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Characteristics and properties of fibres suitable for a low FODMAP diet- an overview

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ABSTRACT

Background: Irritable bowel syndrome (IBS) is one of the most common gastro-intestinal disorders worldwide and is often treated by adjusting the diet of IBS patients. An increased intake of dietary fibre (DF) and a limitation of the intake of fermentable oligo-, di-,monosaccharides and polyols (FODMAP) are the two dietary adjustments which are frequently recommended for people suffering from IBS. However, one challenge of a diet low in FODMAPs is the limited number of suitable dietary fibres.

Scope and approach: The aim of this overview is to identify characteristics and DFs beneficial for IBS patients by comparing the physico-chemical properties of FODMAPs and DFs. Therefore, relevant literature about DFs and FODMAPs was collected and summarised. These characteristics and the associated technological properties were used for a selection of DFs which can be used to develop food products with an increased fibre content and a lower FODMAP content while assuring the product quality expected by the consumer.

Key findings and conclusions: A low fermentation rate, low osmotic activity, insolubility and a high viscosity of soluble DFs have been identified as characteristics which are beneficial independent from the type of IBS. Soluble and non-viscous DFs can be beneficial depending on the occurrence of diarrhoea and their state of hydration. This finding highlights the importance of targeting a specific type of IBS. The above mentioned characteristics and the list of suitable DFs provide a good base for the development of functional foods and for future research regarding DF supporting the needs of IBS patients.

1. Introduction

In recent years, the diet has become the focus of both a healthy lifestyle and the development of therapies for people suffering from gastro-intestinal problems. Functional gastro-intestinal disorders (FGIDS) are a main target of diets designed for medical purposes. FGIDs are one of the most common gastro-intestinal illnesses and are therefore one of the commonly reported causes for medical treatment and sick leave (Lacy et al., 2016; Soncini et al., 2019). One of the most prominent FGIDs is irritable bowel syndrome (IBS) with a prevalence of 15–20% worldwide and of 8% among the European population (Gibson, Varney, Malakar, & Muir, 2015; Sperber et al., 2017). IBS is a FGID which is not related to organic causes and is rather induced by the appearance of certain factors including stress, depression and diet (Spiller & Lam, 2011). The Rome IV criteria is used to diagnose and identify IBS. According to these criteria, people suffering from IBS experience an alteration of defaecation type and frequency, and the intensity of abdominal pain for at least 1 day per week over 3 months and after an onset of at least 6 months (Lacy et al., 2016). Depending on the occurring symptoms and appearing stool forms IBS can be divided into 3 subtypes: IBS-constipation (IBS–C), IBS-diarrhoea (IBS-D), and IBS-mixed (IBS-M) according to the Rome IV criteria (Lacy et al., 2016). The treatment of IBS often involves several approaches due to the vast variety of causes for the occurrence of symptoms. IBS treatment can involve either social or psychological methods, such as education, reassurance, psychotherapy and the reduction of stress, anxiety and a hectic lifestyle or treatment using various drugs and nutritional supplements. The used medications either include drugs treating the psycho-somatic causes, such as anti-depressants, or the use of pharmaceutics targeting the gastro-intestinal symptoms, such as anti-spasmiotics, laxatives, herbal remedies, prucalopride, surpositories/micro-enemas, rifaximin, and mesalamine (De Ponti,

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2013; Soncini et al., 2019). However, the use of those medications is strongly debated since they are mostly affecting a single symptom and are therefore not suitable for the treatment of a complex disorder, such as IBS (De Ponti, 2013). Furthermore, the use of probiotic supplements is commonly recommended as those can support the gut microbiome of people suffering from IBS (Soncini et al., 2019).

Another approach to improve symptoms of both FGIDs in general and IBS especially is the adjustment of the patients' diet (Mann & Cummings, 2009). Two different approaches have been at the centre of finding a diet-based treatment and both of them focus on two different groups of carbohydrates which are not digestible in the human gastro-intestinal tract. One targets dietary fibres (DF) while the other highlights the symptom affliction by fermentable oligo-, di-,mono-saccharides and polyols (FODMAPs) (Chouinard, 2011; Parisi et al., 2002; Soncini et al., 2019).

An association between the relief of gastro-intestinal symptoms and the intake of DF exists since the early 1980s (Stephen & Cummings, 1980). Symptoms, which have been reported to be improved, include stool hardening, frequency of defecation, stool bulking, and abdominal pain (Cameron-Smith, Collier, & O'dea, 1994; Lewis & Heaton, 1999; Mann & Cummings, 2009). Therefore, the supplementary intake of DF is often prescribed to people suffering from FGIDs, including IBS (Bosaeus, 2004; Chouinard, 2011). Besides the improvement of the most prominent symptoms of FGIDS, DFs are also often linked to general health benefits (Slavin & Green, 2007; Stephen & Cummings, 1980). These include lower cholesterol levels, a decreased glucose response, an increase in diversity of the gut microbiome, a lower risk of inflammation and a lower risk of colon cancer (Bingham et al., 2003; Mann & Cummings, 2009). Therefore, various DFs have been tested regarding their potential for clinical treatment of IBS and certain DFs, such as partially hydrolysed guar gum (PHGG) and psyllium, have been identified to improve the overall life quality of IBS patients (Campbell, Ross, & Motoi, 2008; Parisi et al., 2002).

The term FODMAPs describes carbohydrates which are neither digested nor absorbed in the human gut and can therefore be fermented and osmotically active in the large intestine (Varney et al., 2017). Those two characteristics have been hypothesized to be the main factors inducing IBS symptoms (Halmos, Power, Shepherd, Gibson, & Muir, 2014). Because of this, the interest in developing a diet based on a limited FODMAP intake has seen an increase in recent years (Bellini et al., 2020; Soncini et al., 2019). The efficiency of this approach is highlighted by clinical trials which showed that a restriction of FODMAPs lead to an improvement of IBS symptoms in 70% of the subjects (Varney et al., 2017).

Despite its advantages the exclusion of FODMAPs has often been reported to have certain disadvantages. A major disadvantage is the complexity of this diet which can cause difficulties in educating patients. Other difficulties in following the diet are often caused by the limitation to specific foods, higher costs, the need of adapting the diet to individual lifestyles needing advice from a nutrionist, and struggles in ensuring a nutritional adequacy and the intake of specific nutrients, for example DFs (Bellini et al., 2020; Ispiryan, Zannini, & Arendt, 2020). The exclusion of food products based on cereals and pulses, which are both ingredients high in FODMAPs, is often a main reason for discontinuing the diet (Bellini et al., 2020; Ispiryan et al., 2020). Those two ingredient groups are also largely contributing to the intake of DF in the western world. A limited number of DFs is suitable for IBS patients since a vast number of DFs share certain negative characteristics with FODMAPs and most of the commercial DFs are cereal based. Therefore, it is the aim of this overview to provide the knowledge needed to establish characteristics of DFs which can be beneficial for a low FODMAP diet and to also identify examples of these DFs. To achieve this, both established and recent literature were reviewed to gather the most important and relevant information.

2. Dietary fibre

2.1. Definition and classification of DF

The term dietary fibre describes a broad variety of compounds which largely differ in both their chemical structure - including monomeric composition and average degree of polymerisation (DPav) - and their physico-chemical properties, such as solubility, viscosity and fermentability (Guillon & Champ, 2000; Wang, et al., 2017). Therefore, the definition and the classification of DFs is often difficult and based on national regulations. In general, DFs are defined as carbohydrates which are not digestible in the human gut, are active in the human colon and possess scientifically proven health benefits (European Commission, 2012). In Europe, Canada and the USA the definition of DF includes oligosaccharides with an average DPav of at least 3. Therefore, oligosaccharides, such as fructooligosaccharides (FOS), α-galactooligosaccharides (GOS) and xyloseoligosaccharides (XOS) are in those countries considered as DFs (European Commission, 2012).

DFs can be classified and divided into subtypes according to the source from which DFs are derived, or their physico-chemical properties, including solubility, viscosity and fermentability (Dhingra, Michael, Rajput, & Patil, 2012). The classification according to physico-chemical properties enables the prediction of the effect on both the gut health and the general health of humans, since specific benefits are correlated to certain characteristics (Cameron-Smith et al., 1994; Lewis & Heaton, 1999). Furthermore, the information regarding the mechanism of the DFs can be used for recommending specific DFs in for the treatment of certain FGIDs. Therefore, dietary fibre can be divided into six main groups (Table 1) (Eswaran, Muir, & Chey, 2013). Those groups are: i.) soluble, non-viscous, fermentable DF; ii.) soluble, non-viscous, unfermentable DF; iii.) soluble, viscous, fermentable DF; iv.) soluble, viscous, unfermentable DF; v.) insoluble, fermentable DF and vi.) insoluble, unfermentable DF. Examples of DF belonging to the various groups which are commonly used for industry purposes are

Table 1
Examples and characteristics of the different fibre classes according to their physico-chemical properties (Eswaran et al., 2013).

Fibre class	Health benefit	Examples
Soluble, viscous and fermentable	Stool softening Lower cholesterol level and postprandial glucose response Can act prebiotically	Guar gum, Pectin, Gum arabica, β-Glucan, Konjac, Sodium Alginate
Soluble, non-viscous and fermentable	Stool softening Lower cholesterol level and postprandial glucose response Can act prebiotically	Inulin, FOS, GOS, XOS, Polydextrose, Corn fibre
Soluble, viscous and unfermentable	Stool softening Lower cholesterol level and postprandial glucose response Does not cause bloating or odour	Psyllium, Konjac, HPMC, CMC
Soluble, non-viscous and unfermentable	Stool softening Lower cholesterol level and postprandial glucose response Does not cause bloating or odour	PHGG
Insoluble and fermentable	Stool bulking Decreased duration of stool in colon Can act prebiotically	Soy fibre, Maize fibre, Pea fibre, Resistant Starch, Wheat bran
Insoluble and unfermentable	Stool bulking Decreased duration of stool in colon Does not cause bloating or odour	Cellulose, Bamboo fibre, Potato fibre

listed in Table 1 (Eswaran et al., 2013).

2.2. General mechanism of the effect of DF on the gastro-intestinal tract (GIT)

The effects DFs have on the human gut are an alteration of stool type (including softness and mass of stool), a reduced colonic transit time of the food and the metabolization of DFs by the gut bacteria (Mann & Cummings, 2009; Stephen & Cummings, 1980). The mechanisms underlying these effects are dependent on the physico-chemical properties. The differences in the mechanism are explained for each factor separately. The general mechanism in which DFs impact the gastro-intestinal tract (GIT) is depicted in Fig. 1. DFs are effective in the human gut due to their non-digestibility by enzymes active in the bowel or the colon. Therefore, DFs reach the colon intact. Stool bulking and stool softening are induced by an increase of luminal water and an increase of biomass after fermentation. Fermentability of DFs leads to an increase of diversity in the gut microbiome and to the production of short chain fatty acids (SCFA), which trigger a positive chain reaction in the large intestine by being osmotically active or functioning as neuro-transmitters (Bingham et al., 2003; Stephen & Cummings, 1980). Fermentation by the gut microbiota also causes adverse effects, such as

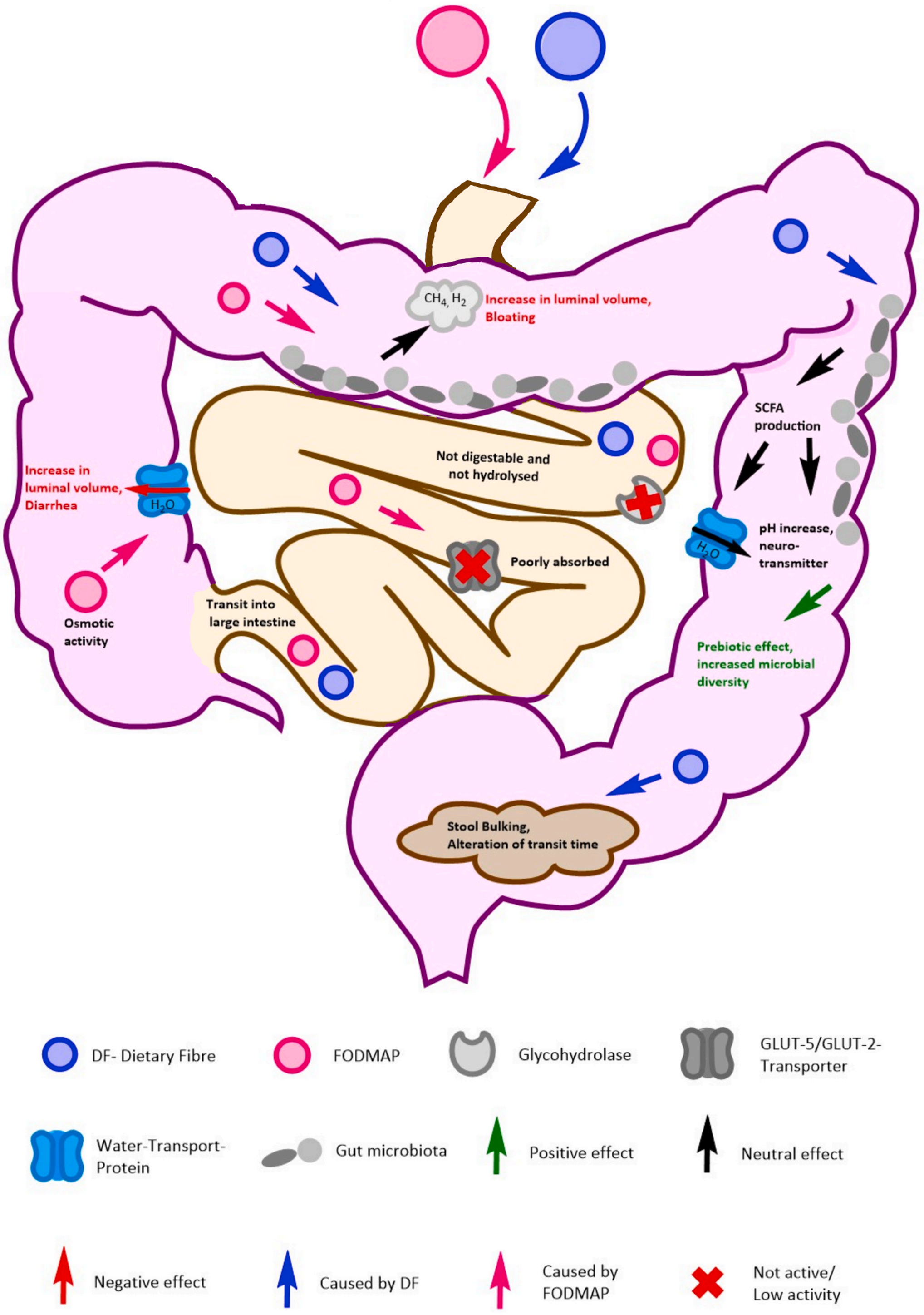

Fig. 1. (Coloured Image)Mechanism of the effect of DF and FODMAPs on the human GIT.

the production of gas and odour (Eswaran et al., 2013).

2.3. Solubility

Depending on their hydrophilic behaviour DFs can be either soluble or insoluble in water. The hydrophilic behaviour and therefore solubility of carbohydrates depends on the DPav, the degree of branching and monomeric composition (Mudgil & Barak, 2013). An increase in the DPav is usually associated with a decline in the solubility of carbohydrates. This effect has been reported for cellulose DFs, fructans and arabinoxylans (Bergenstråhle, Wohlert, Himmel, & Brady, 2010; Cummings, 1984; Li et al., 2015). Increased branching of oligo- and polysaccharides caused a higher solubility due to easier availability of hydroxyl groups (Li et al., 2015; Marlett & Fischer, 2003; Wang, Ma, et al., 2017). Soluble DFs cause stool softening by increasing the luminal water in the colon due to their hydrophilic behaviour and osmotic activity. Furthermore, soluble DFs are largely responsible for the reduction of the glycaemic response and the levels of blood cholesterol (Bijkerk, Muris, Knottnerus, Hoes, & De Wit, 2004; Evans, Hood, Oakenfull, & Sidhu, 1992; Fardet, Leenhardt, Lioger, Scalbert, & Rémésy, 2006; Mudgil & Barak, 2013; Wang, Ma, et al., 2017). Insoluble DFs, such as cellulose, are not associated with the reduction of cholesterol and the glucose response (Cummings, 1984; Goldstein, Ashrafi, & Seetharaman, 2010; Mudgil & Barak, 2013). However, insoluble DFs result in stool bulking and an acceleration of the transition time in the human colon. Stool bulking by insoluble DFs is induced by friction and an increase of faecal mass (Bijkerk et al., 2004; Lewis & Heaton, 1999). The solubility of DFs also has an impact on its availability to the gut microbiota and therefore influences the fermentability. Soluble DFs are more homogenously distributed in the colon since they are dissolved in the luminal water and are therefore more accessible for the bacteria located in the large intestine. This leads to a higher fermentability of soluble DFs compared to insoluble DFs (Holscher, 2017).

2.4. Viscosity

Viscosity is a physico-chemical property occurring in certain soluble DFs. Solubility and viscosity occur together since both characteristics are caused by interaction of hydroxyl groups with freely available water (Guillon & Champ, 2000). However, DFs, such as inulin, FOS, GOS, PHGG and partially hydrolysed konjac are soluble, non-viscous DFs and therefore do not lead to a higher viscosity of the stool bulk (Li et al., 2015). Gums, such as xanthan, guar gum and konjac, make up a majority of the soluble, viscous DFs (Evans et al., 1992; Guo, Cui, Wang, & Christopher Young, 2008; Mudgil & Barak, 2013; Pegg, 2012). Other viscous DFs include psyllium, carboxymethylcellulose (CMC) and hydroxypropylmethylcellulose (HPMC) (Aravind, Sissons, & Fellows, 2012; Haque, Richardson, Morris, & Dea, 1993; Mudgil & Barak, 2013). The viscosity of a fibre largely depends on its ability to form gels. The strength of gel formation varies depending on monosaccharide composition and the molecular structure of the polysaccharides. Examples for this are gums based on galactomannans, such as guar gum or locust gum, since a higher galactose to mannose ratio increases the gel stability and the gelling temperature which are both correlating with a rise in viscosity (Mudgil, Barak, & Khatkar, 2014).

Soluble DFs are responsible for an increased viscosity of the food bulk. In addition to a rise of the viscosity of the contents of the colon, viscous DFs also result in a higher binding of bile acids (Johnson & Gee, 1981; Mudgil & Barak, 2013). This leads to a subsequent decrease of blood cholesterol and low-density lipoproteins (LDL) (Marlett & Fischer, 2003; Zacherl, Eisner, & Engel, 2011). Furthermore, an increase in viscosity of the contents of the bowel and the colon lowers the digestibility and fermentability of foods by decreasing the accessibility to digestive enzymes and bacteria (Mudgil & Barak, 2013; Tomlin & Read, 1988).

2.5. Fermentability and the prebiotic effect

Fermentability is the ability of DFs to be metabolised by the human gut bacteria and is often referred to one of the main causes of the beneficial effect of DFs. DFs are accessible for fermentation since they are not digestible due to a lack of enzymes able to hydrolase those carbohydrates. However, the gut microbiota possesses a higher variety of glycohydrolases which enables the digestion of certain DFs (Bourquin, Titgemeyer, & Fahey, 1996; Koropatkin, Cameron, & Martens, 2012; Titgemeyer, Bourquin, Fahey Jr, & Garleb, 1991). Fermentable DFs result in three main effects: an increased diversity of the gut microbiome, a rise in biomass and the production of metabolites, such as SCFAs and gases (methane and hydrogen) (Holscher, 2017; Rowland et al., 2018). This is also known as the prebiotic effect if a link to health benefits can be established. FOS and GOS are two commonly used prebiotics (Li et al., 2015).

All three effects depend on the monosaccharide composition and the availability of bacteria which can produce the necessary glycohydrolases (Li et al., 2015; Pollet et al., 2012). A rise in the biodiversity of the gut microbiome is often linked to an increased protection against cancer and inflammation. Higher amounts of biomass can cause a decrease of constipation (Holscher, 2017). SCFA production has mainly a positive effect, since butyric and propionic acid can lower the risk of cancer and inflammation (Cummings, Pomare, Branch, Naylor, & MacFarlane, 1987). However, SCFAs can also lead to an increase in luminal water and luminal volume (Cummings et al., 1987; Koh, De Vadder, Kovatcheva-Datchary, & Bäckhed, 2016). Furthermore, the production of gas is often seen as negative, since it can be the reason of flatulences, abdominal pain and odour (Eswaran et al., 2013).

3. FODMAP hypothesis and low FODMAP diet

3.1. Definition and classification of FODMAPs

FODMAPs are oligo-,di-, monosaccharides and polyols which cannot be absorbed or digested in the human gut and are therefore fermentable and osmotically active in the large intestine (Varney et al., 2017; Wang, et al., 2017). This definition already highlights the similarities between FODMAPs and DFs. Like the term DF, the acronym FODMAPs describes a vast variety of carbohydrates. The most common examples for FODMAPs are listed in Table 2 (Varney et al., 2017).

Mannitol, sorbitol and xylitol are polyols which are commonly referred to as FODMAPS. They are commercially used as sugar replacers or they occur naturally in fruits, such as cherries and plums (Muir et al., 2009).

Fructose is a monosaccharide which is insufficiently absorbed in the colon if it is present in excess of glucose (Gibson, Newnham, Barrett, Shepherd, & Muir, 2007). In presence of glucose the absorption of fructose is carried out by the active transport over the transport protein GLUT-5 in co-transport with glucose (Gibson et al., 2007). However, if fructose is consumed in a larger amount than glucose it is passively

Table 2
Classification of FODMAPS with examples and their corresponding cut-off-values (Gibson et al., 2015; Varney et al., 2017).

FODMAP type	Example	Cut-off value [g per serve]
Polyols	Mannitol, Sorbitol, Xylitol	<0.20 (Mannitol and Sorbitol) <0.40 (Total Polyols)
Monosaccharide	Fructose in excess to glucose	<0.15 <0.40 (in fruits where it is the only present FODMAP type)
Disaccharides	Lactose	<1.00
Oligosaccharides	FOS, GOS	<0.30 (core grain products, legumes, nuts, and seeds) <0.20 (vegetables, fruits, and other food products)

transported into the mucosa via the channel protein GLUT-2. The passive transport is of a lower speed compared to the co-transport and therefore leads to an ineffective absorption (Gibson et al., 2007).

Lactose can be defined as a FODMAP if patients are simultaneously suffering from hypolactasia since this disorder results in an indigestibility of this disaccharide which can then act as a FODMAP (Murray et al., 2014).

Oligosaccharides are the main contributor to the FODMAP intake since cereals, such as wheat and rye, and pulses, such as lentils, peas and chickpeas, can contain high concentrations of either FOS or GOS, which are the two most common oligosaccharides (Ispiryan et al., 2020; Varney et al., 2017). The before mentioned ingredients are commonly used to produce staple foods in the western world and are therefore frequently consumed by most of the western population. FOS consist of β-2-1 or β-2-6 linked fructose monomers with a possible terminal glucose residue, while GOS are made of α-1-4-linked α-galactose residues with a terminal sucrose moiety (Li et al., 2015). These two groups of oligosaccharides are not hydrolysed in the human GIT due to the lack of production of β-fructofuranosidases and α-galactosidases (Li et al., 2015). Besides their classification as FODMAPs both groups of oligosaccharides are considered as prebiotically active and are therefore frequently reported as beneficial for healthy patients (Li et al., 2015). This fact highlights the difficulties in separating between DFs with a positive effect and FODMAPs and the importance of identifying certain properties of DFs which can improve the gut health of IBS patients (Halmos et al., 2014).

Despite the focus on FOS and GOS other oligosaccharides fulfil the aforementioned criteria for FODMAPs and therefore it can be hypothesized that these oligosaccharides could also act as FODMAPs (Gibson, Halmos, & Muir, 2020). Those include XOS (Arabinoxylans with a DPav up to 9) and degradation products of GOS, such as melibiose, manninotriose and manninotetraose (Atzler et al., 2020; Gibson et al., 2020). These compounds are not degradable by the digestive enzymes, they are fermentable in the large intestine, and they can also be osmotically active due to their small particle size (Atzler et al., 2020). This fact must be taken into consideration for the development of products with a lowered FODMAP content and for the identification of suitable ingredients for a low FODMAP diet.

3.2. *Mechanism of induction of IBS-symptoms via FODMAPs*

A summary of the mechanism in which FODMAPs impact the GIT is depicted in Fig. 1. Like DFs FODMAPs can only be active due to not being digested and not being absorbed in the GIT.

The infliction of symptoms in IBS-patients after the ingestion of FODMAPs is often hypothesized to be caused by distension of the colon. The rise in the luminal volume is mainly caused by the production of gas after fermentation and the reabsorption of water into the lumen caused by osmotically active molecules. Distension of the colon afflicts abdominal pain by activating mechano-receptors of the large intestine (Gibson & Shepherd, 2010).

Gas production is the main contributor to the increase of luminal water, since gases have a higher impact on the extension of the colon due to their lower density compared to water. Hydrogen and methane are the two most produced gases in the colon. However, hydrogen production is more favoured after the intake of FODMAPs and the distension caused by hydrogen is stronger since hydrogen possesses a lower density then methane. The rate in which gas is generated depends on the ingested type of FODMAP and the affinity of gas producers to the substrate. Oligosaccharides, such as GOS and FOS, are fermented more rapidly and therefore, result in a higher rate of gas production compared to mono- or disaccharides. Beside distension gas production is also the main cause of bloating, which is accelerated after the consumption of fermentable carbohydrates (Gibson et al., 2015).

The increase of luminal water is related to carbohydrates with a small particle size, which are therefore osmotically active. Osmotic activity results in the reabsorption of water into the colon and therefore extends the colon. An increase in luminal water also softens the stool, which can lead to diarrhoea if occurring over a longer term of time or in excess. The intensity of this effect depends on molecule size and weight (Gibson et al., 2015).

3.3. *Disadvantage of low FODMAP diet regarding nutritional value and fibre content*

In order to improve the discomfort of IBS patients the low FODMAP diet has been developed. This diet is based on the reduction of the FODMAP intake by limiting the consumption of ingredients high in FODMAPs, such as pulses, cereals, certain fruits, artichokes, onions and garlic. Products can be qualified as low in FODMAPs if certain cut-off values per serving are not exceeded (Table 2) (Varney et al., 2017). Its efficiency was proven in various clinical trials and no major side effects were reported (Halmos et al., 2014).

Exclusion of specific types of FODMAPs or FODMAPs in general possesses certain disadvantages. A more difficult intake of DF and a possible impairment of gut health including a lowered diversity of the gut microbiota is one of the main disadvantages. This is caused by a limitation of suitable DFs due to shared characteristics of DFs and FODMAPs, such as fermentability and hydroscopic behaviour. Soluble, non-viscous and fermentable DFs and soluble, non-viscous and unfermentable DFs are the two groups of DFs which share most of the characteristics with FODMAPs. Examples for this are GOS and FOS, which are often recommended as prebiotics, are among the most common examples for FODMAPs. Inulin is a further example of a frequently used soluble, non-viscous fibre which is often associated with being harmful for IBS patients. Insoluble, fermentable DFs also fulfil the characteristics of DFs not suitable for a low FODMAP diet. Therefore, only a small number of DFs, which follow certain criteria, can be used as alternatives (Bellini et al., 2020; Soncini et al., 2019).

4. Fibres suitable for a low FODMAP diet

4.1. *Definition of beneficial and non-beneficial effects*

In order to identify DFs suitable for a low FODMAP diet the physico-chemical properties which can be considered as beneficial and which are non-beneficial or even harmful for IBS patients need to be defined. Physico-chemical properties which either avoid or reverse the occurrence of IBS-symptoms need to be defined as beneficial. Properties which trigger symptoms are considered as non-beneficial. It is important to know which IBS subtype is treated since different physico-chemical properties can be beneficial for the various symptoms. This is especially important for the treatment of IBS-C or IBS-D since the appearance of constipation or diarrhoea is either caused by a lack or an excess of luminal water (Eswaran et al., 2013). Therefore, IBS-C needs to be treated by increasing the water content to soften the stool, while IBS-D can be improved by decreasing the water content and therefore leading to a harder stool (Bosaeus, 2004). This needs to be especially considered for the decision if solubility and viscosity are beneficial characteristics of a low FODMAP DF since those two properties can have various effects on the hardness of the stool. Furthermore, it must be considered that IBS-C can be treated by accelerating the transit time of the food bulk, while in contrast IBS-D needs to be treated by increasing the time the food bulk remains in the colon. Symptoms occurring in almost every IBS-subtype are abdominal pain and bloating. Therefore, fermentability – which is usually associated with these symptoms-is a property which should be avoided and has to be defined as a non-beneficial effect (Kalantar-Zadeh, Berean, Burgell, Muir, & Gibson, 2019). The avoidance of fermentable DFs would result in an impairment of the biodiversity of the gut microbiome (Pozuelo et al., 2015). However, the identification of DFs -which are selectively fermented by non-gas-producing bacteria-is difficult due to synergistic effects, such as cross-feeding (De Vuyst &

Leroy, 2011).

Besides the direct influence on IBS symptoms, it is also important that properties which impact the general health or the gut in an indirect way are considered as beneficial. This includes properties which can be associated with a lowered glycaemic index (GI), anti-inflammatory effects, and lowered cholesterol levels (Eswaran et al., 2013; Spiller & Lam, 2011). Properties which are reported to have those effects are an increased viscosity or insolubility (Guillon & Champ, 2000; Lockyer & Nugent, 2017; Park & Jhon, 2009; Zacherl et al., 2011). The anti-inflammatory effect is especially beneficial since it is often proposed that the occurrence of IBS is correlated with a higher risk of subsequent inflammation and inflammatory bowel disease (IBD) (Murray et al., 2014). Therefore, DFs should possess at least one of these characteristics to support the general health of IBS patients.

4.2. Possible characteristics of DFs suitable for a low FODMAP diet

As described in the previous chapters certain physico-chemical properties are linked with specific effects of DFs in the GIT. This enables identification of DF-characteristics which are suitable for a low FODMAP diet using the knowledge available regarding their physico-chemical properties. According to the definition of beneficial and non-beneficial properties four main characteristics of DFs beneficial for a low FODMAP diet were discovered (Table 3). These four characteristics are a low fermentability, a low osmotic activity, insolubility and high viscosity for soluble DFs.

4.2.1. Low fermentability

The use of DFs with a low fermentation rate can lead to a relief of bloating and abdominal pain since excessive gas production is avoided. Furthermore, the inclusion of DFs which are fermented in a low rate can lower the risk of a limited growth of the gut microbiota and increase the chance of a more diverse microbiome compared to the total avoidance of fermentable DFs (Pozuelo et al., 2015). However, a positive or even prebiotic effect of DFs with a low fermentability needs to be tested individually together with the fermentation rate of the DF. Physico-chemical properties which are associated with a lowered fermentation rate are a high DPav and a monomeric composition which can only be hydrolysed by either no or only a selected number of bacteria inhabiting the large intestine (Pollet et al., 2012; Slavin, 2013). The identification of a higher DPav can be carried out using various analytical methods specifically targeting various groups of DFs depending on the monomeric composition. Identification of monomeric compositions which do not favour fermentability includes the quantification of fermentability of those DF using *in vitro* and *in vivo* methods and the chemical characterisation of the DFs. *In vivo* methods which can be used to determine the fermentability include the measurement of the growth rate of bacteria, identification of the growing bacteria, and the production of gases and SCFAs after simulating the digestion and fermentation of DF with bacteria isolated from stool samples (Adiotomre, Eastwood, Edwards, & Brydon, 1990; Bourquin et al., 1996; McBurney, Horvath, Jeraci, & Van soest, 1985; Tamargo et al., 2019; Titgemeyer, Bourquin, Fahey, & Garleb, 1991). For the investigation of the *in vivo* fermentability clinical trials with both healthy people and IBS patients are needed. In order to then gain knowledge not only about the infliction of symptoms but also the mechanism of the fermentability the produced SCFAs and the grown bacteria need to be analysed (Titgemeyer et al., 1991). Chemical characterisation of the DF needs to include the identification of monomers after hydrolysis using HPLC/GC, determination of molecular weight using GC -MS and the analysis of the branching using GC-MS or NMR (Alba et al., 2018; Rakha, Åman, & Andersson, 2010).

4.2.2. Low osmotic activity and solubility of fibres

A low osmotic activity is a characteristic that can be associated with a lowered risk of water reabsorption into the lumen (Gibson et al., 2015). Therefore, it seems that this characteristic is especially promising for the treatment of abdominal pain, as well as the occurrence of diarrhoea. Since osmotic activity and solubility are often correlated the avoidance of highly soluble DFs seems to be favourable (Fåk et al., 2015). However, the total exclusion of DFs with a high osmotic activity and solubility needs to be discussed since those DFs can be both used for avoiding and treating constipation. Soluble DFs offer the potential for treatment of both IBS-C and IBS-D depending on the conditions of application. IBS-C symptoms are improved by pre-hydrated, soluble DFs via softening the stool and increasing the frequency of defaecation. These effects were proven in various studies and therefore highlight the potential of soluble DFs in relieving constipation. The relief of IBS-D caused by soluble and non-hydrated DFs is induced by the potential of these fibres to absorb the excess of luminal water. These facts highlight the importance of targeting the use of DFs directly to the individual patient and of providing choices for each single IBS-subtype (Bijkerk et al., 2004; Eswaran et al., 2013; Giannini, Mansi, Dulbecco, & Savarino, 2006).

The application of insoluble DFs offers also potential for the treatment of IBS-C while also additionally reducing the occurrence of bloating and abdominal pain. Insoluble DFs improve constipation by increasing the amount of luminal water without being osmotically active due to causing friction and irritation of the mucosa (Lewis & Heaton, 1999). Furthermore, insoluble fibre possesses the effect to accelerate the defaecation time and to increase the solid part of the stool (Cummings, 1984; Lewis & Heaton, 1999). The risk of abdominal pain is furthermore lowered since insolubility often correlates with a low fermentability which increases the potential of those DFs.

However, in order to combine the benefits of both characteristics, a low osmotic activity and a low solubility are favourable compared to a total avoidance of hydrophilic DFs. Physico-chemical properties which

Table 3
Characteristics which can be associated with a possible suitability of a low FODMAP diet designed for IBS-patients (Evans et al., 1992; Guillon & Champ, 2000; Johnson & Gee, 1981; Mirhosseini & Amid, 2012; Mudgil & Barak, 2013; Pangborn et al., 1978; Pegg, 2012; Titgemeyer et al., 1991; Tomlin & Read, 1988).

Characteristic of low FODMAP fibre	Physico-chemical properties associated with the characteristic	Cause of suitability	Preferably applied to IBS type/ Treatment of symptoms
Low fermentability	Higher degrees of polymerisation Monomeric composition of DFs which does not promote digestion by gas producers	Avoidance of gas production and the subsequent bloating and abdominal distress	IBS-D; IBS-C; IBS-M/Bloating and abdominal pain
Low osmotic activity	Lower solubility or even insolubility caused by lower number of hydrophilic groups Low water absorption	Avoidance of increase of luminal water and volume	IBS-D/Diarrhoea and abdominal pain
Viscosity and gel forming	High degree of polymerisation Easily available hydroxyl groups for interaction with water	Gel forming DFs have beneficial effects on gut health Lower digestibility and fermentability Promote stool bulking while having lower effect of extension of colon as purely osmotic active compounds	IBS-C/Constipation and decreased defecation rate; IBS-D/Viscosity can improve consistency of diarrhoea due to viscosity
Insoluble	Lower number of hydrophilic groups in dietary fibre components	Lower availability for gut microbes Can lower constipation and increase stool frequency	IBS-C/Constipation and decreased defecation rate

are favourable are a low water holding capacity, a lower DPav, and a low rate of branching (Bergenstråhle et al., 2010; Evans et al., 1992).

4.2.3. Viscosity

The viscosity of DFs is a characteristic which offers significant potential for their application into food products not only targeted at people suffering from IBS-C or IBS-D as it is also often linked with various benefits regarding general health. Viscous DFs decrease stool hardness due to their ability to either introduce water into the food bulk after pre-hydration or to cause reabsorption of water (Guillon & Champ, 2000). The reabsorption of water by viscous DFs has one advantage as it leads to a lower rate of extension of the colon due to gel forming (Johnson & Gee, 1981). Formation of a gel network causes a more viscous stool by interacting and retaining freely available water which lowers the rate at which the luminal volume is increased. A highwater binding capacity can have a similar effect. Beside the treatment of IBS-C viscous DFs also have the potential to stabilize the occurrence of diarrhoea and IBS-D by retaining water. However, the most benefits seem to be in the treatment of IBS-C (Bijkerk et al., 2004; Bosaeus, 2004). Gelling and an increased viscosity lead to a decline in accessibility of carbohydrates for both bacteria and enzymes. This as well improves the frequency of bloating and abdominal pain due to an additional decrease of the fermentation rate (Tomlin & Read, 1988).

Furthermore, viscous DFs are linked to two more attributes which positively impact the general health. These are the lowering of cholesterol levels and the decreasing of the GI (Stephen & Cummings, 1980; Zacherl et al., 2011). Chemical structures which are commonly associated with highly viscous DFs are a high branching, high DPav, and the monomeric composition of polysaccharides (especially gums), since those properties influence the availability of hydroxyl groups needed for the formation of gels and the retention of water (Mirhosseini & Amid, 2012; Pegg, 2012).

4.3. Impact of DF inclusion on technological quality parameters of food products

Besides outlining the correlation of certain physico-chemical properties of DFs and the possible improvement of IBS symptoms, it is important to identify the impact of those characteristics on the technological quality of food products. This is important as both insoluble and viscous DFs are often associated with a decline in food quality which negatively affects the consumer acceptance (Aravind et al., 2012; Ellis, Apling, Leeds, & Bolster, 1981; Wanders et al., 2013). General challenges regarding the fortification with DFs include a darkening of the colour and interactions with both starch and gluten (Ellis et al., 1981; Goldstein et al., 2010; Park, Seib, & Chung, 1997; Ribotta, Pérez, León, & Añón, 2004). However, the improvement of certain quality parameters has been reported as well, depending on the food product and the type of DF used (Almeida, Chang, & Steel, 2013; Curti, Carini, Diantom, & Vittadini, 2016; Kaack, Pedersen, Laerke, & Meyer, 2006). Advantages of DF addition often include stabilizing effects and an increase in water absorption of the food products compared to control products without any addition of fibre (Rosell, Santos, & Collar, 2009; Wang, Rosell, & Benedito de Barber, 2002). Therefore, knowledge about the influence of the properties -which were identified as beneficial-on the product quality can help to develop products to meet the expectation of consumers and therefore in an increase in the acceptance of the low FODMAP diet. This overview focuses on cereal based products, such as bread and pasta, and beverages since those products are often the main contributors to the fibre intake among the western population and are also commonly excluded from a low FODMAP diet (Ispiryan et al., 2020). Both the broad effects associated with the physico-chemical properties, as well as those of the specific examples of DF (Table 4) were investigated and are described in this overview. For both bread and pasta it has to be taken into consideration that the incorporation of DFs into a wheat based system can be used as an indicator for the impact of DFs. This knowledge can be applied to the development of low FODMAP products since these are commonly based on a mixture of wheat starch and gluten.

4.3.1. Effect on breads

Bread is one of the most consumed foods in the western world and has been one of the main sources for the intake of DFs. Studies regarding the enrichment of breads with DFs have been carried out to improve the DF profile of breads. Most of the research has been conducted using DFs originating from cereals, such as wheat bran, which are not in the focus of this literature overview as these DFs often contain higher amounts of FODMAPS, especially FOS which are mainly located in the aleurone layer of wheat grains (Almeida et al., 2013). For this overview the focus was on DFs originating from various non-cereal based sources since these are most promising regarding the use for a low FODMAP diet.

Numerous studies have been executed incorporating insoluble DFs, such as resistant starch and cellulose, or soluble, viscous DFs, such as psyllium or guar gum (Goldstein et al., 2010; Katina, 2003; Ribotta et al., 2004). It must be highlighted that the impact on both the quality of dough and the baked bread depends largely on the use of either soluble, viscous DFs or insoluble DFs. Despite this dependency, an increase in the water absorption of the dough and a decrease in the specific volume (SV) have been identified as the two main effects generally caused by the addition of DF (Noort, van Haaster, Hemery, Schols, & Hamer, 2010; Rosell, Santos, & Collar, 2006). Those effects, especially a lower SV are disadvantages regarding the product quality. A common problem which is often mentioned in regard to the incorporation of DFs is the impairment of the gluten network caused by competition for water between DFs and gluten, and the interaction of the free hydroxyl groups of glutelin and gliadin with the hydroxyl groups of DFs (Wang et al., 2002). The weakened gluten network results in an increased mixing time, a lower dough extensibility and a decreased dough rise (Noort et al., 2010; Rosell et al., 2006). Furthermore, a hindered gluten network affects quality parameters of the finished bread since the gluten network is strongly associated with water retention in the finished bread and the gas retention. Therefore, this is often seen as the cause of a faster staling rate and of the lower SV. However, this effect is largely dependent on several characteristics of the DFs including viscosity, water holding capacity and particle size (Rosell et al., 2009; Wang, et al., 2017). Despite the common association between gluten impairment and enrichment with DF, it was reported that cellulose can accelerate the gluten aggregation by acting as a plasticizer (Goldstein et al., 2010).

The effect DFs have on hardness and staling of bread depends on their viscosity or insolubility. Soluble, viscous DFs are reported to soften the breadcrumb and slow down the staling due to their high water holding capacity which increases the water retention. This effect was often reported for gums, such as guar gum or locust gum, and other viscous DFs, such as psyllium (Hager & Arendt, 2013; Park et al., 1997; Pegg, 2012). Insoluble DFs however are associated with hardening the breadcrumb and to accelerate the staling of the crumb compared to unfortified wheat bread (Chaplin, 2003; Goldstein et al., 2010). The cause which was often hypothesized is the impairment of gluten aggregation and the subsequent impairment and water retention. Another cause for the increased staling rate is an interference with both the interaction between gluten and starch and the gelatinisation of starch (Almeida et al., 2013; Ayala-Soto, Serna-Saldívar, & Welti-Chanes, 2017). Both effects would then result in an accelerated retrogradation of starch which can be linked to an increase of hardness and staling rate (Curti, Carini, & Vittadini, 2017).

4.3.2. Pasta

The mechanism in which the quality parameters of pasta products are influenced depends -similar to the quality of bread-on the viscosity and insolubility of DFs. Therefore, it can be predicted if the product quality is improved or decreased. Parameters, which are affected by incorporation of DFs are mainly firmness, extensibility, cooking loss and

Table 4
Fibres fitting the criteria of DFs suitable for a low FODMAP diet designed for IBS-patients.

Low FODMAP fibre	Characteristics of fibre	Chemical Structure of fibre	Health Benefits related to IBS	Health Benefits not related to IBS	Impact on product quality
Cellulose (Bergenstråhle et al., 2010; Cummings, 1984; Evans et al., 1992; Goldstein et al., 2010)	Insoluble and not fermentable	β-1-4-linked glucose residues	Not identified	Improves calprotectin (anti-inflammatory factor) Alters bile acid profiles Increases fecal bulking and transit time No reported effect on gut microbiome	**Bread:** Various effects on bread and dough quality depending on particle size In general, negative impact on bread quality **Pasta:** Decreases firmness of cooked pasta **Beverages:** Not commonly used in beverages due to insolubillity
Bamboo (Park & Jhon, 2009; Rosell et al., 2009; Wang, Ma, et al., 2017) fibre	Insoluble and not fermentable DF ingredient consisting of celluloses and hemicelluloses	No clear structure due to several fibre components	Not identified	Improves stool bulking and can lower cholesterol levels Improves GI of foods	**Bread:** Increases water absorption of the dough Impacts quality of final bread in a negative way (increased hardness and decreased SV) **Pasta:** Increases cooking loss of pasta and decreases firmness **Beverages:** Not commonly used in beverages due to insolubillity
Psyllium (Bijkerk et al., 2004; Eswaran et al., 2013; Marlett & Fischer, 2003; McRorie Jr., 2015; Park et al., 1997; Zacherl et al., 2011)	Soluble and viscous DF consisting of arabinoxylans with a high DPav	No clear or very complex structure which can vary	Improvement of frequency of bowel movement, gas and abdominal pain	Improves cholesterol levels, insulin sensitivity, and satiety (qualified health claim – reduced risk of type 2 diabetes) Possesses a laxative effect which can be used for treatment of IBS-C	**Bread:** Possesses both positive (increased softness and lower staling rate) and negative impact (decreased SV) on bread quality **Pasta:** Increases water absorption, cooking loss and darkness of the cooked pasta Generally, associated with negative impact **Beverages:** Not used for the improvement of quality properties of beverages
Guar gum (Ellis et al., 1981; Evans et al., 1992; Johnson & Gee, 1981; Ribotta et al., 2004; Tomlin & Read, 1988)	Soluble and highly viscous galactomannan DF which can be fermented	β-1-4-linked mannose residues and α-1-6-linked galactose side groups with high branching and degree of polymerisation	Not identified	Improves cholesterol levels and postprandial glucose responses Induces satiety	**Bread:** Mainly negative influence such as decrease in SV and dough handling due to high viscosity **Pasta:** Reduces cooking loss and increases swelling index Can increase firmness of cooked pasta **Beverages:** Stabilizes oil-water emulsions Thickens beverages and significantly increases thickness of beverages
Partially hydrolysed guar gum (PHGG) (Giannini et al., 2006; Parisi et al., 2002)	Soluble and non-viscous galactomannans which are fermentable and produced by hydrolysis of guar gum	No clear structure due to random partial hydrolysis of guar gum by acids	Improvement of abdominal pain, bowel movement and spasms Treatment of both constipation and diarrhoea possible depending on the hydration level of PHGG and of the milieu as well	Improves cholesterol levels Induces satiety and improves postprandial glucose response	**Bread:** Improved dough handling compared to guar gum due to lowered viscosity **Pasta:** No incorporation into pasta is reported Could not possess the positive impact on pasta compared to guar gum due to reduced viscosity **Beverages:** Enhances the body and mellows flavour of beverages Stabilizes foaming capacity and oil in water emulsions Reduced thickness

(*continued on next page*)

Table 4 (*continued*)

Low FODMAP fibre	Characteristics of fibre	Chemical Structure of fibre	Health Benefits related to IBS	Health Benefits not related to IBS	Impact on product quality
					compared to application of guar gum
Potato fibre (Curti et al., 2016; Kaack et al., 2006; Panasevich et al., 2015)	Non-fermentable DF consisting of hemicelluloses, celluloses, resistant starch and lignin which possesses both soluble and insoluble characteristics	No clear structure due to several fibre components	Not identified	Improves stool bulking and increases frequency of bowel movement	**Bread:** Improves water absorption of the dough Positive effects on bread quality such as softness and colour **Pasta:** No incorporation of potato fibre into pasta reported **Beverages:** Not commonly used in beverages due to insolubillity
Konjac (Davé & McCarthy, 1997; Devaraj et al., 2019; Katsuraya et al., 2003; Wang, Ma, et al., 2017; Zhou et al., 2013)	Soluble and viscous forming glucomannans with varying DPav	β-ᴅ-glucose and β-ᴅ-mannose residues in a ratio of 1.6/1	Not identified	Proven to be effective for treatment of IBD and gastro-intestinal symptoms such as constipation and abdominal pain Improves cholesterol levels Induce satiety and leads to improvement of postprandial glucose response	**Bread:** Improved staling rate and water absorption **Pasta:** Not reported for pasta, however incorporation into noodle formulations lead to improvement of cooking properties and sensory quality **Beverages:** Possesses very good thickening properties and forms thermostable gels which limits the application in beverages
Carboxymethylcellulose (CMC) (Aravind et al., 2012; Johnson & Gee, 1981; Mirhosseini et al., 2008; Mudgil & Barak, 2013; Rosell et al., 2009)	Chemically modified cellulose which is soluble and viscous but not fermentable	Cellulose with additional carboxymethyl-groups	Not identified	Improves stool bulking and bowel movement	**Bread:** Improves SV of bread as well as the softness of the bread **Pasta:** Impacts quality parameters of pasta both in positive (lower firmness) and negative ways (increases stickiness and cooking loss) **Beverages:** Reduces the intensity of acidity and bitterness Increases both the physical and sensorical viscosity Increases stability of beverages, such fruit juices and smoothies
Hydroxypropyl-methylcellulose (HPMC) (Hager & Arendt, 2013; Mudgil & Barak, 2013; Reppas et al., 2009; Rosell et al., 2009; Tebben, Shen, & Li, 2018)	Chemically modified cellulose which is soluble and viscous but not fermentable	Cellulose with additional hydroxypropyl-groups	Not identified	Improves cholesterol levels	**Bread:** Decreases quality of dough handling Improves staling rate and water absorption **Pasta:** Improves overall pasta quality including firmness and cooking loss **Beverages:** Increases viscosity and thickens beverages
Resistant Starch (Almeida et al., 2013; Bustos et al., 2011; Foschia et al., 2013; Fuentes-Zaragoza et al., 2010; Lockyer & Nugent, 2017)	Insoluble, non-viscous and slowly fermented DF based on starch which is not digestible due to physical or chemical modifications of starch	No clear structure due to five distinct types of resistant starch	Not identified	Improves insulin sensitivity Effects on microbiome are dependent on resistant starch type Depending on type of resistant starch production of butyric or propionic acid is enhanced	**Bread:** Improves dough mixing behaviour except extensibility Improves bread quality regarding staling rate up to 5 days Decreases SV of bread loaves in a dose dependent manner **Pasta:** Decreases sensory quality of pasta Improves firmness of pasta **Beverages:** Not commonly used in beverages due to insolubillity

swelling properties of the pasta (Aravind et al., 2012; Foschia, Peressini, Sensidoni, & Brennan, 2013; Tudorică, Kuri, & Brennan, 2002). Two effects which are caused by both soluble, viscous DFs and insoluble DFs are the hindrance of starch-gluten interaction and an increase of water absorption of the pasta system since both types of DFs are commonly reported to possess higher water holding capacities compared to durum wheat flour (Foschia et al., 2013). This effect is observed to be stronger in viscous DFs since those have higher water holding capacities than insoluble DFs. This results in a competition between starch, gluten and DFs for the available water. Competition for freely available water leads to a decreased quality of the pasta by hindering gluten aggregation and swelling of starch granules while cooking (Aravind et al., 2012; Zhou et al., 2013). Insoluble DFs are commonly reported to decrease the quality of pasta including an increased cooking loss or a lower acceptance regarding their sensory properties, especially regarding mouth feel. However, it is reported that the incorporation of resistant starch or cellulose leads to an improvement of the pasta texture (Bustos, Perez, & León, 2011; Tudorica et al., 2002).

Soluble, viscous DFs, such as guar gum, psyllium and chemically modified celluloses, on the other hand are often associated with an overall improvement of pasta. Improved properties include an increased swelling index, a decreased firmness, lowered cooking loss and a higher extensibility (Aravind et al., 2012). The positive impact is related to the formation of a gel network and an increased water retention. Those aspects lead to a higher water absorption during cooking and the retention of organic material inside the matrix of the pasta. However, it depends largely on the degree of viscosity if the quality of the pasta is increased. High viscosities result in negative effects as this increases the impairment of gluten development and starch gelatinisation which has a higher impact on the quality than the improvement related to the addition of viscous DFs. The degree in which the viscosity is increased is strongly associated with both the incorporated DF itself and the concentration used. Artificial celluloses, such as CMC and HPMC, decrease firmness while psyllium and guar gum resulted in higher firmness compared to a control and they also effect swelling and cooking loss positively. This is caused by the formation of stronger gels after incorporation of psyllium and guar gum. Higher DF concentrations correlate with a rise in viscosity and are therefore linked with a decline in quality (Aravind et al., 2012; Brennan & Tudorica, 2007; Li, Zhu, Guo, Brijs, & Zhou, 2014). This suggests that low concentrations and moderately viscous DFs are promising for the development of DF enriched low FODMAP pasta.

4.3.3. Beverages

The use of DFs as additives in beverages is less common compared to their use in the production of pasta or bread. One exception is the production of drinks especially designed for the use as DF supplements. The use of DFs for beverage production is restricted to soluble DFs including psyllium and PHGG. However, soluble, viscous DFs, especially gums, are reported to be used for industrial purposes regarding the production of beverages (Pegg, 2012). They are used as stabilisers for emulsions, foams and fruit juices. Common examples for this are guar gum, CMC and HPMC. Furthermore, viscous DFs are used to thicken and to stabilize the consistency and viscosity of beverages (Dhingra et al., 2012; Pegg, 2012). However, the viscosity and the thickening effect of gums and soluble, viscous DFs have limitations since the use of high concentrations can lead to products which exceed the viscosity associated with beverages. Therefore, those DFs need to be applied, while at the same time considering the viscosity of individual DFs and the dose dependency. Another use of viscous DFs is related to their ability to alter the sensory profile of drinks. The alteration includes positive effects, such as suppressing bitterness and off-flavours (Pangborn, Gibbs, & Tassan, 1978).

4.4. Examples of DFs suitable for a low FODMAP diet

Examples of DFs which possess the potential to be used for the development of foods suitable for a low FODMAP diet while providing the benefits of DF enriched foods have been selected according both the before mentioned criteria and the positive or at least neutral effects on the quality of food products. Furthermore, those DFs were investigated regarding their contribution to the general health of IBS patients. The DFs which were identified as beneficial were divided into two different groups according to their solubility and viscosity. A selection of DFs fulfilling the criteria are listed in Table 4 and they are described in the following section. Structures of cellulose, guar gum, konjac, CMC and HPMC are depicted in Fig. 2.

4.5. Soluble, viscous fibres

4.5.1. Psyllium

Psyllium is a soluble, intermediate viscous and unfermentable fibre which can be found in the seed husk of the plant of the genus Plantago (Marlett & Fischer, 2003). The viscous part of the husk is mainly composed of arabinoxylans which have a high DPav and are highly branched (Guo et al., 2008). Psyllium has been widely investigated regarding its therapeutic use for FGIDs. It is commonly used to relief constipation. Psyllium also lowers cholesterol levels, insulin sensitivity, and satiety level. Furthermore, psyllium possesses a health claim regarding its reduction of insulin (Marlett & Fischer, 2003). Research regarding the treatment of IBS patients has been carried out. Results of double-blind studies revealed that supplementation with psyllium caused either slight improvement or no significant change in the frequency of IBS symptoms. The symptoms which are slightly improved by psyllium intake include bloating and constipation. This and the before mentioned health benefits point towards the suitability of psyllium for the treatment of IBS-C patients (Bijkerk et al., 2004; Chouinard, 2011).

4.5.2. Guar gum

Guar gum is a soluble and slowly fermentable DF which belongs to the group of gums. It is derived from the seeds of the plant *Cyanopsis tetragnoloba* (Mudgil, Barak&Khatkar, 2014). Guar gum is a galactomannan composed of β-1-4-linked mannose residues and α-1-6-linked galactose side groups and has a high branching rate and molecular weight. Furthermore, this DF has a high solubility and viscosity (Mudgil & Barak, 2013; Mudgil et al., 2014; Rosell et al., 2009).

The therapeutic use of guar gum is strongly linked to its viscosity since this property is often responsible for the decrease in cholesterol levels and the postprandial glucose response. Guar gum causes an accelerated feeling of satiety and a lowered food intake. Due to its high viscosity it could also be used for the treatment of constipation or diarrhoea depending on its hydration rate. Despite the beneficial effects of guar gum, its use for improving IBS-symptoms has not been tested (Ellis et al., 1981; Tomlin & Read, 1988; Wanders et al., 2013).

4.5.3. Partially hydrolysed guar gum (PHGG)

Partially hydrolysed guar gums (PHGGs) are soluble and non-viscous DFs with a varying degree of polymerisation. They are produced by acid hydrolysis of guar gum. PHGGs possess a lowered viscosity and higher fermentability compared to guar gum which makes them more suitable for the food industry and the development of different food products (Giannini et al., 2006). Despite the modification of physico-chemical properties PHGGs possess health benefits similar to guar gum. These include the decrease in cholesterol levels, acceleration of satiety levels and the inulin sensitivity. PHGGs were tested in double-blind studies for their use as IBS medication. Those studies revealed that PHGG lead to a significant improvement of different IBS symptoms including bloating and abdominal pain (Giannini et al., 2006). One advantage of PHGG is that it can be used for treatment of both IBS-D and IBS-C depending on the hydration rate of PHGG and the water content of the colon.

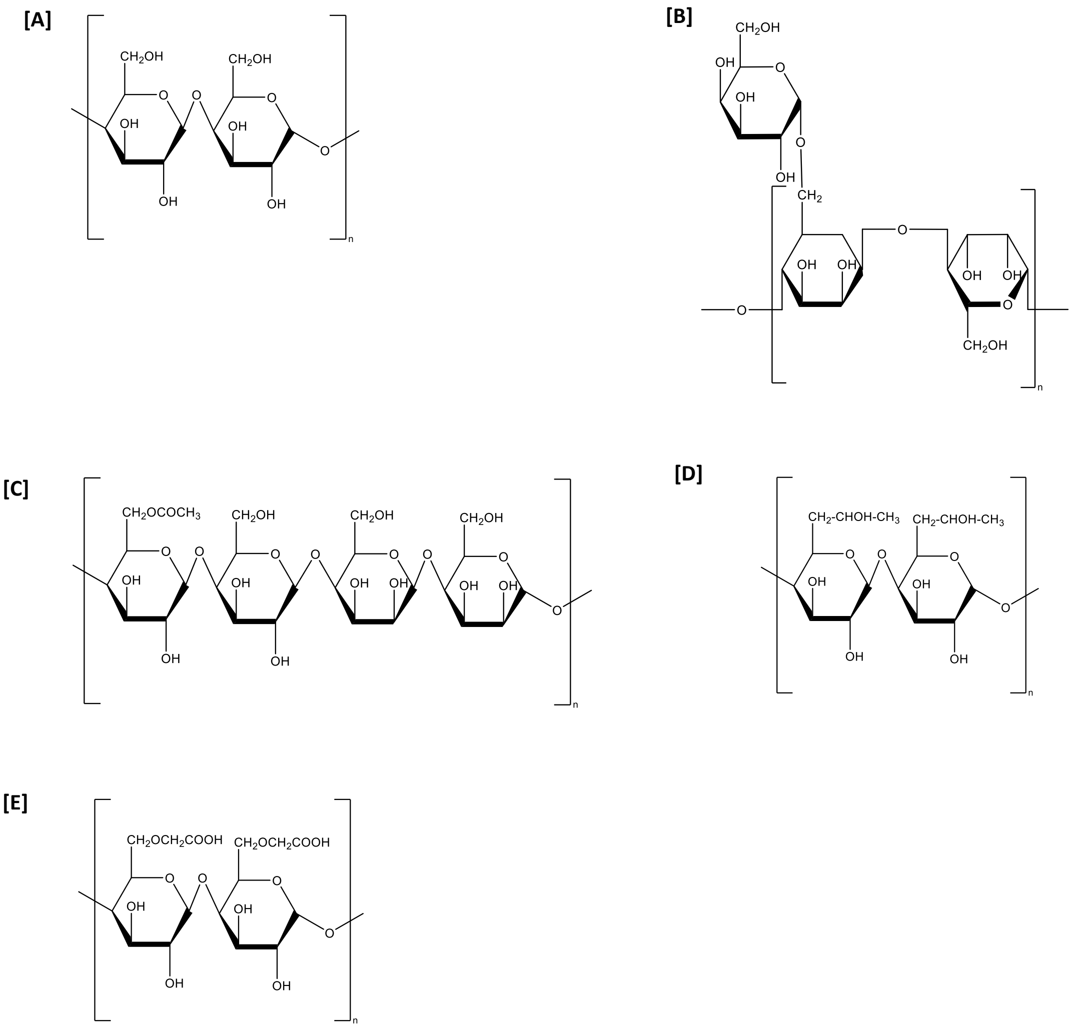

Fig. 2. Chemical Structures of DFs suitable for a low FODMAP diet including cellulose [A], guar gum [B], konjac [C], CMC [D] and HPMC [E].

Pre-hydrated PHGG can applied to IBS-C patients if the water content since they increase the luminal water content and they also soften the stool. Non-hydrated PHGGs can be used for the treatment of IBS-D since non-hydrated PHGG can absorb the luminal water and therefore, harden the stool. The binding of water by non-hydrated PHGG is also responsible for a lower frequency of defaecation which also supports the relief of diarrhoea (Giannini et al., 2006; Parisi et al., 2002).

4.5.4. *Chemically modified celluloses (CMC and HPMC)*

Chemically modified celluloses are produced by introducing new side groups into the structure of cellulose. Therefore, they possess different physico-chemical properties compared to cellulose (Aravind et al., 2012; Hager & Arendt, 2013; Rosell et al., 2009). Solubility and viscosity are the two main physicochemical properties which are increased by the alteration of cellulose. However, the alteration does not affect the fermentability and therefore most chemical modified celluloses are not fermentable. Because of this, chemically modified celluloses offer a good potential for the use in treatment of both IBS-C and IBS-D depending on their state of hydration. Two commonly used chemically modified celluloses are CMC and HPMC. CMC is produced by treating cellulose with chloroacetic acid and HPMC by a reaction between cellulose and hydroxypropyl- and methyl groups (Mudgil & Barak, 2013). Both DFs are used and known for their gel forming properties. It was found that both DF can improve stool and bowel movement (Wanders et al., 2013). Furthermore, HPMC is as well reported to lower cholesterol levels (Reppas, Swidan, Tobey, Turowski, & Dressman, 2009). However, both DFs have not been tested for their effect on IBS patients.

4.5.5. *Konjac*

Konjac is derived from the tubers of the konjac plant which is indigenous to Asia. It belongs to the group of glucomannans and is composed out of β-D-glucose and β-D-mannose residues in a ratio of 1.6/1 (Davé & McCarthy, 1997; Katsuraya et al., 2003). It possesses a good solubility and viscosity and is also slowly fermentable (Katsuraya et al., 2003). Konjac is proven to be beneficial for IBD patients and can help to prevent inflammation which is often mentioned as a subsequent effect of IBS. Konjac is also reported to relief abdominal pain and constipation. Therefore, it has the potential for the treatment of IBS-C. Due to its viscosity it possesses similar effects to psyllium and guar gum regarding satiety, cholesterol levels and glucose response (Devaraj, Reddy, & Xu, 2019).

4.6. *Insoluble or moderate soluble fibres*

4.6.1. *Cellulose*

Cellulose is one of the most common and commercially used DFs. Cellulose is one of the main compounds which form the plant cell wall. Therefore, cellulose is not only used as a single fibre but is often part of DFs derived from the outer layers of plants. However, cellulose can also be extracted and then used as a single fibre. Depending on the production process cellulose is available in different particle sizes and purities

(Dhingra et al., 2012; Mudgil & Barak, 2013). Cellulose ranges in its DPav, however, the insolubility of this DF is a universal feature of this DF and reported in literature (Bergenstråhle et al., 2010). Also, it has not been reported to be fermented by the gut bacteria (Cummings, 1984). Cellulose was proven in clinical trials to cause stool bulking and to accelerate defaecation, which subsequently improved symptoms often associated with constipation. Furthermore, the reduction of the GI and the postprandial glucose response which were both tested *in vitro* and *in vivo* are reported, as well as the reduction of cholesterol levels. The mechanism of the lowered cholesterol levels is still not fully understood; however, evidence exists which links the decline to the binding and excretion of bile acids (Mudgil & Barak, 2013). Even though no clinical trials have been executed for IBS treatment with cellulose it possesses a high potential, as it is completely unfermentable, coupled with the widely reported relief of constipation it does show potential for the treatment of IBS-C.

4.6.2. *Bamboo fibre*

This DF is derived from the cell walls of bamboo shoots. Therefore, this fibre ingredient consists of various indigestible compounds such as cellulose, lignins and hemicelluloses. As part of the cell wall of bamboo shoots it is a common source for the intake of DF in Asia. However, the indigestible part of the bamboo shoots can be isolated and then used as a high fibre ingredient (Rosell et al., 2009; Wang, et al., 2017). Bamboo fibre has both characteristics of insoluble and slowly fermentable DFs and therefore possesses physico-chemical properties similar to cellulose (Rosell et al., 2009). In contrast to cellulose the incorporation of bamboo fibre is not that commonly researched regarding the effect on the GIT. However, due to its insolubility it can be believed that it has benefits which are similar to those caused by cellulose, including lowering of glucose and cholesterol levels (Park & Jhon, 2009). The reduction of the GI of pasta products was measured *in vitro* after the fortification with bamboo fibre. A reduction of the GI of food products is explained by decreasing the starch digestibility (Brennan & Tudorica, 2007).

4.6.3. *Potato fibre*

Potato fibre is a slowly fermentable DF which consists of the undigestible carbohydrates sourced from potato peel. Therefore, various compounds naturally occurring in plant cell walls are part of this ingredient high in DF. These compounds include lignin, resistant starches, celluloses and hemicelluloses (Curti et al., 2016; Kaack et al., 2006). Since it is composed of several compounds it can possess both characteristics of soluble and insoluble DFs. This DF ingredient has been reported to be efficient in the treatment of constipation similar to cellulose, except that no impact on cholesterol levels was observed (Panasevich et al., 2015).

4.6.4. *Resistant starch (RS)*

DFs which belong to the group of resistant starch are insoluble and slowly fermentable polysaccharides based on starch. RS cannot be hydrolysed by the digestive enzymes because of either their inaccessibility or their chemical composition. Therefore, resistant starch is commonly divided into four groups: RS 1, which is physically inaccessible; RS 2, which consists of starch granules which are not digestible; RS 3, which consists of retrograded amylose; and RS 4, which describes chemically modified starch. Furthermore, the existence of a fifth type of resistant starch (RS 5) was discovered, which consists of indigestible amylose-lipid complexes (Gutiérrez & Tovar, 2021). RS occurs in many different plant-based ingredients and various food products depending on the way they are processed and/or stored. Corn starch is often used as a source material to produce RS. The use of RS 3 and RS 4 should be favoured since these two types are the most resistant to processing and can therefore reach the colon undamaged (Fuentes-Zaragoza, Riquelme-Navarrete, Sánchez-Zapata, & Pérez-Álvarez, 2010). The health benefits of resistant starch include improvement of the insulin response and stool bulking. Furthermore, due to its variability it also was identified to have a variety of effects on the GIT and especially the gut microbiota due to different rates of fermentability. Therefore, it seems that resistant starch can be used to avoid fermentation by gas producers while supporting the diversity of the gut microbiome. RS is reported to increase the production of propionic and butyric acid which are linked with protection against colon cancer. Therefore, the treatment of IBS with resistant starch seems promising due to its avoidance of properties which trigger IBS and its general health benefits (Lockyer & Nugent, 2017).

5. Conclusion

The purpose of this overview is to provide the knowledge about both DF and FODMAPs needed to identify characteristics of low FODMAP DFs which can be beneficial for IBS patients. Four main characteristics were identified: low fermentability, low osmotic activity, insolubility of a DF or its viscosity. It was revealed that low fermentability is the only characteristic which is independent from the IBS type since this property is mainly responsible for the affliction of abdominal pain and bloating. The beneficial effect of the other characteristics depends on the sub-type of IBS which is treated or targeted for the diet. This is especially evident for soluble and viscous DFs which can be used for the treatment of both IBS-C and IBS-D depending on the hydration state of the DF. All characteristics provide beneficial effects on the GIT and the general health. These effects include the prevention of diseases which are associated with an increased risk for IBS patients, such as IBD and Crohn's disease. However, the disadvantage of an impaired gut microbiome cannot be resolved with the DFs possessing the recommended characteristics since the selection of DFs selectively fermented by beneficial bacteria is difficult due to cross-feeding and other synergistic effects.

Despite this disadvantage several examples of DFs (Cellulose, Bamboo, Resistant starch) have been selected. They can improve the overall life-quality of IBS-patients since they offer several beneficial effects regarding gut health. However, all low FODMAP DFs possess both positive and negative effects on the product quality which need to be carefully taken into consideration when developing products with a decreased FODMAP content and a quality expected by the consumer.

Abbreviations

DF	Dietary fibre
FODMAP	Fermentable oligo-, di-, monosaccharides and polyols
FGID	Functional Gastrointestinal Disorders;
IBS	Irritable Bowel Syndrome
IBS-C	Irritable Bowel Syndrome-constipation
IBS-D	Irritable Bowel Syndrome-diarrhoea
IBS-M	Irritable Bowel Syndrome-mixed
GIT	Gastrointestinal tract
GI	Glycemic Index
LDL	Low density lipoproteins
SV	Specific Volume
PHGG	Partially hydrolysed guar gum
RS	Resistant Starch

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Declaration of interest

None.

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