the serving size of the products, other ingredients present and the interaction of sugar with them (Goldfein and Slavin., 2015). Whilst sensory evaluation studies are useful to identify taste preferences to food products by single exposure, it may be worth exploring repeated exposure of reformulated foods to ensure participant acceptability in the longer term.

Another challenge is to find ingredients that can provide not only sweetness, but also, all the characteristics that sugar contributes to a food product, such as taste, texture, colour, bulk and preservation (Goldfein and Slavin., 2015). In products such as chocolate, BS that replace sucrose can maintain good sensory properties only if they have smaller particle size. On the contrary, rheological properties of chocolate can be improved by sugar substitutes with large particle size (Sokmen and Gunes., 2006). Such contrasting effects may pose challenges to the manufacturer during sugar reformulation. One of the sugar alcohols, maltitol was found to affect the texture, flavour and appearance of chocolate samples that underwent 44% reduction in NMES (Markey et al., 2015).

As a result, multiple strategies are needed to mimic the use of various bulking agents and humectants commonly used by food manufacturers to retain product characteristics while substituting sugar with NNS. In a modelling study on sugar reformulation, five different strategies were used: two of which were just removal of added sugars and replacement of added sugars with non-nutritive sweeteners. The remaining three options were using other ingredients with non-nutritive sweeteners

such as sugar alcohols, 50% fibre and 50% maltodextrin (Yeung et al., 2017). It is vital that the product development team trials many such options to create an acceptable product that can result in a sustainable behaviour change in sugar reduction. Nevertheless, a recent study investigating the impact of 'silent reformulation' of a few products from a retailer showed a significant impact on reducing the consumers' calorie intake, without having a major impact on the sales of the reformulated products (Jensen and Sommer., 2017).

There are further challenges involved in matching energy and macronutrients in the diet/test foods when comparing the intake of sugars versus NNS. These combined with other methodological shortcomings in nutrition studies, such as the non-specific nature of data collected using food frequency questionnaires and the lack of databases including all NNS composition are also limitations in reformulation research (Gardner et al., 2012). The above issues may be the reason for varying effects reported in different study designs investigating replacement of caloric sweeteners with low calorie sweeteners on body weight and composition. In a meta-analysis by Miller and Perez (2014), RCTs presented a significant reduction in body weight, body composition and waist circumference following the consumption of LCS. According to the authors, even though the mean change in body weight was only -0.8 kg, the use of LCSs could be a viable strategy to ensure compliance to weight loss and management plans while maintaining the palatability of foods. But, prospective cohort studies in this meta-analysis failed to demonstrate the same result and in fact showed an average increase in BMI of 0.03 kg/m^2 with the use of LCSs, partly due to the limitations in the study designs, including difficulties in controlling confounding variables and interpreting their effects (Miller and Perez., 2014).

In one of the earlier systematic reviews on the metabolic effects of ASs on young people, the results were opposite with large scale studies showing a positive link between sweeteners and weight gain whilst RCTs did not show this effect (Brown et al., 2012). Another recent review also supported this finding showing an increase in weight gain following NNS consumption in observational studies (Sylvetsky and Rother., 2018). On the contrary, in the RCTs reviewed, the authors reported weight loss following the intake of NNS when combined with other strategies such as behavioural support. Furthermore, a recent systematic review reported a negative

association between added sugar intake and dietary quality (indicated by lower intake of cereal grain and products, fruit and fruit-based products, dairy products and vegetables AND higher intake of confectionary and SSBs) as well as micronutrient intake (Louie and Tapsell., 2015). However, this relationship was not observed for total sugar intake and quality of diet. This explains the qualitative differences in the impact of different carbohydrates present in natural and processed foods on food choices and intake.

The impact of sweeteners and dietary fibre on food choice and energy compensation in blind and non-blind studies have to be investigated further (Bruyere et al., 2015). Furthermore, whilst helpful in planning long-term intervention studies, just measuring satiety and energy intake after one test meal may not be enough to demonstrate the weight loss potential of a test food/ingredient, simply because the effect was shown to not last for more than one test session by Wanders et al (2014). This is supported by the fact that although there are satiety-related effects proven for fibres such as pectin, hydroxymethyl cellulose, sodium alginate, beta glucan, chitosan, wheat bran fibre, guar gum and glucomannan, a claim for weight loss has been approved by EFSA for glucommanan only (Brownlee et al., 2017; Mackanzie et al., 2006; EFSA., 2010b).

3. Reformulation of Foods to Reduce Fat Content

As a nutrient in food, fat has many sensory, nutrition and physiological benefits. Consumer surveys show that of those choosing to diet, 49% try cutting back on “fatty” foods (Mintel., 2013). However, there is increasing pressure on food producers to develop foods that are healthier but are just as tasty and palatable as their original formulations. Fat contributes to creaminess, aroma, appearance, palatability, texture, and lubricity of foods (Keast and Costanzo, 2015). From a physiological and nutritional perspective, fat is a source of fat-soluble vitamins, essential fatty acids, precursors for prostaglandins, and is a carrier for lipophilic drugs. Fat plays an important role in the flavour of foods as it carries lipophilic flavour compounds, acts as a foundation for flavour development (e.g., by lipolysis or frying), and stabilizes flavour (Keast and Costanzo, 2015). However fat is the most energy dense nutrient contributing 9kcal/g compared to the 4kcal/g of carbohydrates and proteins. Fat has been implicated in the rise of obesity due to its energy density, palatability and weak effects on satiety (Blundell and MacDiarmid, 1997), and because of this is an important target for

reformulation to aid weight loss. Dietary recommendations from the Department of Health have for some time recommended that average fat intake should be 35% of food energy or less and saturates to 11% of food energy or less (Department of Health., 1991). Reformulation in terms of fat is often focused on reducing saturated fats because of their purported health implications, however for calorie reduction and weight loss overall fat reduction is more important. This can be achieved through fat replacement or by altering the type of fats added to products to make them more satiating.

3.1. Fat Reduction

Foods may claim that they are low in fat when the product contains 3g of fat per 100g of solids or 1.5g of fat per 100ml of liquids (European Commission., 2012). In the case of milk, it must contain 1.8g fat or less per 100 ml for milk to be labelled semi-skimmed. To claim that a food is fat free the product must contain no more than 0.5 g of fat per 100g or 100ml. A claim stating that the content of fat has been reduced can only be made where the reduction is at least 30% compared to a similar product (European Commission., 2012).

One way to reduce the fat content of a product is to simply remove it. An example of this being achieved and widely accepted is for milk. Reformulation of milk through reduction of fat and saturated fat by ‘skimming’ means that consumers can reduce fat intake without affecting intake of the essential nutrients present in milk such as calcium, riboflavin and vitamin B12. Currently the milk of choice is primarily semi-skimmed as consumers follow public health advice to reduce saturated fat in their diets. However, the amount of milk being consumed at home has decreased substantially and is expected to continue declining (European Commission., 2017) increasing the importance of identifying alternative ways to reduce or replace fat in the diet.

When fat is reduced in the diet it must in some way be replaced by something else. This may just be by traditional techniques such as substituting water or air for fat, using lean cuts of meats or extra vegetables in prepared meals, skimmed milk instead of whole milk in frozen desserts, and baking instead of frying for manufacturing snack

722 foods. Fat may also be replaced in foods by reformulating with lipid-, protein-, or
723 carbohydrate-based ingredients, individually or in combinations. Fat replacers
724 represent a variety of chemical types with diverse functional and sensory properties
725 and physiological effects (Munday, 2017).
726
727 **3.2. Strategies for Fat Reformulation**
728 Fat can be replaced in the diet in a variety of ways. Fat substitutes are ingredients that
729 physically and chemically resemble triglycerides and could be used to replace fat on
730 a gram for gram basis. Fat mimetics, often called protein- or carbohydrate- based fat
731 replacers, are substances that imitate organoleptic or physical properties of
732 triglycerides but cannot replace fat on a one-to-one basis. Fat extenders allow a
733 decrease in the in the amount of fat in a product and fat analogues have a lower
734 digestibility than other common dietary fats. There have been a wide variety of
735 products developed to replace fat in the diet however the current chapter focuses on
736 those that have been researched sufficiently in relation to food intake and weight loss.
737 Many of those developed have not been permitted for use in food or have not been
738 taken to market and hence have not been researched for their effect on food intake or
739 weight loss. Hence they have been excluded from this chapter.
740
741 **3.3. Fat Substitutes**
742
743 ***3.3.1. Sucrose fatty acid polyesters***
744 Olestra (Olean® The Procter & Gamble Co., Cincinnati, Ohio) is a sucrose fatty acid
745 polyester and is one of the most commonly known and well researched fat substitutes**.**
746 Sucrose fatty acid polyesters are mixtures of sucrose esters formed by chemical
747 transesterification or interesterification of sucrose with six to eight fatty acids.
748 Transesterification is the exchange of an acyl group or radicals between an ester and
749 an acid, alcohol, or an amine. Interesterification is the exchange of an acyl group or
750 radicals between two esters. Olestra is manufactured from saturated and unsaturated
751 fatty acids of chain length C12 and higher, obtained from conventional edible fats and
752 vegetable oils (Shieh et al., 1996, Akoh and Swanson, 1990).
753
754 Olestra is approved (FDA, 1996) for replacing up to 100% of the conventional fat in
755 savoury snacks and for frying of savoury snacks. It is non-caloric as it passes through

the gastrointestinal tract without being digested or absorbed (Grossman et al., 1994) because the large size and number of the nonpolar fatty acid constituents prevent olestra from being hydrolyzed by digestive lipases. However, as Olestra passes through the gastrointestinal tract without being absorbed, it has the potential to cause abdominal cramping and stool softening or loosening, and to reduce absorption of fat-soluble vitamins and nutrients, which partition into olestra when ingested at the same time. Significant gastrointestinal events related to the appearance of fat in the colon were anticipated follow its approval, and a label disclosing this possibility was required by the Food and Drug Administration (FDA) initially. However, following a series of studies to assess the potential for olestra to cause physiological and nutritional effects was published in August 1997 in a Supplement to the Journal of Nutrition (Volume 127, Issue 8). The FDA withdrew the need for this labelling requirement in 2003. However the approval of Olestra is still controversial and there are only a limited number of foods that are currently on the market that use it (Jandacek, 2012).

Research has suggested that the use of Olestra in food products could drive people to over–consume them in the belief that more could be consumed to achieve the same energy intake (Jandacek, 2012). However the evidence to support this is limited. In general there is a tendency to eat larger portions of reduced fat products but not in sufficient amounts to compensate for the reduced energy content (Rolls and Miller, 1997, Miller et al., 1998).

In 2001, Stubbs published a review of 24 clinical feeding studies that examined the effects of olestra-containing foods on hunger, satiety, and the regulation of food intake. Overall, these studies have found consistent evidence that consumption of olestra containing foods is associated with reduced intake of energy and/or percentage of energy from fat in various subpopulations (except among those who cannot afford a prolonged energy deficit such as active lean adults or children) and usually results in weight maintenance or modest weight loss. However, the generalizability of these studies to free-living individuals is limited by their small sample sizes, short study durations, highly controlled study settings, and the use of dietary manipulations that do not permit increased intakes that might occur if participants knew they were consuming the reduced-fat products.

As mentioned above olestra is one of the most widely researched fat substitutes and there have been studies undertaken looking at its longer-term effects on food intake and body weight. De Graaf and Hulshof reported the results of 12-day studies in which olestra was substituted for 52 g/day of absorbable dietary fat (de Graaf and Hulshof, 1995, De Graaf et al., 1996). These studies similar to the short duration studies indicated that there was not compensation when olestra was substituted in the diet. Similar findings were obtained by Hill et al. (1998) over 14 days in a double-blind, placebo-controlled crossover study. Kelly et al. (1998) undertook a 12 week, double-blind controlled trial in healthy volunteers. After the intervention with olestra substituted for absorbable fat, body weight was significantly less than that of the control group, although not different from baseline. Based on analysis of the diet diaries there was no differences in energy intake between the olestra diet and the control diet.

Patterson et al., (2000) carried out a post-marketing surveillance study of olestra consumption. Measurements of diet composition and body weight were made prior to the marketing of olestra in Indianapolis and after 1 year of commercial availability of olestra foods in a cohort of 335 participants. The change in total daily energy consumption from baseline to 1 year was not related to olestra consumption however there was a significant trend in a reduction of total absorbable fat and saturated fat consumption with increasing olestra consumption. The investigators reported that there was an indication that olestra intake was associated with weight loss that was not statistically significant. Another post-marketing analysis study was conducted by Satia-Abouta et al., (2003). This analysis included 1178 adults whose baseline weight and blood samples were obtained at the beginning of the study (before olestra was marketed) and then one year after the introduction of olestra into the market in snack foods. Only 2% of the subjects were categorized as moderate to high consumers, eating 2 or more g of olestra per day. No significant changes in body weight were seen with olestra consumption, however given the low doses consumed this is probably not surprising.

A large intervention study by Bray et al., (2002) examined the effects of olestra in three groups of obese men over a 9-month period. One group received a control diet with 33% of energy as absorbable fat. A second group received a fat-reduced diet (25% of energy as fat), and a third group received a diet with 33% of the absorbable fat

replaced with olestra. Body weight and body fat in the fat-substituted group declined by a mean of 6.27 and 5.85 kg, respectively, compared with 3.8 and 3.45 kg in the control group and 1.79 and 1.68 kg in the fat-reduced diet group. The results indicated that the replacement of dietary fat with olestra reduces body weight and total body fat when compared with a 25%-fat diet or a control diet containing 33% fat. As in the short-term studies, long-term studies of olestra consumption are consistent with varying levels of compensation in which the subjects did not completely sense the caloric dilution.

3.3.2. Medium chain triglycerides (MCTs)

Medium chain triglycerides (MCTs) are triglycerides whose fatty acids have a chain length varying between 6 and 12 carbon atoms in length (Babayan, 1987, Bach and Babayan, 1982). MCTs come from coconut oil and palm kernel oils and are also found in camphor tree drupes. Once ingested, MCTs are treated quite differently to the long chain triglycerides that make up the majority of people's diets. MCTs are absorbed when there are decreased intraluminal concentrations of pancreatic enzymes and bile salts (Fernandes et al., 1962), therefore MCTs have been reported to have a faster transit time through the gastrointestinal tract than both glucose and long chain triglycerides (LCTs) (Bach and Babayan, 1982). Once absorbed MCTs are converted to medium chain fatty acids (MCFA) and transported directly in the portal venous system, as opposed to being transported as chylomicrons in the lymphatic system like LCTs (Bloom et al., 1951). Therefore MCTs bypass peripheral tissues, such as adipose tissue, which makes them less susceptible to the actions of hormone sensitive lipase and to deposition into adipose tissue stores (Bach and Babayan, 1982). In addition, MCFA can cross the mitochondrial membrane of the liver and muscle independently of the acylcarnitine transfer system making them a much more readily available energy source (Williamson et al., 1968). Although MCTs contain less energy per gram (8.3 kcal versus 9kcal for LCT) it is not this that is thought to mediate its effects on weight loss. MCTs are reported to increase satiety and decrease food intake, as well as increase postprandial energy expenditure (Table 5).

Potential mechanisms for increasing satiety include the production of ketones due to the increased acetyl-CoA influx which is necessary to oxidize fatty acids (Tsuji et al., 2001). Furthermore, Van Wymelbeke et al., (2001) and Rolls et al., (1988) indicate

that the increase in satiety maybe due to the rapid rate of absorption of MCTs. Where LCTs result in two peaks during absorption; the initial peak at the point of ingestion and a second delayed peak at the beginning of the next meal, MCTs are fully absorbed at the point of ingestion (Fielding et al., 1996) and may contribute to satiation due to this complete absorption mechanism.

Research is mixed on the satiating properties of MCTs with many showing that MCTs does increases satiety (St-Onge et al., 2014, Van Wymelbeke et al., 1998, Van Wymelbeke et al., 2001, Rolls et al., 1988, Clegg et al., 2013, Coleman et al., 2016) yet others showing no effect (Barbera et al., 2000, Kovacs et al., 2001a, Kovacs et al., 2001b). However there are many differences in study methodologies which have sought to explain these divergent results, such as the dose given and the time difference between the preload and *ad libitum* meals. Research on energy expenditure has shown some positive effects (Alexandrou et al., 2007, Clegg et al., 2013, Dulloo et al., 1996) with MCTs increasing energy expenditure.

There have been many interventions studies that have shown very positive effects of MCTs weight loss and body fat. Han *et al.* (2007) assessed the effect of 18g/day MCTs or corn oil (LCTs) for 90 days and found that body weight and waist circumference decreased in the MCTs group compared to the LCTs group. These changes were associated with a reduction in energy intake. Another study found that a dose as low as 5g/day of MCTs in margarine for 84 days resulted in a reduction in body fat, subcutaneous and visceral body fat compared with a group consuming margarine with LCTs (Nosaka et al., 2003). In 19 overweight males, placed on weight maintaining diets consisting of 40% energy as fat, 75% as added fat and 66% of the added fat as MCTs or all the fat as LCT for 28 days, body weight decreased more on the MCTs diet than on the LCT diet (St-Onge and Jones, 2003). In Tsuji et al., (2001) participants were fed MCTs (average 9.24 g/day) or LCTs in their diet for 84 days. In the participants with BMI ≥ 23 $kg \cdot m^{-2}$, the decrease in body weight and body fat was significantly greater in the MCTs group than the LCTs group which the authors postulate may be due to difference in hepatic lipid turnover rates in those with a higher BMI.

A 16 weeks intervention study (St-Onge and Bosarge, 2008), participants were fed 18-24g of MCTs or olive oil per day combined with weight loss counselling. The MCTs intervention resulted in a significantly lower endpoint body weight, endpoint fat mass, total fat mass and intrabdominal fat mass than olive oil with a trend towards a significantly greater loss of fat mass and trunk fat mass. This study provides encouraging evidence for the use of MCTs oil as part of a weight loss program.

One of the potential issues with recommending MCTs for weight loss is that it unfavourably affects the blood lipid profile (Cater et al., 1997, Hill et al., 1989, Swift et al., 1992). As a potential solution to this problem, a functional oil containing a blend of vegetable oils and plant sterols, known for their hypocholesterolemic properties, was created (St-Onge et al., 2003a, St-Onge et al., 2003b). This functional oil combined MCT oil with tall oil phytosterols and flaxseed oil which is a rich source of (n-3) fatty acids (Cunnane et al., 1993). Overweight men who consumed the functional oil as part of a weight maintaining diet for 29 days, decreased total cholesterol 12.5% and 4.7% on functional oil and olive oil respectively. LDL cholesterol was reduced by 13.9% and peak LDL particle size was greater on functional oil (St-Onge et al., 2003a). The functional oil was also researched for its effects on energy expenditure and body composition (St-Onge et al., 2003b). Twenty-eight days on the oil reduced upper body adipose tissue and there was trend towards greater reductions in whole body subcutaneous adipose tissue loss. Energy expenditure and fat oxidation were greater on day 2 but not on day 28 with the functional oil but not olive oil.

Structured triglycerides consist of both MCFA and long-chain fatty acids on the same glycerol backbone. Structured lipids were first developed by Babayan (1987) for parenteral nutrition (Chambrier et al., 2006). However they have also been researched in terms of weight loss. One of the advantages is that they can have a higher smoke point than MCTs which makes them useful as cooking oil (Ogawa et al., 2007).

Ogawa *et al.* (2007) found increases in diet induced thermogenesis after ingesting a liquid meal with medium-long chain triglycerides (MLCTs) compared with LCTs. Results from Matsuo et al (Matsuo et al., 2001) showed that over a 12-week period replacing LCTs with MLCTs over long periods of time could produce body fat loss in the absence of reduced energy intake. However one of the primary benefits of

structured triglycerides is that not only are decreases in body weight being observed in the MLCTs groups as compared with those of the LCTs group, significant decreases in serum total cholesterol have also been found following MLCTs compared with LCTs at 8 weeks (Kasai et al., 2003). Data from an 8-week intervention study indicates that consumption of MLCTs can reduce body weight and body fat and improve blood lipid profiles in hypertriglyceridemic males and in those under the age of 60 years (Liu et al., 2009, Xue et al., 2009). In hypertriacylglycerolemic Chinese subjects randomly allocated to ingest 25-30 g/day MLCTs or LCTs oil for 8 consecutive week the MLCTs group showed a significantly greater decrease in body weight, BMI, body fat, WC, ratio of WC to HC, total fat area and subcutaneous fat area in the abdomen, as well as blood TAG and LDL-C levels at week 8 (Zhang et al., 2010). In contrast in a six-week study of overweight males Roynetter *et al,* (2008) found that structured medium-long triglyceride oil increased short-term fat oxidation but failed to modulate body weight or adiposity through a change in Energy Expenditure (EE).

Salatrim now marketed as BENEFAT® is the name for a family of structured triglycerides comprised of a mixture containing at least one short chain fatty acid (primarily C2:0, C3:0, or C4:0 fatty acids) and at least one long chain fatty acid (predominantly C18:0, stearic acid) randomly attached to the glycerol backbone. As short chain fatty acids have a lower caloric value than long chain fatty acids and because stearic acid is incompletely absorbed, BENEFAT® has a reduced caloric value of only 5 kcal compared to 9 kcal for LCT (Smith et al., 1994). Developed by Nabisco Foods Group, Salatrim is licensed to Cultor Food Science, which established the brand name BENEFAT® for manufacture and marketing. FDA accepted for filing in 1994 a GRAS affirmation petition submitted by Nabisco Foods Group. BENEFAT® was approved in the EU in 2003 but food products containing salatrim must bear a caution informing the consumer that excessive consumption may lead to gastro-intestinal disturbances. Excessive intake is above 30g/day. Products containing salatrim must bear a caution informing consumers that they are not intended for use by children (Byrne, 2003).

A study on the appetite effects of salatrim showed that a meal containing it increased fullness and decreased hunger significantly more than did the traditional fat meal

however it had no effect on ad libitum energy intake or overall energy intake. The effect did not appear to be mediated by gastrointestinal hormones (Sorensen et al., 2008).

3.3.3. Coconut oil

Coconut oil has gained considerable popularity in recent years in food and beverages (Mintel, 2013) with coconut oil exports across Asia having grown 3.3% annually over the past five years, according to the Asian Pacific Coconut Community (Mahr, 2012). Many media articles promote the consumption of coconut oil for weight loss, believing it to have similar benefits to that of medium chain triglycerides (MCT). Articles are wide ranging promoting adding it to stir-fries, baking with it and even adding it to coffee (Waters, 2014, Sacks, 2015). This has contributed to an increase in intake of coconut oil in recent years (Lockyer and Stanner, 2016). Coconut oil is said to aid weight loss through a combination of increased energy expenditure and satiety induced by MCT.

As outlined above it has been proposed that MCT can affect satiety via a number of mechanisms; but a lot is still unknown. Coconut oil, however, only contains limited amounts of MCT. Lauric acid (carbon chain length 12) is found in much larger quantities in coconut oil, making up 47.7 % of the total fat, where no lauric acid is found in MCT oil. Other MCFA in coconut oil are capric acid (C10– 5.5%), caprylic acid (C8-7.6%) and caproic acid (C6 – 0.52%) (Orsavova et al., 2015). There is some debate as to whether lauric acid is a MCT or not. Unlike with fatty acids of shorter carbon length (C6-C10), only twenty to thirty percent of lauric acid is taken directly to the liver via the portal vein to be used as energy (Denke and Grundy, 1992). This means that in total only ~23.16% of the coconut oil contains MCTs that is absorbed and metabolised in the same way as pure MCT oil (Clegg., 2017).

To date there is less research on coconut oil compared to the large of body of work undertaken on MCT oil. Studies examining the effects of coconut oil compared to LCTs reported no increase in satiety and no effect on food intake (Rizzo et al., 2016, Poppitt et al., 2010). Poppit et al., (2010) found no difference in visual analogue scale ratings of satiety or differences in ad libitum food intake at lunch following the consumption of either coconut oil (containing 10g MCT), high short chain triglyceride (3g SCT, 7g MCT) (from soft fraction milk fat) or long chain triglycerides (from tallow). Rizzo et al.,

(2016) found that in a dinner meal following ice-cream with varying quantities of coconut oil there was trend towards reduced consumption with the coconut oil, however this was compensated for later when there was a significant increase in snack consumption resulting in no overall difference between the ice-creams. The amounts of coconut oil used in the high dose in this study was 7.5g coconut oil consisting of only ~4.8 g MCT (carbons 6-12). A more recent study by Kinsella et al., (2017) found that coconut oil did reduce food intake throughout the day following a coconut smoothie compared to a smoothie containing vegetable oil.

In terms of energy expenditure a study published across three papers providing 14 days of coconut oil, found no effect on total energy expenditure or thermic effect of feeding. However they did find an increase in basal metabolic rate after 7 days but not 14 days and an increase in endogenous long chain saturated fatty acid oxidation after 14 days (Papamandjaris et al., 1999, Papamandjaris et al., 2000, White et al., 1999). However a recent study by LaBarrie and St-Onge (2017) found no difference in postprandial thermogenesis in fifteen children, aged 13-18 years following 20g of coconut oil enriched baking fat compared to corn oil.

The research available on the use of coconut oil on satiety and energy expenditure is limited (Table 6) and particularly there have been no long term clinical trials looking at the effects on weight loss. Given both the publicity and the increased consumption of coconut oil further research in this area is warranted. Many recipes advocate adding coconut oil to foods that would otherwise not contain much fat. In this context weight loss is unlikely to occur due to the added energy intake from the oil itself.

3.3.4. Diaclyglycerol

Diacylglycerol (DAG) is a glyceride which consists of two fatty acids on a glycerol backbone. DAG oil is similar in taste, appearance, and fatty acid composition to other oils including rapeseed, soybean, and safflower oil (Takase et al., 2005) and can be easily incorporated into food products. It also naturally occurs in small amounts in cooking oils; from 0.8% in rapeseed oil, to 5.5% in olive oil and 9.5% in cottonseed oil (Rudkowska et al., 2005). Although DAG is naturally produced during digestion in the

form of 1,2 diacyl-sn-glycerol (1,2-DAG) or 2,3 diacyl-sn-glycerol); 1,3-diacyl-sn-glycerol (1,3-DAG) can be synthetically manufactured.

Even though it is mainly comprised of long-chain fatty acids, the transport and absorption of DAG are similar to medium-chain triglycerides. It is hypothesized that the 1,3-DAG is less readily resynthesized as chylomicrons and is directly transported to the portal vein for ß-oxidation (Yasunaga et al., 2004). Chronic studies examining the effects of DAG on weight loss have attributed the decrease in adipose tissue to greater levels of β-oxidation (Maki et al., 2002, Nagao et al., 2000), although to the authors' knowledge only one study has directly measured this (Kamphuis et al., 2003). Long-chain fatty acids (≥12 carbon atoms) also slow gastric emptying and increase gut hormones (McLaughlin et al., 1999) so DAG may mediate its effects by combined mechanisms of increased ß-oxidation (like MCT) and increased satiety hormone release (like LCT).

It has been repeatedly shown that chronic intake of DAG can lead to decreased body weight and reduced accumulation of adipose tissue (Yasunaga et al., 2004, Kawashima et al., 2008, Li et al., 2008, Maki et al., 2002, Yamamoto et al., 2001, Taguchi et al., 2001) (Table 7). A systematic review and meta-analysis by Xu et al. (2008) including six studies from 5 papers found a significant difference in body weight reduction between group receiving DAG and group receiving Triacylglycerol (TAG). This was confirmed using linear regression analysis that showed there was significant correlation between daily dose and body weight reduction.

In 1999, the Kao Corporation in Japan introduced a DAG oil, Econa cooking oil, which contained over 80% DAG and sold over 70 million bottles between then and 2003 (Flickinger and Matsuo, 2003). In 2009, Kao Corporation, maker of Econa voluntarily suspended sales of products containing DAG oil in Japan due to concerns it may cause cancer (Kao Group).

3.3.5. Small Particle Lipids

Small particle lipid (SPL) emulsions are produced through fractionation, resulting in lipids droplets surrounded by a phospholipid monolayer (Tauchi-Sato et al., 2002, Fujimoto and Parton, 2011). SPL range in size from 0.3 μm to 20 μm in various milks

and infant formulas (Fave et al., 2004) with the size of the droplet being known to influence its satiating properties (Armand et al., 1999). Smaller lipid droplets lead to an increased surface area, this mean that there is a larger surface area for the action of lipase. The result of this is increased hydrolysis of lipids (Maljaars et al., 2012). Human pancreatic lipase is inhibited by the accumulation of free fatty acids at the surface of lipid droplets. A greater surface area means that fatty acids do not accumulate and the lipase release is not inhibited, thereby increasing the amount of hydrolysis (Armand et al., 1999). Increased rates of hydrolysis may increase satiety by increasing fatty acid sensing in the small intestine (Maljaars et al., 2012). Emulsified fat delivered intra-duodenally, increased Cholecystokinin (CCK), pancreatic polypeptide (PP), and gallbladder contraction compared with unemulsified fat (Ledeboer et al., 1999).

A well-known SPL that has been widely researched is Fabuless®. Fabuless* is a 42% fat emulsion formulated from palm oil coated with galactolipids from oat oil, used as a food ingredient. It is produced by Lipid Technologies Provider AB (LTP, Karlshamn, Sweden) and marketed for satiety benefits in food applications by DSM (Koninklijke DSM N.V., Heerlen, the Netherlands) (DSM.). Initial studies all from the same research group showed that Fabuless® did have satiating effects (Burns et al., 2001; Burns et al., 2000; Burns et al., 2002) however more recent studies have not found any effects on satiety (Chan et al., 2017; Smit et al., 2011).

A few studies have investigated SPL over longer than one day, using Fabuless®. Logan et al., (2006) and found no significant effects of the lipid emulsion on either satiety or food intake. Diepvens et al., (2007) found that hunger was significantly decreased in an emulsion group, and weight re-gain occurred in a placebo group while on a weight maintenance diet, indicating Fabuless® may be useful in weight maintenance. A more recent study investigated the concurrent application of a low-calorie diet, an exercise program, and supplementation of 4.2 g of Olibra or 3.9 g milk fat for a 12-week period. Weight and waist circumference reductions were not significant. Hunger scores decreased more in the test group however there were not significant differences between groups for body fat, waist-hip ratio, food intake, appetite, and satiety (Rebello et al., 2012 (Table 8).

3.4. Fat Mimetics

Fat mimetics usually have an energy density of between 0-4 kcal/g and generally contain large amounts of water. They bind excessive water and hence denature or caramelize at high temperatures however they are generally suitable for baking. Fat mimetics are generally less flavourful than the fats they are intended to replace because they carry water-soluble flavours instead of lipid-soluble flavour compounds (Akoh, 1998).

3.4.1. Protein-based Fat Mimetics

Protein based fat replacers come from a variety of sources, such as egg, milk, whey, soy, gelatin, and wheat gluten because. Some of these protein-based fat mimetics are microparticulated to form microscopic coagulated spherical particles that mimic the creamy mouthfeel of fat. Many of the fat replacers from protein have an energy density of 4 kcal/g however some fat mimetics are processed to modify other aspects of ingredient functionality, such as water binding and emulsification properties. If they bind to water they may provide as little as 1 kcal/g. An example of this is Simplesse®, whereby 1g of Simplesse® can replace 3g of fat in a food. Although the substances are generally not sufficiently heat stable to withstand frying, they are suitable for use as ingredients in foods that may undergo cooking, retorting, and ultra-high temperature processing (Akoh., 1998; Gershoff., 1995).

A well-known protein-based fat mimetic, Simplesse®, is manufactured from whey protein concentrate by a patented microparticulation process. Developed by the NutraSweet Kelco (now CP Kelco, Georgia, USA). The caloric value of Simplesse®, on a dry basis, is 4 kcal/g however as described above once hydrated it is calorie reduced to 1 kcal/g. Although Simplesse has been widely used in food products research into its effects on food intake and weight loss are limited. However, given that protein is the most satiating macronutrient (Johnson and Vickers, 1993), it does have the potential to result in a negative energy balance.

3.4.2. Carbohydrate-based Fat Mimetics

Digestible carbohydrates such as modified starches and dextrins provide 4 kcal/g. Carbohydrates that have the ability to bind with water and nondigestible complex carbohydrates such as fibres that are only fermented, have an even lower energy density. Carbohydrate-based fat mimetics are not suitable for frying but can be used as fat barriers for frying and for baking (Akoh, 1998).

Gums are high molecular weight negatively- charged carbohydrates used as thickeners to increase viscosity at concentrations of 0.1–0.5%, and as stabilizers and gelling agents. Gums that are used in fat replacing systems with other gums, fat replacers, or bulking agents include guar, xanthan, locust bean gum, carrageenan, gum arabic, and pectins (Akoh, 1998). Several gums including agar, guar gum, and pectin have been found to have effects on measures of satiety and appetite (Clegg and Shafat, 2014; Arshad et al., 2016; Rao, 2016; Wanders et al., 2014) however the research on this has not been in the form of fat replacement. This follows a similar trend for much of the other research in this area.

Inulin is a plant-derived fructose polymer that is undigested in the human upper gastrointestinal tract (Niness, 1999), and is consider a form of dietary fibre (Cherbut, 2002). It is most often manufactured from chicory roots to form a white, odourless powder with very little sweetness (Franck, 2002). Inulin has fat-like properties, so can reduce the energy content of the food as a fat replacer without much compromise on taste and texture (Devereux et al., 2003; Franck, 2002).

A study looking at the effect of fat replacement by inulin or lupin-kernel fibre on sausage patty acceptability, post-meal perceptions of satiety and food intake in men found that the breakfast containing lupin-kernal fibre was more satiating than the inulin and full fat patty breakfasts (Archer et al., 2004). Total fat intake was 18 g lower on the day of the inulin and 26 g lower on the day of the lupin-kernal fibre breakfast compared with the full fat patty. Energy intake was also 1521 kJ lower on the day of the inulin breakfast. Lupin-kernel fibre is a novel insoluble non-digestible carbohydrate that may also have potential as a fat replacer. Lupin-kernel fibre is manufactured from the dehulled seeds of Australian sweet lupin after extraction of the protein, lipid and soluble carbohydrate fractions (Lee et al., 2006). Research into the effects of oligofructose (a subgroup of inulin) on weight loss have shown mixed results (Parnell

and Reimer, 2009; Daud et al., 2014; Guess et al., 2015; Pol et al., 2018; Liber and Szajewska, 2014).

Polydextrose is a highly branched, randomly bonded glucose polymer. Because of its complex structure, polydextrose is not digested in the small intestine, passing intact into the colon. Here it is partly fermented by the microbiota and the remainder, approximately 60%, is excreted in the faeces resulting in an energy contribution of 1 kcal/g (do Carmo et al., 2016). The results of a meta-analysis on the influence of polydextrose on energy intake (Ibarra et al., 2015) showed that when included in a midmorning snack, PDX leads to a significantly reduced energy intake at the subsequent lunch. This effect was observed to be dose-dependent. This reduction at lunch did not lead to a compensation of energy intake during the following dinner, thus the overall daily energy intake was reduced, also in a dose-dependent manner (Ibarra et al., 2015). A further meta-analysis by Ibarra et al. (2016) showed that desire to eat during the satiation period favours polydextrose for the reduction of this subjective feelings of appetite. Although there has been much research into the effects of polydextrose on satiety, again many of these studies were not designed with the purpose of fat replacement in mind and this was not the control used. There is also a need for some longer-term clinical trials into the effect of polydextrose on body weight (Canfora and Blaak, 2015). One study using Litesse® polydextrose, a commercial polydextrose brand owned by Dupont, found that the polydextrose in combination with a probiotic for six months could reduce fat mass and decrease food intake but the polydextrose on its own had no effect (Stenman et al., 2016).

Although not many of the individual products developed to replace fat from carbohydrates have been researched for their effects on food intake and body weight. Intake of a 14-day ad libitum high-starch diet was shown to decrease energy intake and body weight compared with a high-fat or high-sucrose diet (Raben et al., 1997). Starches from a variety of sources have been used to replace fats to provide sensory and textural properties of oil. They are often used in conjunction with gums to replace fat. Other products that have been developed to replace fat include Ztrim and Oatrim, which were developed by the U.S. Dept. of Agriculture's (USDA) National Center for Agricultural Utilization Research (Peoria, Ill.) and patented by USDA. Oatrim consists of soluble 5% ß-glucan and amylodextrins from oat flour. It forms a fat-like gel when

hydrated with water that provides 1 kcal/g (Inglett and Newman, 1994). Oatrim can be added to foods as a dry powder (4 kcal/g) or as a gel (1 kcal/g) hydrated with three parts water. The mouthfeel of Oatrim mimics that of regular triglycerides. Although there has been research into the Oatrim as a fat replacer there is limited work on its effects on food intake. Z-Trim (Z represents zero calorie), developed by the USDA for blending with Oatrim, is an indigestible insoluble fiber made from the high-cellulose portion of the hulls of oats, soybeans, peas, rice, or bran from corn or wheat. The hulls or bran are processed into broken cellular fragments and purified, then dried and milled into a powder. The powder may be rehydrated for use as a gel. There is limited research on either of these products with regards to weight loss or food intake (Hallfrisch et al., 2002).

4. Conclusion

Reformulation is a challenging concept due to the many arguments for and against it presented in this chapter. Whilst it is perceived by some as a tool to improve public health by making significant reduction in intake of free sugars by consumers, others acknowledge the need to promote healthy eating behaviour, portion control, clarity in food labelling, addressing food/nutrition insecurity, education and generating awareness as long-term strategies to achieve weight loss. Moreover, there are not enough long-term studies that have tested the effect of AS on various metabolic markers and weight gain in different populations. In the case of dietary fibre, due to their multitude of beneficial physiological effects, most of the long-term studies consider weight loss as a secondary or tertiary outcome only. Therefore, adequately controlled and well-powered studies using reformulated foods high in fibre, are needed to prove the theoretical assumptions on their role in weight loss. Additionally, more research is also needed to demonstrate the effect of plant-based IS such as those from Stevia on weight loss and weight management. There are a wide variety of fat replacement products available, however the functional, and physiological properties of these differ considerably. Many of the fat substitutes have both lower energy densities and may also aid weight loss or satiety through other mechanisms. The properties of the fat mimetics rely quite often on their reduced energy density, however research is still lacking into the use of fat mimetics on appetite, satiety and weight loss when used as fat replacement products. Research on fat replacement products and appetite needs further research, particularly in the understanding if there is a

disconnect between the taste and feeling of fat in the mouth and the sensing of fat in the gastrointestinal tract.

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Abbreviations

Artificial sweeteners (ASs)

Association of Official Agricultural Chemists (AOAC)

Body mass index (BMI)

Body mass index (BMI)

Bulk sweeteners (BS)

Cholecystokinin (CCK)

Diacylglycerol (DAG)

Energy Expenditure (EE)

European Food Safety Authority (EFSA)

Food and Agriculture Organization (FAO)

Food and Drug Administration (FDA)

Generally recognized as safe (GRAS)

Intense sweeteners (IS)

Long chain triglyceride (LCT)

Low-calorie sweeteners (LCS)

Medium chain fatty acids (MCFA)

Medium chain triglycerides (MCT)

Medium-long chain triglycerides (MLCT)

National Health Service (NHS)

Non-milk extrinsic sugars' (NMES)

Non-nutritive sweeteners (NNS)

Pancreatic polypeptide (PP)

Randomised controlled trials (RCTs)

Resistant starch (RS)

Scientific Advisory Committee on Nutrition (SACN)

Small particle lipid (SPL)

Sugar-sweetened beverage (SSB)

Triacylglycerol (TAG)

World Health Organization (WHO)

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Table 2 Summary of the observational studies investigating the relation between LCS, energy intake and body weight

Reference	Participant number	Study duration	Foods/Drinks	Energy intake	Weight change
Schulze et al 2004	51603 women from the Nurses' Health Study II	8 years	SSBs	NA	Greater magnitude of weight gain in consumers of sugar-sweetened soft drinks
Fowler et al 2008	3371 from the San Antonio Heart Study	8 years	AS beverages	Mean 223 kcal/day reduction in AS users compared to non-users	ΔBMIs were 47% greater among AS users than nonusers
Nettleton et al 2009	6,814 from the Multi-Ethnic Study of Atherosclerosis (MESA)	7 years	Regular soda or Diet soda	NA	Increased risk of elevated waist circumference measurement in LCS users
Bleich et al 2014	23 965 National Health and Nutrition Examination Survey 1999–2010	Cross-sectional	Diet drinks	Mean increase in 88 -194 kcal/day in overweight and obese diet drink users	NA

Table 3 Summary table showing the characteristics of the randomised controlled trials included on low-calorie sweeteners, energy intake and body weight

Reference	Participant number	Study duration	Test foods	Energy intake	Weight change
Raben et al, 2002	Overweight adults, parallel design; n=21 in sucrose group and n=20 in sweetener group	10 weeks	Test foods with sucrose or sweeteners (aspartame, cyclamate, acesulfame K, and saccharin)	Sucrose group increased energy intake by 1.5 MJ/d. Sweetener groups's energy intake remained same as at baseline.	Sweetener group had reduction in body weight and fat mass. Sucrose group had increase in body weight and fat mass.
Van Wymelbeke et al 2004	24 young healthy participants	10 weeks	Orange or raspberry flavoured mineral water with sucrose or a mixture of sweeteners (aspartame, acesulfame K and saccharin)	Significant increase in energy intake following sucrose sweetened beverages	No change
Gostner et al 2005	20 healthy participants	4 weeks	A range of sweet foods with 30 g/d isomalt or sucrose	NA	No change
Reid et al 2007	133 mornal weight women	4 weeks	Soft drinks with sucrose or aspartame	1000 kJ increase in energy intake in the sucrose group	Women on sucrose drink showed a tendency for weight gain
Anton et al 2010	19 lean and 12 obese participants; Post-prandial study	NA	Cream cheese pre-load with sucrose, aspartame and stevia	300-334 kcal reduction in energy intake following stevia and aspartame pre-load	NA

Reid et al 2010	53 overweight women	4 weeks	Soft drinks with sucrose or aspartame	No change	No change
Njike et al 2011	44 overweight participants	6 weeks	Sucrose or sweetener based cocoa beverage	NA	No change in body weight
Tate et al 2012	318 overweight and obese adults	6 months	Caloric beverages replaced with Water or Diet beverages	Reduction in 225 kcal/day	Average of 2 to 2.5 % weight loss in the water and diet beverage group
Maersk et al 2012	47 overweight participants; Parallel randomised trial	6 months	Sucrose sweetened cola or aspartame-sweetened cola (1 L /day)	No change in energy intake between the groups	No change in body weight; Significant increase in Visceral fat in the sucrose cola group
Markey et al 2016 The REFORM study.	RCT, cross over design with normal and overweight participants; n= 50	8 weeks	Various commercially available sugar-reformulated products	No change from baseline	No change from baseline

Table 4 Summary table showing the studies investigating the effect of dietary fibre in reformulated foods on energy intake and body weight

Reference	Participant number	Study duration	Test foods	Energy intake	Weight change
Beck et al 2009	14 overweight adults; postprandial stidy	NA	Oat beta glucan enriched cereals	Increase in PYY AUC with dose of beta glucan	NA
Vitaglione et al 2010	20 healthy volunteers; postprandial study	NA	Barley beta glucan enriched biscuits	Increased satiety and fullness ratings. No effect on subsequent energy intake.	NA
Beck et al 2010	66 overweight females	3-month parallel study	Energy deficit diet consisting of Cereal, muesli bars, porridge and extruded snack with 5-6 g or 8-9 g beta glucan	Increase in PYY after the beta glucan diet compared to the control diet	No increase in weight loss achieved by the energy deficit diet
Pentikainen et al 2014	30 healthy female participants; postprandial study	NA	Biscuits and juice with 4 g and 8 g oat beta glucan	Increased feelings of satiety with beta glucan biscuits and juice.	NA
Clegg and Thondre 2014	23 healthy male adults; postprandial study	NA	Soup with 3 g beta glucan	No effect on satiety or subsequent energy intake	NA
Yeung et al 2018	16 healthy adults; postprandial study	NA	Noodles with 100% or 50% Konjac glucomannan	No effect on the subsequent meal; 47% and 23% reduction in cumulative energy intake	NA

Table 5 Summary table showing the characteristics of the randomised controlled trials examining the effect of MCTs on energy intake, energy expenditure and body weight. Table is adapted from Clegg (2017)

Reference	Participant number	Study duration	Test foods	Energy intake/exp	Weight change
Alexandrou et al. 2007	Eight healthy women	NA	45% CHO, 40% fat, 15% pro. The diets had either 60.81% or 1.11% of fat energy from MCTs.	Days 1 & 7 no difference between diets for resting metabolic rate or mean postprandial EE. Days 1 & 7 FO was increased with MCTs diet	NA
Binnert et al. 1998	Eight control and eight obese	NA	30g of olive oil or 30 g – (50% olive oil, 50% MCTs) mixed with lemon juice	LCT oxidation was decresed in obese & negatively correlated with fat mass. Plasma dietary TAG-derived LCFA were decreased in the obese & negatively related to fat mass & positively to LCT oxidation. The proportion of MCTs oxidized was increased in both groups compared to LCTs	NA
Clegg et al. 2013	Seven healthy volunteers	NA	Breakfast containing either chilli and 20g MCTs oil, chilli and sunflower oil,	Differences in DIT existed between the chilli-MCTs oil and	NA

			bell pepper and sunflower oil or bell pepper and MCTs oil	chilli-sunflower oil, between chilli-MCTs oil and pepper-sunflower oil and between pepper-sunflower oil and pepper-MCTs oil. There was a significant difference in fat oxidation between the pepper-sunflower oil and pepper-MCTs oil.	
Coleman et al. 2016	Nineteen healthy	NA	Smoothies with either 5 g CLA and 16g vegetable oil, 25 g MCTs or 22 g vegetable oil	The MCTs meal decreased food intake over the entire day. There significant differences in ad libitum food intake or satiety from VAS scores.	NA
Dulloo et al. 1996	Eight healthy young men	NA	Combinations of MCTs & LCTs totalling 30g/day consumed with habitual diet in 3 equal parts in the ratio of MCTs: LCTs (g/g) 0:30, 5:25, 15:15 & 30:0.	EE increased with increasing MCTs:LCTs ratio. No differences were observed in RQ or in urinary nitrogen losses, but 24-h urinary noradrenaline was increased with MCTs.	NA
Han et al. 2007	40	90 days	Either MCTs or corn oil (LCT). The test oil (18 g/d) was administered as part of daily food intake for 90 days	Insulin resistance & serum cholesterol as well as increased in serum C-peptide. LCTs group did not. Changes	MCTs group had across-time decrease in BW and WC,

				were associated with an involuntary decreased in EI.	
Kasai et al. 2002	Eight male and eight female subjects	NA	Study 1 meals had 10 g MCTs (10M), 5 g MCTs & 5 g LCT (5M5L) or 10 g LCT (10L). Study 2 meals had 5 g of MCTs or LCTs	PPT was increased after 5M5L & 10M compared to 10L. Ingestion of 5 g MCTs caused increased PPT compared to LCTs.	NA
Kovacs et al. 2001	Seven male and 14 female normal to moderately obese	2 weeks	3 meals & four snacks daily with either no addition to diet (PLA), 500 mg HCA (HCA), or 500 mg HCA & 3 g MCTs	HCA & HCA combined with MCTs did not increased satiety or decreased EI compared to PLA in subjects losing BW.	No change in body weight compared to PLA
Kovacs et al. 2001	Eleven overweight male	2 weeks	Controlled diet with no addition (PLA), 500 mg HCA (HCA), or 500 mg HCA & 3 g MCTs	HCA & HCA combined with MCTs did not result in increased satiety, FO or 24 h EE compared to PLA, in subjects losing BW.	No change in body weight compared to PLA
Krotkiewski, 2001	Sixty-six female patients (22 per group)	4 weeks	Isoenergetic (578.5 kcal) VLCD) enriched with MCTs or LCTs (8.0 and 9.9 g/100 g) or a low-fat (3 g/100 g) and high-carbohydrate regimen	NA	MCTs group had a greater decrease in body weight during the first 2 weeks and hunger feelings were less intense while satiety was higher. Differences were observed during the first 2 weeks of treatment and declined after that

Nosaka et al. 2003	73 subjects	12 weeks	2100-2400 kcal/day including 65-73 g/day total fat (27.9-31.2 energy %) Diet contain 14g test margarine with 5g MCTs or LCTs	NA	The MCT diet demonstrated significant decrease in BF, subcutaneous & visceral fat after 12 weeks.
St-Onge and Bosarge 2008	Forty-nine overweight men and women,	16 weeks	18-24 g/d of MCTs oil or olive oil as well as weekly weight loss counselling	NA	MCTs oil resulted in decreased BW, trunk fat mass, total fat mass, & intraabdominal adipose tissue than olive oil
St-Onge and Jones 2003	19 healthy overweight men	4 weeks	Diets rich in either MCTs or LCTs	Men with decreased initial BW had a greater increase in EE with MCTs consumption relative to LCTs on day 28 but not day 2. Similar results for FO on day 28.	BW decreased 1.03 kg with MCTs compared to 0.62 kg with LCTs.
Scalfi et al. 1991	six lean and six obese young males	NA	38 g LCT or 30 g MCTs plus 8 g LCT	PPT was increased in both groups after MCTs. Postprandial glucose, insulin, & free fatty acids did not differ between meals	NA
St-Onge et al. 2003	Seventeen healthy obese women	27 days	Weight maintaining diet. 75% of fat as treatment fat (67% MCT oil or 100% beef tallow)	EE & FO were increased during MCTs than LCTs consumption. The BC change with MCTs consumption, although not statistically	Changes in total and subcutaneous adipose tissue volumes following consumption of MCTs and LCTs were not different

				different, was consistent with the shifts in EE	
St-Onge et al. 2003	Twenty-four healthy, overweight men	28 days	Weight maintaining diet. 40% of energy as fat, (75% primarily as functional oil or olive oil)	EE and FO was ↑ on day 2 with FctO compared with OL.	Upper body adipose tissue decreased to a greater extent with functional oil compared olive oil
Stubbs and Harbron 1996	Six healthy male		3 HF diets for 3 days each. MCTs to LCTs was 1:2, 1:1 & 2:1 on the low, medium- & high-MCTs diets	EI was decreased on the HMCTs diet. Mean values were 13.50, 13.67, & 12.43 MJ/d on the LMCTs, MMCTs & HMCTs diets. Food intake followed parallel.	By day 14 BW changes amounted to +0.45, +0.41 & -0.03 kg, respectively
Tsuji et al. 2001	78 healthy men and women	12 weeks	9218 kJ/d & 60 g/d of total fat. The energy, fat, PRO & CHO intakes did not differ significantly between the groups. MCT group consumed 9.28g MCTs per day	NA	BW & BF decreased by wk 4, 8 & 12 in both groups. In volunteers with BMI ≥ 23 kg/m^2 BW decreased more in the MCT than the LCT group, the loss of BF was increased in the MCTs group than the LCTs group at 8 wk. the change in area of subcutaneous fat was ↑ in the MCTs than the LCTs group at wk 4, 8 & 12.

Van Wymelbeke et al. 1998	12 healthy, adult, male	NA	4 high-CHO breakfasts (1670 kJ) supplemented either with a fat substitute (70 kJ) or 1460 kJ fat as monounsaturated LCTs, saturated LCTs or MCTs.	The addition of fats to the high-CHO breakfasts did not alter hunger but delayed the request for lunch compared with LF breakfast. Free-choice lunch was decreased after MCTs breakfast. Blood glucose & insulin were decreased after the 3 fat breakfasts followed by larger increase in glucose & insulin 30 min after lunch.	NA
Van Wymelbeke et al. 2001	10 male	NA	1 lunch was a basic 2310-kJ meal containing 40 kJ fat substitute (Sub). The 3 other lunches were the same but contained 1200 kJ LCTs, MCTs or 900 kJ CHO + 300 kJ LCTs	CHO oxidation was ↓ after the MCTs & LCTs lunches where FO was ↑ after the MCTs & LCTs lunches. The dinner request was delayed after the CHO lunch. FI at dinner was ↓ after the MCTs lunch than after the Sub & CHO lunches, but the dinner meal request was not delayed.	NA

EE = energy expenditure
BW = body weight
WC = waist circumference
CHO = carbohydrate
EI = energy intake
RQ = respiratory quotient
PPT = post prandial thermognesis
PRO = protein
BC = body composition
BF = body fat
FO = fat oxidation

Table 6 Summary table showing the characteristics of the randomised controlled trials examining the effect of coconut oil on energy intake, energy expenditure and body weight. Table is adapted from Clegg (2017)

Reference	Participant number	Study duration	Test foods	Energy intake/exp	Weight change
Kinsella et al. 2017	Twenty-eight healthy male and female	NA	test breakfast smoothie containing 205 kcal of either (i) MCTs oil (ii) coconut oil or (iii) vegetable oil (control)	The MCTs oil reduced food intake at the ad libitum meal compared to the coconut and control oil. The control had increased food intake throughout the day compared to the MCTs and coconut. The MCTs also increased fullness over the three hours after breakfast compared to the control and coconut oils.	NA
Labarrie and St-Onge. 2017	Fifteen children	NA	Two test meals, containing 20 g of fat from either corn oil or a coconut oil-enriched baking fat	There was no significant effect on TEF, appetite/satiety, glucose, and insulin area under the curve. Leptin concentrations were lower and peptide YY	NA

				concentrations were higher with corn oil consumption.	
Poppitt et al. 2010	18 lean men	NA	SCTs- (dairy fats), MCTs- (coconut oil) and LCTs- enriched (beef tallow) test breakfasts (3.3 MJ) containing 52 g lipid (58 en% fat). 15g coconut oil was used to provide 10g MCT.	No significant effect of fatty acid chain length on satiety ratings or energy intake at an ad libitum meal.	NA
Rizzo et al. 2016	36 healthy female participants	NA	10g of fat in ice-cream consisting of either 25% coconut oil and 75% sunflower oil; 50% coconut oil and 50% sunflower oil; 75% coconut oil and 25% sunflower oil	Participants ate significantly less fat at dinner after the 75% coconut ice cream. There was no difference in intake at the dinner though a trend towards reduced consumption with increases in coconut oil. Calorie intake from snacks was lower after low coconut oil ice-cream. No effect of condition on satiety VAS data over the day.	NA
(Papamandjaris, White et al. 2000)	Twelve healthy females	14 days	Weight maintaining diet. 80% of fat was either butter & coconut oil (MCTs) or beef tallow (LCT)	No difference in exogenous LCSFA as a function of diet on day 7. On day 14, increased LCSFA was observed in	NA

				those fed the MCT vs LCT diet.	
(Papamandjaris, White et al. 1999)	Twelve healthy females	14 days	Weight maintaining diets. 80% of fat was either 26% MCTs & 74% LCTs or 2% MCTs & 98% LCTs	TEE on the MCT diet did not differ from the LCT diet. BMR was increased on the MCTs diet on day 7, but not day 14.	NA
(White, Papamandjaris et al. 1999)	Twelve healthy females	14 days	Weight maintaining diets. Each meal contained 40% energy as fat (80% of which was treatment fat)	On day 7 BMR was increased on the MCTs compared to the LCTs diet. EE on day 7 was increased with the MCTs diet than the LCTs diet. No differences in the TEF were evident between diets.	NA

TEF = Thermic effect of feeding TEE = Total energy expenditure

BMR = Basal metabolic rate LCSFA = endogenous oxidation of long chain saturated fatty acids

Table 7 Summary table showing the characteristics of the randomised controlled trials examining the effect of DAG oil on energy intake, energy expenditure and body weight. Table is adapted from Maher and Clegg (2018).

Reference	Participant number	Study duration	Test foods	Energy intake/exp	Weight change
Kamphuis et al. 2003	12 healthy women	4.5 days	Energy-maintenance diets where 40% of the fat was consumed as DAG-rich (80% DAGs) oil	Fat oxidation was higher with DAG treatment than with TG treatment. Appetite profiles during day 1 did not differ between treatments; however, feelings of appetite, were all significantly lower on day 2 with DAG treatment.	NA
Kawashima et al. 2008	312 overweight or obese and women	1 year parallel trial	Participants were given DAG or TAG oil to replace normal cooking oil.	No difference in energy intake between groups	Body weight decreased significantly in the DAG group when compared to the TAG group
Li et al. 2008	127 individuals with T2D	120 days	25 g/day DAG 25 g/day TAG	Increased carbohydrate intake after DAG Reduced EI (non-sig) after DAG	Body weight, BMI and waist circumference, were reduced from baseline in the DAG oil group but not in the TAG oil group
Maki et al. 2002	131overweight or obese men and women	24 weeks	Substitution of fats in the diet with the goal of achieving ≈15% of the total	NA	Body weight and fat mass decreased significantly more in

			energy in the diet from either TAG or DAG oil		the DAG group than in the TAG group
Nagoa 2000	38 healthy men	16 weeks	10 g/day of the DAG-rich oil contained 5.5 g 1,3-DAG, 2.5 g 1,2-DAG and 2 g TAG	NA	Body weight, BMI, waist circumference, total fat, visceral fat area and subcutaneous fat area decreased more in the DAG group than in the TAG group. Decreases in the DAG group were also greater than in the TAG group.
Yamamoto et al. 2001	16 diabetic patients	12-week parallel trial	10 g/day DAG) 10 g·day TAG from normal cooking oil	No differences between groups for energy intake	No differences between groups for body weight

TAG = Triacylglyceride DAG = Diaclyglyceride EI = energy intake

Table 8 Summary table showing the characteristics of the randomised controlled trials examining the effect of small particle lipids on energy intake, energy expenditure and body weight. Table is adapted from Maher and Clegg (2018)

Reference	Participant number	Study duration	Test foods	Energy intake/exp	Weight change
Burns et al. 2000	Two groups of 30	NA	Control: Yoghurt containing 6 g dairy fat; Test: Yoghurt containing 5 g Olibra™ and 1 g dairy fat	Decreased energy intake, food intake, and intake of all macronutrients after test food at 4 h. No change in subjective sensations of appetite and hunger	NA
Burns et al. 2001	20 healthy weight, 20 overweight and obese participants	NA	Control: Yoghurt containing 6 g dairy fat Test: Yoghurt containing 5 g Olibra™ and 1 g dairy fat	Decreased fat, carbohydrate, protein and total energy intake at both 4 h and 8 h after test. No difference in subjective sensations of appetite and hunger	NA
Burns et al. 2002	50 healthy individuals	NA	Yoghurt with varying doses of Olibra™: 0g (control), 5 g, 10 g, or 15 g. 5 and 10 g amounts also had 10 and 5 g of milk fat, respectively, whereas the control was 15 g of milk fat.	Increased suppression with food intake as dose of Olibra™ increased. No change in subjective sensations of appetite and hunger	NA
Chan et al. 2012	18 lean men	NA	4.2 g lipids from a control or 15 g of	Increased fullness after LE + Yoghurt, no effect	NA

			Fabuless™ provided in (or alongside) liquid form, semi-solid form and solid form, with a control for each state: Liquid emulsion (LE) Liquid control (LC) Semi-solid emulsion (LE + Yoghurt) Semi-solid control (LC + Yoghurt) Solid emulsion (LE + Muffin) Solid control (LC + Muffin)	of Fabuless™ in liquid or solid form. No change in EI across all conditions	
Chan et al. 2017	18 lean men	NA	6 conditions, 4 lipids and 2 controls: Fabuless™ emulsion Dairy emulsion with dairy emulsifier Dairy emulsion with soy lecithin emulsifier Dairy control (non-emulsified) Palmolein emulsion with dairy emulsifier Palmolein control (non-emulsified)	No change in satiety ratings between lipids and respective controls. No change in EI between lipids and respective controls	NA
Diepvens et al. 2007	50 overweight women	18-week weight maintenance	Control: 500 g of yoghurt containing 10 g milk fat, split into 2 doses	Decreased hunger after test product. Increased CCK, GLP-1, and βHB after test product	No significant increase in body weight in the test group, the placebo

			Test: 500 g of yoghurt containing 6 g milk fat and 4 g vegetable fat from Olibra^{TM}, split into 2 doses		group did gain weight
Hussein et al. 2014	Crossover feeding study in 11 healthy people	NA	3 emulsions: Control: Coarse emulsion (6 μm droplets) Coarse+locust bean gum (LBG): Coarse emulsion (6 μm droplets) + 0.5% locust bean gum Fine+LBG: Fine emulsion (0.4 μm droplets) + 0.5% locust bean gum	Increased CCK after both LBG trials, no diff between Coarse+LBG and Fine+LBG. Decreased EI after both LBG trials, greater decrease after Fine+LBG compared to Coarse+LBG. No change in VAS	NA
Logan et al. 2006	28 (14 male, 14 female)	2 x 3-week study phases	Control: 5 g milk fat Test: 12.5 Olibra^{TM} providing 5 g fat	No change EI across trials. No change in subjective sensations of appetite across trials	There was no significant treatment effect on the changes in body weight
Marciani et al. 2009	Eleven healthy male	NA	Emulsions made from [^{13}C] palmitate-enriched olive oil, providing 50 g of fat in 3.6 μm droplets. Two conditions were 'acid-stable' and 'acid-unstable' emulsions	Decreased ratings of hunger and appetite after acid-stable emulsion	NA

Ohlsson et al. 2014	Study 1) 19 male and female Study 2) 15 female	NA	Study 1) 35 g lipids from LOO or yoghurt in a breakfast meal. Study 2) Three doses of lipids from yoghurt (control) or fractionated oat oil (LOO): 1.8 g, 14 g, and 35 g	Increased satiety after study 2 in women not study 1. Increased GLP-1, PYY and CCK after 14 g and 35 g of LOO. No change in EI across trials	NA
Peters et al. 2014	24 volunteers	NA	Fat-free drink with: 5g fat in 3 μm droplets 9g fat in 3 μm droplets 5g fat in 0.1 μm droplets 9g fat in 0.1 μm droplets	No change in EI across all trials. Increased CCK release in smaller droplet trial, but only in 9 g fat load	NA
Rebello et al. 2012	82 overweight or obese	12-week dietary supplementation study	Control group: yoghurt providing 1.95 g milk fat twice daily Test group: yoghurt providing 2.1 g Olibra™ twice daily	Decreased hunger after Olibra™ supplementation. No change in EI and ratings of appetite and satiety between trials	Both groups reduced weight but differential weight and waist circumference reductions were not significant.
Smit et al. 2011	24 healthy volunteers	NA	Test drinks with 5 g milk/corn fat added ('Control') or 12.5 g of Fabuless™ (containing 5 g of fat) added: During the manufacturing process ('Processed')	No change in EI at ad lib lunch. Decreased EI at ad lib dinner after Unprocessed. No change in subjective sensations across trials	NA

			After the manufacturing process ('Unprocessed')		
Smit et al. 2012	Twenty-four healthy	NA	100 g test drinks comprising of: 2.0 g added milk fat 2.0 g added fat from 5 g Fabuless™ 3.2 g added milk fat 3.2 g added fat from 8 g Fabuless™	No change in energy intake and subjective sensations of satiety when comparing each dose to the control Increase in hunger at one timepoint after the Fabuless™ drink, no other differences Increased EI at one timepoint after the Fabuless™ drink	NA

CCK = cholecystokinin GLP-1 = glucagon like peptide 1 βHB = β hydroxybuterate

EI = energy intake VAS = visual analogue scales PYY = peptide tyrosine tyrosine