Carbohydrate Polymers 147 (2016) 444–454

Contents lists available at ScienceDirect

Carbohydrate Polymers

journal homepage: www.elsevier.com/locate/carbpol

Review

Inulin: Properties, health benefits and food applications

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ARTICLE INFO

Article history:
Received 21 January 2016
Received in revised form 23 March 2016
Accepted 6 April 2016
Available online 8 April 2016

Keywords:
Inulin
Dietary fiber
Prebiotics
Oligo-fructose
Fructose

ABSTRACT

Inulin is a water soluble storage polysaccharide and belongs to a group of non-digestible carbohydrates called fructans. Inulin has attained the GRAS status in USA and is extensively available in about 36,000 species of plants, amongst, chicory roots are considered as the richest source of inulin. Commonly, inulin is used as a prebiotic, fat replacer, sugar replacer, texture modifier and for the development of functional foods in order to improve health due to its beneficial role in gastric health. This review provides a deep insight about its production, physicochemical properties, role in combating various kinds of metabolic and diet related diseases and utilization as a functional ingredient in novel product development.

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http://dx.doi.org/10.1016/j.carbpol.2016.04.020
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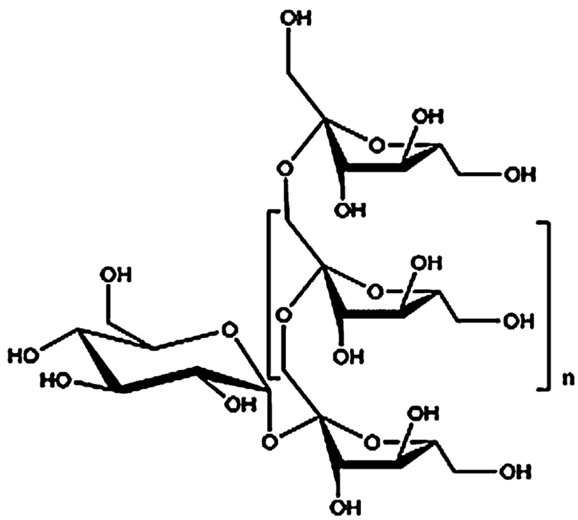

Fig. 1. Chemical chair structure of inulin [GFn].

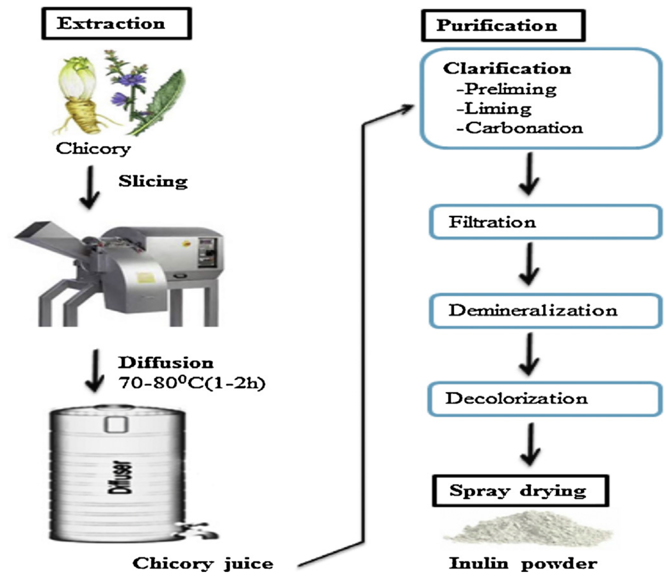

Fig. 2. Production line of inulin from chicory roots. Adopted from (Zhu et al., 2016).

1. Introduction

Inulin, owing to its presence in over 3000 vegetables, is considered to be extensively distributed in various plants, being present (Wichienchot et al., 2011). It has been a part of our daily food intake for centuries contributing to nutritional properties and exhibits significant technological benefits (Giarnetti, Paradiso, Caponio, Summo, & Pasqualone, 2015; Kalyani Nair, Kharb, & Thompkinson, 2010). In the early 1800s, a German scientist named Valentine Rose discovered inulin from the roots of Elecampane (*Inula helenium)* and was later on named inulin by Thomson in 1817. Inulin spherocrystals were detected in dahlia, Jerusalem artichoke and elecampane by Julius Sachs in 1864. Natural sources of inulin include chicory roots, Jerusalem artichoke, dahlia tubers, yacon, asparagus, leek, onion, banana, wheat and garlic (Table 1) (Bornet, 2008; Roberfroid, 2007). Synthetically, inulin type fructans are prepared from sucrose (Cooper et al., 2015). Inulin is widely used in the processed foods as a fat or sugar replacer or to impart desirable characteristics and it gives only 25–35% energy as compared to digestible carbohydrates. The sweetness level of inulin is about 10% of the sucrose. It is a versatile ingredient owing to its health benefits, specifically increased mineral absorption and also considered as Fermentable Oligo-,Di-, Monosaccharides and Polyols (FODMAP), group of carbohydrates which are readily digested in the colon by drawing water into colon to manage constipation and related ailments. It also promotes the growth of micro-flora in digestive tract and is considered as an appropriate ingredient to prepare low caloric foods for diabetics to manage blood sugar levels.

1.1. Chemical structure

β-(2-1)-D-frutosyl fructose bonds are present between the fructose units of inulin and β-configuration of anomeric carbon, making it indigestible in human small intestine, however, can be fermented in large intestine by the intestinal micro-flora (Apolinario et al., 2014). Inulin-type fructan consists of linear $(2 \rightarrow 1)$-linked β-D-fructosyl units attached to the fructosyl moiety of sucrose. G represents glucose unit, F denotes units of fructose, whereas n denotes number of fructose units. In chicory inulin, the number of fructose unit vary from 2 to 60 indicating a combination of oligomers and polymers (Roberfroid, 2005). Fig. 1. shows the chemical structure of inulin compounds.

The DP (Degree of polymerization) and branches have an effect on the functionality of the inulin. Plants inulin have relatively low DP (maximally < 200) which depends on plant species, climatic conditions and the plant's physical condition. Inulin present in bacteria has a very high DP, ranging from 10,000 to above 100,000; furthermore, a bacterial inulin is 15% more branched than the plant inulin (Cho & Samuel, 2009).

1.2. Production

Commercially most of the inulin is produced from chicory, however, dahlia and Jerusalem artichoke are also considered as good sources for industrial production in temperate areas (Flamm, Glinsmann, Kritchevsky, Prosky, & Roberfroid, 2001). Besides, this some new plants with high inline contents have been reported (Table 1). Chicory is a bi-yearly plant belonging to the *Asteraceae* family. During the first year of growth, chicory plants persist in the vegetative phase and form only leaves, taproots and fibrous roots. The root stocks have resemblance with small oblong sugar beets (Boeckner, Schnepf, & Tungland, 2001; Kelly, 2008). Inulin production goes through two stages. In the first phase extraction and initial purification of raw syrup is done, which is further refined to produce commercial product (above 99.5%) during second phase of processing. Some advanced technologies like, supercritical carbon dioxide (CO_2) (Mendes, Cataldo, da Silva, Nogueira, & Freitas, 2005) ultrasound (Lingyun et al., 2007) simultaneous ultrasonic/microwave (Lou, Wang, Wang, & Zhang, 2009) and pulsed electric field (PEF) (Loginova, Shynkaryk, Lebovka, & Vorobiev, 2010) are also being implicated in the inulin extraction process for getting higher yields of purified final product with less energy consumption. But in the classical purification process in order to remove impurities from the extracted juice, clarification requires multiple steps (pre-liming, liming and carbonation) at relatively high temperature (80–90 °C) as shown in Fig. 2 (Franck & De Leenheer, 2005). This may lead to the hydrolysis of inulin molecules in the extracted juice and may also introduce additional calcium ions into clarified juice which requires further purification treatments (Kim, Faqih, & Wang, 2001). Membrane based technologies like microfiltration and ultrafiltration are also reported to ease these laborious and time consuming steps. The resultant inulin having DP ranging between 3 and 60 imitates the original DP present in chicory. A high quality long chain inulin with DP more than 23 is also attainable (Cho & Samuel, 2009).

Table 1
Recent reports on plants with inulin content.

Inulin source	Plant part	Inulin content (g/100 g)[a]	Reference
Yacon (*Smallanthus sonchifolius*)	Roots	35	(Castro, Céspedes, Carballo, Bergenståhl, & Tornberg, 2013)
Sweet Leaf (*Stevia rebaudiana*)		18–23	(Lopes et al., 2015)
Garlic, Chinese garlic(*Allium sativum*)	Bulb	14–23	(Álvarez-Borroto, Ruano-Nieto, Calle-Miñaca, & Lara-Fiallos, 2015; Judprasong, Tanjor, Puwastien, & Sungpuag, 2011; Zhang, Huang, Zeng, Wu, & Peng, 2013)
Barley (*Hordeum vulgare*)	Grains	18–20	(Nemeth et al., 2014)
Chicory (*Cichorium intybus*)	Root	11–20	(Figueira, Park, Brod, & Luis Honório, 2004)
Jerusalem artichoke(*Helianthus tuberosus*)	Tuber	12–19	(Bach et al., 2015, nullChapter Bach, Clausen & Edelenbos, 2015; Judprasong et al., 2011; Li et al., 2015; Ruiz-Aceituno, Garcia-Sarrio, Alonso-Rodriguez, Ramos, & Sanz, 2016)
Asparagus (*Asparagus* sp.)	Roots	15	(Chi et al., 2011)
Agave (*Agave* sp.)	Stem	12–15	(Moreno-Vilet et al., 2016, nullChapter Moreno-Vilet, Camacho-Ruiz, & Portales-Pérez, 2016)
Dendelion (*Taraxacum officinale*)	Roots	12–15	(Kango, 2008)
Dahlia (*Dahlia pinata* cav.)	Tuber	10–12	(Kosasih, Pudjiraharti, Ratnaningrum, & Priatni, 2015; Zhu et al., 2016)
Suma (*Pfalia glomerate*)	Roots	11.45	(Caleffi et al., 2015)
Onions (Red & White), shallot (*Allium cepa, Allium sp.*)	Bulb	5–9	(Judprasong et al., 2011)
Burdock (*Arctium* sp.)	Roots	8.3–9.9	(Lou et al., 2009)

1.3. Physicochemical properties

Inulin, being a distinctive food element, offers many important dietary benefits along with certain industrial properties for its extensive use in food applications (Roberfroid, 2005). Chicory inulin is a white powder with fine particles having greater clarity. The neutral flavor of the inulin offers no aftertaste. Although, long-chain inulin is not sweet, however, regular chicory inulin when compared to sucrose carries a sweetness level of about 10% (Valluru & Van den Ende, 2008). Inulin behaves similar to bulking ingredients and along with high levels of artificial sweeteners like aspartame and acesulfame K, it provides a good mouth feel with a little aftertaste (Franck, 2002). Such blends can also show an important quantitative sweetness recipe.

Chicory inulin is moderately dissolved in water (nearly 10% at 25 °C) which enables its addition in aqueous medium without any precipitation. Use of heated water at 50–100 °C is recommended to make inulin solution. Chicory inulin solutions are of relatively low viscosity e.g., for 5% solution, 1.65 mPa s at 10 °C and for 30% solution, 100 mPa.s (Kalyani Nair et al., 2010). Freezing and boiling points of water are affected by inulin to a small extent (e.g., 15% chicory inulin reduces the freezing point by 0.5 °C). Low pH, high temperature and less dry-substance environments are the critical parameters for inulin hydrolysis (Roberfroid, 2000; Roberfroid, 2007). Further, β-(2-1) bonds between the fructose units can be (partially) hydrolyzed in highly acidic environment.

Inulin shows gelling properties at high level (for standard chicory inulin > 25% and for long-chain inulin > 15%) and makes a gelling structure afterwards shearing. When the inulin is totally dissolved in water or any other aqueous medium, with shearing instrument like a rotor-stator mixer or homogenizer, it results in the formation of a white creamy structure that can easily be added in foods as a fat replacer up to 100% (Imeson, 2010). The gelling property of inulin is greatly influenced by inulin concentration, quantity of total dry substance, shearing factors (for example temperature, time, speed, or pressure) and moreover by the kind of shearing instrument used; however, it is not affected by pH (between pH 4 and 9). Further, Cryo-electron microscopy revealed that such inulin gels are made up of a 3-D structure which are normally non-soluble submicron inulin fragments in water (Zimeri & Kokini, 2002).

2. Nutritional and health benefits

Inulin provides numerous nutritional and health benefits to humans, some of them are shown in Fig. 3

2.1. Function as dietary fiber

Currently, dietary fiber is considered as a key ingredient for improving human health and the attention towards dietary fiber enriched foods has been intensified manifolds due to its health promoting properties. The basic characteristics of dietary fiber are: impervious to hydrolysis by the gastric secretions and absorption in the small intestine while fermentable by the microflora of large intestine (Roberfroid, 2007; Turner & Lupton, 2011; Wong, De Souza, Kendall, Emam, & Jenkins, 2006). Inulin is a storage carbohydrate in plants, having fructose moieties joined by β-(2-1)-D-frutosyl linkages and is resistant to digestion in the human small intestine due to the β-configuration of anomeric C-2 but it can be fermented in large intestine (Apolinario et al., 2014). Almost 90% of the inulin passes to the colon and digested by bacteria present there (Cherbut, 2002). It is thus a significant component of the dietary fiber complex and is labeled as dietary fiber on food items.

2.2. Caloric value

The low caloric value (1.5 kcal/g or 6.3 kJ/g) of inulin is due to its non-digestibility in contrast to its constituent monosaccharide moieties. By the action of intestinal bacteria, inulin is transformed into short-chain fatty acids (like acetate, propionate, and butyrate), lactate, bacterial fuel and gases (Nyman, 2002). Merely, short chain fatty acids and lactate can add to the energy metabolism of host organism. Bacteria and host cell can also use some part of short chain fatty acids. On the evidence of *In-vitro* and *In-vivo* results, the energy rate of inulin and oligofructose was reported to be 1.5 kcal/g (Roberfroid, 1999). Further scientific observations have also proved less energy account of inulin, where, the energy value ranging from 1 and 1.5 kcal/g is being used for food tagging (Flamm et al., 2001).

2.3. Effect on lipid metabolism

The addition of non-digestible carbohydrate like inulin to a diet can decrease the risk of high triacylglycerol concentrations.

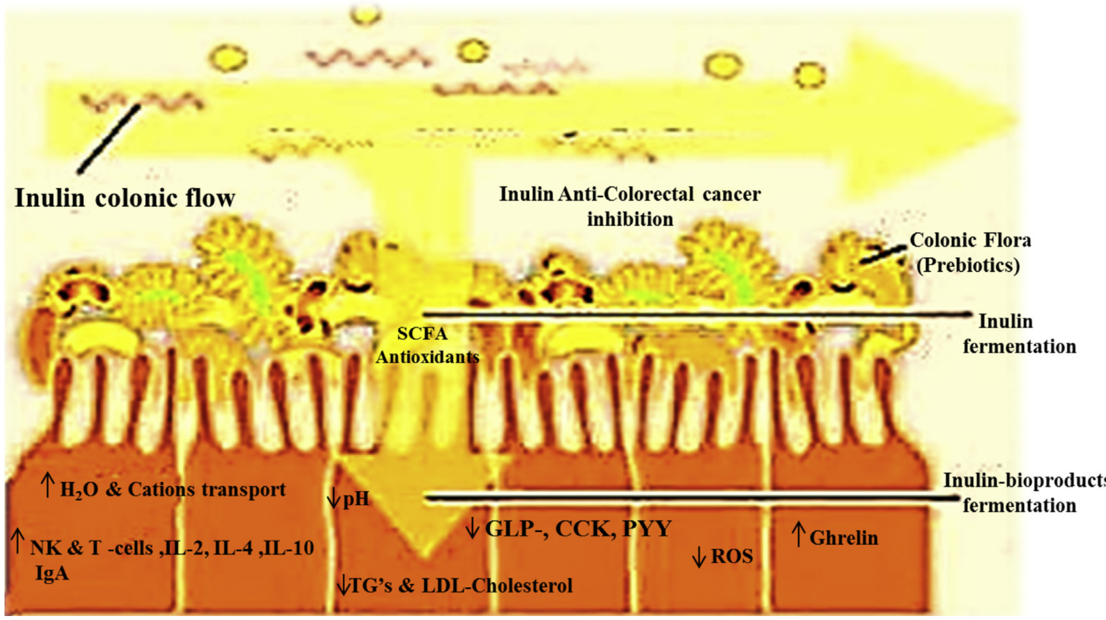

Fig. 3. Overview of inulin fermentation, absorption in colon and its function in human body.

Letexier, Diraison, and Beylot (2003) concluded from a study that incorporation of high-performance inulin i.e., 10 g/d to a carbohydrate rich and reduced lipid food exerted positive outcome on plasma lipids of human by lowering blood lipogenesis and plasma triacylglycerol concentrations thereby reducing the risk of atherosclerosis (Letexier et al., 2003). However, Williams and Jackson studied the effect of inulin or oligofructose supplementation on blood lipids (LDL-cholesterol and triacylglycerol) in ten human volunteers. Three of them had no effect of inulin or oligofructose on blood cholesterol levels or triacylglycerol. However, three volunteers showed considerable reductions in triacylglycerol, whereas a moderate decrease in LDL-cholesterol was found in remaining four persons (Williams & Jackson, 2002). Inulin supplementation in diet of hypercholesterolemics might improve blood lipid profiles. Inulin and oligofructose exert systemic effect by altering the blood metabolism of lipids in different experimental animals. Animal have shown that inulin influences lipid metabolism mainly by lowering triglyceridemia and slightly decreases cholesterolemia (Delzenne, Daubioul, Neyrinck, Lasa, & Taper, 2002). Various studies on humans are evident that inulin is more efficient as compared to oligofructose in reducing triglyceridemia, while in animals (particularly in rats); both were found to have similar effect. Concerning the mechanism, inulin and oligofructose addition to a rat's feed lowered the lipid breakdown in liver by suppressing the production of the genes responsible for lipogensis of enzyme. In humans, the process occurs in the same way but the mechanism that how inulin actually affects lipid metabolism is still under discussion (Roberfroid, 2007). Studies on rodents demonstrate that inulin and oligofructose can decrease the plasma cholesterol and triacylglycerol. Additionally, it can oppose triacylglycerol's accumulation in liver and has favorable influences on hepatic steatosis. The decrease in liver lipogenesis is perhaps the main mechanism accountable for the decrease in plasma triacylglycerol's levels, both in humans and animals, while the mechanism of the hypocholesterolaemic action is still unclear.

2.4. Effect on constipation and stool frequency

Inulin is a soluble fiber which is not digested by human enzymes and produces distinctive fiber-alike results on the effectiveness of the gut, thus, lowering the pH of intestine, providing assistance in relieving constipation and increasing stool load or rate (known as bulking effect), having similar fecal bulking effect of other soluble fibers like pectin and guar gum (Anderson et al., 2009). There is an increase of 1.5–2 g of wet fecal weight by consuming every gram of inulin. This can also be imitated by an enhanced dry weight of fecal secretion. Inulin and oligofructose results in improved stool frequency and consistency (Den Hond, Geypens, & Ghoos, 2000). The improvement is more in participants having decreased initial stool frequency. The most widespread gastrointestinal problem amongst elder people is surely the constipation. Deficiency of fluid intake and less consumption of fiber rich foods can promote constipation (Rubel, Pérez, Manrique, & Genovese, 2015; Russell, Rasmussen, & Lichtenstein, 1999). Similarly altered constitution of the short chain fatty acids and micro-biotic colonies results in variations in the intestinal activity. In old age, probiotic and prebiotics strains facilitate to ease constipation (Kolida & Gibson, 2007). Owing to prebiotic action of inulin, it acts as a substrate for probiotics. Chicory inulin (20–40 g/day) had a sufficient cathartic result in relieving constipation (Fernández-Bañares, 2006; Kolida & Gibson, 2007).

2.5. Bifidogenic effect

The large intestine retains more than 400 kinds of bacteria which imply the dry solid content of colon above 50%. Every individual constituent of the intestinal micro flora is distinctive with enormous inter-individual differences (Zoetendal, Vaughan, & De Vos, 2006). In general, the bacteria of intestine can be distributed into 3 groups on the basis of their possible effects such as: (1) *Lactobacilli* and *Bifidobacteria*; (2) possibly pathogenic bacteria, like some species of *Clostridia* and (3) further commensal bacteria, such as *Bacteroides*, also possesses positive and negative characteristics. Though there is no certainty but normally it is understood that a gut micro flora that contains *Lactobacilli* and *Bifidobacteria* in high quantity is good for health (Eckburg et al., 2005; Kamarul Zaman, Chin, Rai, & Majid, 2015).

The microbial environment of the large intestine is necessary for physical condition and imbalances can lead diseases (Kleessen, Hartmann, & Blaut, 2001). Inulin stimulates the development and metabolic action of a limited number of bacteria in the colon, particularly *Bifidobacteria* and *Lactobacilli*, and thus promotes their health. This is referred as a prebiotic or bifidogenic effect. Probiotics are the live micro-organisms having host beneficial effects by enhancing microbial balance in intestine, whereas, prebiotics are indigestible food components having beneficial effects by enhancing the activity and growth of one or more colonic bacteria (Karimi, Azizi, Ghasemlou, & Vaziri, 2015; Roberfroid, 2000).

In-vitro trials have demonstrated that the colonic fermentation depends on chain length of the inulin. Fermentation time of short-DP fractions is two times higher than long chain inulin. Thus, the long-chain inulin part possess unique character for the initiation of the metabolic action in the last part of the colon (Cho & Samuel, 2009). Oliveira, Perego, Oliveira, and Converti (2011) determined that the addition of inulin at a low concentration in low fat milk has considerably enhanced the growth and sustainability of *Lactobacillus acidophilus*, *Lactobacillus rhamnosus* and *Bifidobacterium lactis*. Thus inulin can be used as a fat replacer in non-fat functional dairy products, providing approximately the same sensory characteristics (Akın, Akın, & Kırmacı, 2007; Cruz et al., 2010). Inulin incorporation in different products improved their firmness as a result of increased microbial activity caused by metabolic relations between lactic acid bacteria and partial inulin metabolization (De Souza Oliveira, Perego, De Oliveira, & Converti, 2011). Patients suffering from intestinal irregularity and some serious diseases showed that inulin and oligofructose re-established the microbial stability in case when the microbial population of gut was changed thus hindered the development of diseases. The nutritional use of inulin and oligofructose provides a favorable way to encourage microbial balance and assists in overcoming the difficulties of the epithelia by prebiotic action. This may provide the host defense against attack and translocation of microbes (endogenous and exogenous) and in the inhibition of GIT diseases (Bosscher, Van Loo, & Franck, 2006).

2.6. Reduction in risk of gastrointestinal diseases

Inulin exerts favorable properties in decreasing the risk of many diseases of the intestinal tract, particularly irritable bowel diseases (IBD) and colon cancer. Ulcerative colitis (UC) and Crohn's disease are jointly called as inflammatory bowel diseases (IBD). Both are chronic inflammatory ailments of GIT that influence up to 500 for every 100,000 individuals in the western world. IBD is usually considered as western world disease, and its incidence has increased significantly during the past few decades (Sartor, 2004). Latest study, have shown that a combination of a number of genetic, environmental and immunological factors affects IBD (Mendis, Leclerc, & Simsek, 2016). Manipulating the composition of intestinal microflora by using probiotics and/or prebiotics can be employed as therapeutic approach in preventing chronic intestinal inflammation.

Hoentjen et al. (2005) determined that feeding inulin and oligofructose mixture by 5 g/kg body weight decreases colitis in transgenic rats. Reduction in colitis and improvement in growth of intestinal *Bifidobacteria* and *Lactobacilli* has been observed by using the combination of inulin and the probiotic microorganisms *L. acidophilus* La-5 plus *Bifidobacterium lactis* to the HLA-B27 transgenic rats. This combination therapy not only lowered mucosal pro-inflammatory cytokines but also enhanced the immune regulatory transforming growth factor-β (Schultz et al., 2004). Further, the combination of inulin with lactulose has shown to reduce inflammation in dextran sodium sulphate (DSS)-induced colitis rats (Videla et al., 2001). Inulin has been proved to be helpful in the treatment of chronic pouchitis after removal of colon for ulcerative colitis. Videla and Furrie concluded from a study in 18 active ulcerative colitis patients that, the use of prebiotics and probiotics in combination (i.e., *B. longum* and a prebiotic blend of inulin and oligofructose) cause reduction of intestinal inflammation (Furrie et al., 2005; Welters et al., 2002).

The significant reduction of Crohn's disease in 10 patients and an enhanced growth of intestinal *Bifidobacteria* using 15 g oligofructose and inulin combination for 21 days has been elucidated (Lindsay et al., 2006) Inulin in combination with oligofructose has shown improvement in the metabolic functions of the microflora (Cummings, Christie, & Cole, 2001; Van Loo et al., 1999). Clinical and experimental evidence demonstrated that their combination enhanced the gut mucosal barrier and could assist in the inhibition of IBD. The inflammation inhibitory results of oligofructose and inulin have been evaluated in the rats due to same histological human ulcerative conditions with distal colitis brought by dextran sodium sulphate. Both inulin and oligofructose enhance the short chain fatty acids production and prefer *Lactobacilli* or *Bifidobacteria* production (Guarner, 2005).

Colon cancer also referred as colorectal cancer, rectal cancer, or bowel cancer, results from colon cell mutation (portions of the large intestine), or in the appendix. It is one of the most common reasons of death due to cancer in the people of developed countries. Some analysis demonstrates that basically colon and rectal cancers are genetically similar (Cancer Genome Atlas, 2012). Rectal bleeding and anemia are the common signs of colorectal cancer that are occasionally related to weight loss and changed bowel habits. Concerning the risk of colon cancer, studies in rats and mice demonstrates that inulin and oligofructose have the ability to prevent colon carcinogenesis caused by the chemicals and increase symbiotic preparations with lactic acid bacteria (Pool-Zobel, 2005).

Studies suggest that symbiotic formulation of inulin enriched with oligofructose in combination with *Lactobacillus rhamnosus* and *Bifidobacterium lactis* is able to decrease the risk of colon cancer in humans (Rafter et al., 2007). Further researchers have found that inulin HP and synergy are more beneficial as compare to oligofructose since the long-chain molecules take more time for fermentation in large intestine, thus extending its influences in the distal colon. Certainly, the small oligomers are fermented in advance in the proximal colon and therefore cannot reach the distal colon. Inulin HP and synergy take action generally in the progression of the cancer, by decreasing the amount and mass of lesions as well as lowering the chance of development of these lesions to malignancy (Poulsen, Molck, & Jacobsen, 2002). Inulin and oligofructose therefore help in the prevention of oncogenesis. These two mechanisms explained the beneficial role of inulin in modulation of colonic microflora, change in the short-chain fatty acids composition; particularly an increase in butyrate production through anaerobic fermentation. Secondly, fructans like inulin improve and promote immune system of gastrointestine, specifically the intestinal resistance (Pool-Zobel, 2005; Van Loo, Clune, Bennett, & Collins, 2005).

2.7. Enhance absorption of calcium, magnesium and iron

For the optimization of bone mass, sufficient consumption of calcium in combination with its enhanced absorption is required. Daily recommended dietary intake of magnesium differs for males from 350 to 420 mg/day and for females from 280 to 320 mg/day. In case of calcium it accounts for 800 mg/day in males, while 800–1000 mg/day in females (Gupta, Lakshmi, & Prakash, 2006). The proximal part of small intestine is the chief spot of mineral assimilation in humans, whereas, vitamin D controls this action by producing cytosolic calcium binding protein and calbindin D_{9K}. Further accumulation of calcium by intestines can also take place by a passive paracellular way, via the tight junctions among mucosal cells. This process is non-saturable, dose-dependent, vitamin D independent and follows across both intestines (Weaver & Liebman, 2002). Fermentable substances assist to attain calcium equilibrium via transforming the chief site of mineral absorption to the large intestine (Scholz-Ahrens, Schaafsma, van den Heuvel, & Schrezenmeir, 2001).

Many theories have been proposed about the contribution of inulin and oligo-fructose to the enhanced mineral absorption. One way might be the reduction of intestinal pH, as colonic fermentation of inulin produces short chain fatty acids or additional organic acids that results in decreased pH of large intestine (Coxam, 2005). In fact, calcium present in diet as a mineral or in association with other components should be essentially in ionized form prior to its absorption. Subsequently, the low pH increases the bioavailability of calcium. Thus it results in improvement of calcium absorption through passive diffusion in the small intestine and the first part of the large intestine. Furthermore, by ion exchange system there is a possibility that short chain fatty acids influence the calcium absorption (Scholz-Ahrens & Schrezenmeir, 2002). Additionally, by changing the action of vitamin D receptor and increasing calbindin $D_{9K,}$ inulin and oligo-fructose can amend trans-cellular active calcium transport. Another way of increasing mineral incorporation is amplifying butyrate yield or some polyamine through which inulin and oligofructose can incidentally stimulate cell growth and increase the intestinal absorptive region (Scholz-Ahrens et al., 2001).

Research trials on animals (commonly rats) have shown that inulin-type fructans remarkably enhanced the mineral absorption, particularly calcium and magnesium (Weaver, 2005). In developing male rats, 5 or 10% of chicory inulin diet enhanced whole body bone mineral content (BMC) and bone mineral density (BMD) (Roberfroid, 2002). In another study, combination of oligo-fructose and inulin were given to adolescent girls for 3 weeks, calcium absorption was enhanced by 18% (Griffin, Davila, & Abrams, 2002). Further studies on girls showed enhanced Ca absorption with oligo-fructose-enriched inulin diet which were supplemented with inulin at 8 g/day (Bosscher et al., 2006).

Studies demonstrated that a synergy (combination of inulin and oligofructose) was more vigorous than using them individually in increasing Ca and Mg absorption (Coudray, Tressol, Gueux, & Rayssiguier, 2003). It has been proved that inulin-type fructans show their effect on mineral absorption even after ovarical surgery in female rats. So, it should be hypothesized that, in female rats, these things are not dependent on hormones and inulin-type fructans can be advantageous in postmenopausal women (Tahiri et al., 2003). In humans, inulin-type fructans have little influence in small intestine for mineral absorption, and their beneficial impact on calcium or magnesium absorption are probably influenced by changes in the last part of the intestine facilitated by the action of the microflora (Holloway, Moynihan, Abrams, Kent, Hsu & Friedlander, 2007). The beneficial effects of inulin are not only evident in adolescents (Griffin & Abrams, 2005; Griffin, Hicks, Heaney, & Abrams, 2003) but also postmenopausal women (Tahiri et al., 2003; Takahara et al., 2000). However, only few studies has demonstrated the beneficial impact of inulin on mineral absorption in adult men (Roberfroid, 2000). Differences in ability of calcium absorption are due to genetic polymorphisms, it has been considered that few genotypes could possibly attain more benefits from utilization of inulin-type fructans, particularly synergy (Griffin et al., 2003). Both trials and human data validates the supposition that the advantageous results of inulin-type fructans aim not merely on mineral absorption but also additional role in bone strengthing, particularly bone density, bone mineralization, bone growth and resorption, i.e., bone turnover (Coxam, 2005).

Current studies also determine the effects of inulin on Fe absorption, especially in a case of its deficiency. Iron deficiency is a very common nutritional disorder in humans. Though, food fortification and iron supplements have been utilized to effectively prevent this problem (Clark, 2009). Young weaning piglets are thought to be a proper prototype for examining iron nutrition in human due to their resemblances in the internal structure of the GIT system or digestive makeup. Soluble level of Fe in colon of anemic pigs can be enhanced by supplementation of diet at 4% along with increased blood HB levels and its saturation efficacy. Sulfide degree was found to be lower and the positive effects of inulin are considered to be linked with lower sulfide degree in the colon (Yasuda, Roneker, Miller, Welch, & Lei, 2006).

2.8. Regulation of food intake and appetite

The procedure to regulate appetite is complicated and includes the interaction between several orexigenic and anorexigenic hormones that are secreted by the GIT and peripheral tissues of body, as a food feedback. These hormones give messages to the hypothalamus (part of brain) to identify the sense of craving or satiety (Smitka et al., 2013). Cholecystokinin (CCK), PP-fold peptide (PYY) and glucagon-like peptide-l (GLP-l) (appetite hiding peptides) in the blood at elevated level are linked with lesser subjective hunger assessment and decreased food ingestion. In contrast, during fasting ghrelin hormone stimulates hunger and consequently begins food ingestion (Date et al., 2000; Drucker, 2002).

Experimental data was collected relating to the function of inulin and oligofructose on GIT hormone to modify blood levels which affected appetite. Short chain fatty acids (SCFs) (basically acetate, propionate and butyrate) were produced by fermentation of inulin in colon (Tarini & Wolever, 2010). High level of SCFs in the colonic lumen may enhance the expression of glucagon-like peptide-l (GLP-l) in the mucosa thus increase blood GLP-l levels and lower the levels of hormone ghrelin (Cho & Samuel, 2009). This has been shown in many experimental models (like, rats fed on a regular or high-fat diet, overweight and diabetic rats) and is constantly linked with a considerably less energy (and food) ingestion, along with less body mass and fat accumulation in tissue (from high-fat diets). Research data determined the regulation of GLP-1 and ghrelin production by inulin-type fructans as one significance appetite regulation. Earlier human data is likely to validate such an influence, which at rest requires additional and broad investigation (Delzenne, Cani, Daubiou, & Neyrinck, 2005).

2.9. Stimulation of immune system

The immune system is possibly the highly complex system in human body. It is comprised of masses of fully distinct cell types, each cell with its own group of signaling molecules, mechanism of antigens and effector functions. Complexity of immune system allows it to respond to foreign substances and protects from invasion by pathogenic organisms, thus it protects the body from probably harmful substances by identifying and acting on antigens (Norvell, 2013, nullChapter). Several research trials have shown the immune-modulating effects of inulin and oligo-fructose (Schley & Field, 2002). These studies demonstrated that inulin and oligo-fructose indirectly stimulated T cell functions, NK cells and phagocytic activities through alteration in concentration of lactic acid bacteria in the gastrointestinal tract, which not only protects mice from pathogens but also from tumor (Kelly-Quagliana, Nelson, & Buddington, 2003). Various nutritional supplements improved the vaccine efficiency by stimulating the immune system (de Vrese et al., 2005).

In a study on mice, mixture of inulin and oligofructose (70:30) and suboptimal low dose of *Salmonella typhirnuriurn* via oral shot has shown to stimulate immune responses, thus increasing oral vaccine efficacy. Anti-salmonella antibody responses improved in mice by blood Salmonella immunoglobulin G and fecal immunoglobulin A. The combined treatment of inulin and oligo-fructose in mice showed that rate of vaccination protection enhanced from 40% to 73% (Benyacoub et al., 2008). In another study, diets comprising of cellulose, oligo-fructose or inulin were fed to mice for a time period of six weeks. Results showed that inulin and oligo-fructose supplemented diet enhanced NK cell activity and peritoneal macrophage activity (Kelly-Quagliana et al., 2003).

Studies on aged personals showed that suitable dietary supplements could stimulate immune system however age factor was also associated with modulation in the immune system. In a study a dietary supplement comprising proteins, vitamin B_{12}, vitamin E, vitamin B_9, *Lactobacillus paracasei* with a combination of inulin and oligo-fructose was fed to healthy elderly volunteers for four months, before immunization against *Influenza virus* and *Pneumococcus*. After 120 days, the NK cell activity was enhanced by the dietary supplement. NK cell action is one of the most important immune system in opposition to viral illness. Furthermore, volunteers who followed the dietary supplement for one year were found to report less infection (Bunout et al., 2004). Further study showed improvement of vaccination-induced immune response, in infants vaccinated for measles and nourished on baby foods supplemented by a symbiotic diet comprising of inulin and oligo-fructose. After vaccination, particular IgG-antibody levels were greater using the symbiotic, demonstrating an improved immune response to vaccination (Hegar, Boediarso, Firmansyah, & Vandenplas, 2004). All these mentioned functions in immune system are postulated that inulin and its derived compounds has a direct interaction with the gut-associated lymphoid tissues of mice (Roberfroid, 2005). However, this interaction has not yet been found in human-beings.

2.10. Intestinal acceptability

Two facts have demonstrated the intestinal acceptability of non-digestible constituents. Firstly, the indigestible components exert osmotic effects that brought about an enhanced presence of water in the colon. Minor compounds induce a greater osmotic stress and excess water moves into the colon. That's why sorbitol and lactulose have a considerably greater purgative effect than inulin. Secondly, there are some after effects produced by the fermented goods, mostly the production of gases (Cho & Samuel, 2009). Composite that takes more time to ferment is better than compounds which ferment quickly. This is the reason inulin is easy to endure than polyols and short-chain fructo-oligosaccharides. Flatulence is a recognized and frequently assuming after effects of dietary fiber ingestion (Turner & Lupton, 2011). In a study of 26 healthy men and women aged between 18 and 60 years have been given a food supplemented with 10 g of native inulin and oligo-fructose per day. Results showed that inulin consumed in practical doses were generally well-tolerated. Although, the higher doses of inulin and oligo-fructose caused flatulence in some sensitive individuals (Bonnema, Kolberg, Thomas, & Slavin, 2010). Further study demonstrated that short and long-term intakes of inulin-rich soluble chicory extract given at a daily dose of 5 g were well tolerated by healthy subjects (Ripoll, Flourie, Megnien, Hermand, & Janssens, 2010).

3. Food applications

The wide use of inulin in the food sector is based on its techno-functional attributes. Inulin is of great interest to develop healthy products because it concurrently responds to a range of consumer requirements: it is fiber-enriched, prebiotic, low fat and low sugar as detailed in Table 2 (Franck, 2002). As a dietary fiber, inulin goes through the gastrointestinal tract largely undigested. In the colon it function as a prebiotic as it is selectively fermented by the beneficial micro-flora, enhances their growth and strengthens its action against pathogenic microorganisms (Van Loo, 2004). Inulin can be highly branched or linear depending on the source. Highly branched inulin polymers have more solubility and in the presence of water as they are capable to develop a particulate gel, thus altering the product texture and providing a fat-like mouthfeel (Tungland & Meyer, 2002), while short-chain molecules enhance flavor, sweetness and are used to partially replace sucrose (De Castro, Cunha, Barreto, Amboni, & PrudÊNcio, 2009)

3.1. Fiber enrichment

Technical and dietetic benefits of inulin make it a good choice to be used as an essential ingredient in diet, and mostly it is used to offer dual benefits: a better organoleptic character and a sound nutritional make-up (Roberfroid, 2007). As a fiber constituent, inulin mostly results in enhancing taste and texture. In breakfast cereals and bakery items, inulin offers important improvement as compared to other fibers (Franck, 2002). Incorporation of inulin in baked products not only keeps them moist and fresh for long time but also improve their crispiness. A study in which gluten free layered cakes were prepared by the addition of 20% inulin in rice flour resulted in an increased dietary fiber content, reduced fat content and favored air incorporation during mixing (Gulati, 2012). Its solubility permits fiber addition in aqueous environment like drinks, dairy products, thickened beverages and table spreads. A study conducted in institutionalized adults with the supplementation of inulin to thickened beverages witnessed the enhanced fiber content, improved bowel movement and weighted stool frequency increased by 13% (Dahl, Whiting, Isaac, Weeks, & Arnold, 2005).

3.2. As a prebiotic

For an efficient prebiotic, a molecule should have some qualities such as: it should not be hydrolyzed or absorbed in the upper part of the GIT; gut micro-flora should be fermented and beneficial bacteria of colon should be stimulated by it (Van Loo, 2004). As previously studied, inulin and oligo-fructose were proved as the most widely examined prebiotic compounds with the most important prebiotic efficacy (Gibson, Probert, Loo, Rastall, & Roberfroid, 2004). Now, inulin is gradually being used in functional foods, particularly in a complete variety of dairy products to enhance the intensification of the beneficial intestinal bacteria (Menne & Guggenbuhl, 2000). In recent times, researches showed that the low dose level inulin supplemented in skim milk, considerably increased the growth and sustainability of *Lactobacillus acidophilus, Lacto-bacillus rhamnosus* and *Bifidobacterium lactis* in non-fat fermented milk (Oliveira et al., 2011). A clinical trial conducted in healthy new born babies of four months of age demonstrated that supplementation of 0.8 g/dL Orafti® Synergy1 (oligo-fructose-enriched inulin) in infants diet was safe, effective and promoted a gut micro-flora close to that of breastfeeding (Closa-Monasterolo et al., 2013).

Various prebiotic dairy desserts having low fat content have been prepared using inulin as a prebiotic, in which inulin supplementation not only given prebiotic effect but also reduced the fat content and sugar content (12% reduction) without affecting its acceptability to consumers (Arcia, Costell, & Tárrega, 2011). As inulin is metabolized in different parts of the large intestine (short-chain inulin in the proximal colon portion and long-chain inulin in more distal colonic portion), the use of blend of short and long-chain inulin to increases fermentative and prebiotic effects is suggested by several nutritional studies (Biedrzycka & Bielecka, 2004; Coudray et al., 2003). The blend of short-chain and long-chain inulin at 50:50 ratios provides various additional advantages in enhancing prebiotic effectiveness. It increases Ca deposition and mineral contents of bone in adults and proved to be effective in reducing the amount of gas production while enhancing or maintaining its prebiotic effect (Ghoddusi, Grandison, Grandison,

Table 2
Food usage of Inulin.

Applications	Function	Concentration level (%w/w)	References
Bakery foods (bread, cakes)	Prebiotic and fiber preservation of moisture Sugar replacer	2–15	(Nieto-Nieto, Wang, Ozimek, & Chen, 2015; Rodriguez Furlan, Perez Padilla, & Campderros, 2014)
Breakfast cereals	Fiber and prebiotic Crispiness and increase in size	2–25	(Foschia, Peressini, Sensidoni, & Brennan, 2013)
Dairy products	Replacement of fat and Sugar Synergy with sweetness Texture and mouthfeel Foam stabilization Fiber and prebiotic	2–10	(Meyer, Bayarri, Tarrega, & Costell, 2011)
Meat products	As a fat replacer Texture and stability Fiber	2–10	(Keenan et al., 2014; Rodriguez-Garcia, Sahi, & Hernando, 2014)
Frozen desserts	Replacement of fat and sugar Improve texture Melting behavior Fiber and prebiotic Less energy value	2–10	(Krasaekoopt & Watcharapoka, 2014)
Table spreads	Replacement of fat Texture and spreadability Emulsion stability Fiber and prebiotic	2–10	(Glibowski, 2010)
Fillings	Replacement of fat Texture improvement	2–30	(Salvatore et al., 2014)
Salad-dressings	Replacement of fat Body and mouthfeel	2–10	(Mantzouridou, Spanou, & Kiosseoglou, 2012)
Chocolate	Replacement of sugar and fat Fiber Heat resistance (melting behavior)	5–30	(Aidoo, Afoakwa & Dewettinck, 2014; Aidoo, Afoakwa & Dewettinck, 2014)
Fruit preparations	Replacement of sugar Synergy with sweeteners Body and mouthfeel Fiber and prebiotic	2–10	(Krasaekoopt & Watcharapoka, 2014)
Dietic products and meal replacers	As a sugar and fat replacer Combination with sweeteners Low caloric value Body and mouthfeel Fiber and prebiotic	2–15	(Brambillasca, Zunino, & Cajarville, 2015; Tiengtam, Khempaka, Paengkoum, & Boonanuntanasarn, 2015)
Tablets	Replacement of sugar Fiber and prebiotic	5–100	(Eissens, Bolhuis, Hinrichs, & Frijlink, 2002)

& Tuohy, 2007). However, the magnitude of the sensory variations depends on the combination of short and long-chain inulin ratio and on the total inulin concentration (Bayarri, Chuliá, & Costell, 2010; Ghoddusi et al., 2007; Tarrega & Costell, 2006)

3.3. *As a fat replacer*

Inulin products consisting mainly of long-chain molecules are applied for fat replacement, since in the presence of water they are capable to develop a particulate gel, thus alter the product texture and provide a fat-like mouthfeel (Karimi et al., 2015; Tungland & Meyer, 2002). In non-fat functional dairy foods inulin can be used as a fat replacer and provides them nearly the same sensory characters as of full fat products (Akın et al., 2007 Cruz et al., 2010; Solowiej et al., 2015). Some scientists have analyzed the effect of long chain inulin addition on physical and sensorial features of dairy foods such as yogurt or custard. Long-chain inulin has been used in low-fat yogurts to replace fat where it was exposed to considerably improve creaminess, mouthfeel and smoothness (Kip, Meye, & Jellema, 2006; Modzelewska-KapituŁA & KŁĘBukowska, 2009). Addition of long-chain inulin to low fat custards enhanced creaminess and consistency, also same results were obtained by its addition to full-fat custards (Lobato, Grossmann, & Benassi, 2009; Tarrega & Costell, 2006). Inulin addition (2–7%) in fresh caprine milk cheese allows the replacement of fat, provides a creamier mouth feel and adds a reasonable flavor with softening effect. However, the softening effect rely on the inulin level (Salvatore, Pes, Mazzarello, & Pirisi, 2014).

Fat replacer can additionally be used in meal replacers, meat products, sauces and soups, thus less fat meat products are available having a juicy and creamy mouthfeel and an enhanced firmness due to water control (Cho & Samuel, 2009). The addition of inulin to added-fat containing meat products like sausages could be an attraction to health conscious consumers as they are significant to human nutrition in the situation of dietary guidelines (Selgas, Caceres, & Garcia, 2005).The addition of inulin to sausages results in reduced fat content, improves texture, and sensorial appraisal. Fructan analysis suggested that the inulin remained stable during processing and successive heat treatment (Keenan, Resconi, Kerry, & Hamill, 2014). Further studies showed that fermented chicken sausages made with inulin as a partial oil replacement persisted stable without any significant loss of physicochemical, microbiological and sensory characteristics during storage at 4 °C for 45 days (Menegas, Pimentel, Garcia, & Prudencio, 2013). Inulin addition in biscuits to a level of 15% could be used to attain fat replacement and good sensory properties (Laguna, Primo-Martín, Varela, Salvador, & Sanz, 2014).

3.4. *As a sugar replacer*

Inulin products contain mainly short-chain molecules which enhance the sweetness of sucrose up to 35%, thus it is useful to partially replace sucrose molecule's flavor (De Castro et al., 2009; Villegas, Tárrega, Carbonell, & Costell, 2010). However, its HP high form is comparatively less sweet. Inulin has been proved an attractive applicant as a low-calorie bulking agent in chocolate, mostly in combination with a polyol which replaces sugar contents without any effect on fat contents. Sugar free chocolates were produced by (Farzanmehr & Abbasi, 2009; Palazzo, Carvalho, Efraim, & Bolini, 2011; Shah, Jones, & Vasiljevic, 2010) replacing sucrose with inulin (HP) having different degree of polymerization and poly-dextrose and suggested inulin with high degree of polymerization as an appropriate ingredient for sucrose free chocolate preparations. Inulin is also used in tablets for the replacement of sugar. In custards, the supplementation of short-chain inulin improved flavor and enhanced sweetness, though it did not significantly change the texture (Gonzalez-Tomas, Bayarri, & Costell, 2009). So, inulin has become an important component providing new ways for the food manufacturing in development of novel food having better sensorial and nutraceutical properties.

4. Conclusion

In modern era, consumers are more conscious about their diet and demand low caloric foods with better health enhancing properties. The current investigations present a deep knowledge about the role of newly discovered active components for the development of functional foods. Although, the role of inulin has also been explored in the past few years but nutritional and health benefits along with food applications, specifically its use as functional food was focused in this review. It has been discussed that inulin possesses tremendous effects on growth and health status of humans. Furthermore, it can be a decent replacement of carbohydrates and fat along with being a good source of fiber to enrich different foods for product development. Many studies have proved its role as a good fat replacer (up to 50%) for developing products with healthier properties and desired sensory characteristics. Inulin types, length and concentration have significant effect on the activity of starter, probiotic cultures and the pH value when it is used as prebiotic in dairy industry. Therefore, more research work is needed for further specification and characterization of potential prebiotic and inulin-oligo-fructose fructans combinations for the development of novel functional foods.

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