Carbohydrate Polymers 332 (2024) 121918

Contents lists available at ScienceDirect

Carbohydrate Polymers

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

Quality characteristics of cereal-based foods enriched with different degree of polymerization inulin: A review

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ARTICLE INFO

Keywords:
Inulin degree of polymerization
FODMAPs
Pasta
Bread
Quality
Sensory properties
Glycemic index α-amylase inhibition

ABSTRACT

Vegetables, cereals and fruit are foods rich in fibre with beneficial and nutritional effects as their consumption reduces the onset of degenerative diseases, especially cardiovascular ones. Among fibres, inulin, oligofructose or fructooligosaccharide (FOS) are the best-studied. Inulin is a generic term to cover all linear β(2–1) fructans, with a variable degree of polymerization. In this review a better understanding of the importance of the degree of polymerization of inulin as a dietary fibre, functions, health benefits, classifications, types and its applications in the food industry was considered in different fortified foods. Inulin has been used to increase the nutritional and healthy properties of the product as a sweetener and as a substitute for fats and carbohydrates, improving the nutritional value and decreasing the glycemic index, with the advantage of not compromising taste and consistency of the product. Bifidogenic and prebiotic effects of inulin have been well established, inulin-type fructans are fermented by the colon to produce short-chain fatty acids, with important local and systemic actions. Addition of inulin with different degrees of polymerization to daily foods for the production of fortified pasta and bread was reviewed, and the impact on sensorial, technological and organoleptic characteristics even of gluten-free bread was also reported.

1. Introduction

The functional foods market is constantly increasing all over the world, to satisfy the needs of consumers for a healthier diet, thus leading to the development of several innovative products, especially those that have an impact on the development of gut microbiota. The intestinal tract is populated by a high number of microbes that produce a great biodiversity of the intestinal microbiota, with specific metabolic activities, functions, and effects on the health of the host, having an important impact on colon metabolism and human physiology. In particular, some microbial conversions of undigested material occur in the colon, including the production of short-chain fatty acids (SCFAs) such as acetate, propionate, butyrate, and lactate (Shoaib et al., 2016) through the fermentation of undigested carbohydrates. Dietary fibre is resistant to enzymatic hydrolysis and absorption from the small intestine. In recent years it has been demonstrated that these fermentation products have positive effects on the health of the host, contrary to those resulting from the degradation of proteins and the fermentation of amino acids, which include ammonia, phenols, indoles, thiols, amines, and sulphides (de Graaf & Venema, 2008). Non-digestible carbohydrates are called prebiotics. Originally, prebiotics were defined by Gibson & Roberfroid (1995) as "non-digestible food ingredients that positively affect the host by selectively stimulating the growth and/or activity of one or a limited number of bacterial species in the colon, and therefore improving the host health" (Gibson et al., 2004). The different types of dietary fibre are classified based on the number of monomeric units that compose them. EFSA (European Food Safety Authority) has defined dietary fibre as non-digestible carbohydrates, such as lignin, non-starch polysaccharides, cellulose, hemicelluloses, pectins, hydrocolloids (gums, mucilages, β-glucans), resistant oligosaccharides – fructo-oligosaccharides (FOS), galactooligosaccharides (GOS), other resistant oligosaccharides, resistant starch. The chemical classification of fibre is usually based on molecular weight and monomer composition. The main groups are resistant oligosaccharides (3–10 monomers) which include galactooligosaccharides (GOS) fructooligosaccharides (FOS) and fructans, and non-starch polysaccharides (11 or more monomers), e.g. cellulose, hemicellulose, gums, pectin, mucilage, inulin, psyllium and β-glucan and resistant starch (RS) (Fuller et al., 2016; Hijová et al., 2019). Inulin,

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https://doi.org/10.1016/j.carbpol.2024.121918
Received 8 November 2023; Received in revised form 2 February 2024; Accepted 4 February 2024
Available online 6 February 2024

oligofructose or fructooligosaccharide (FOS) are the best-studied prebiotics. Inulin is a generic term to cover all linear β(2–1) fructans, with a variable degree of polymerization, and due to the presence of β(2–1) bonds, it is not digestible by intestinal digestive enzymes and reaches the colon intact, where it is fermented by colon bacteria. Different types of food can be converted into healthier forms by incorporating functional ingredients supplying beneficial effects in addition to the nutritional components (Verma & Banerjee, 2010). Fortified foods positively influence specific biological functions, improve the general state of health, and prevent the risk of suffering from certain diseases, as well as being sources of nutrients (Bhanja et al., 2022; Pathania & Kaur, 2022). The addition of dietary fibre in meat (Illippangama et al., 2022), dairy products (Khorshidian et al., 2018), chocolate products, and cereal products such as baked goods (Ranasinghe et al., 2022) and pasta (Melilli et al., 2020) has increased. Vegetable fibre is used in the food industry, due to its potential to inhibit tumor growth, especially in the breast and colon, and thanks to their beneficial effects on glucose and lipid metabolism, reduce the risk of cardiovascular disease and obesity (Barclay et al., 2016; Hathwar et al., 2012; Rastall & Gibson, 2015; Shoaib et al., 2016; Watson et al., 2019). Dietary fibre has shown a positive impact on diabetic patients. It absorbs glucose, preventing its massive release into the bloodstream, thus reducing the glycemic and insulin index. The studies carried out have highlighted an inverse relationship between dietary fibre, insulin resistance and the appearance of metabolic syndromes and type 2 diabetes (McKeown et al., 2004). Enrichment of dietary fibre in bakery products, also influenced rheological properties and cooking performance (Talukder, 2015). In this review, an overview of the effects of food fortification with inulin, its composition and its activity on the colonic microbiota will be presented.

2. Fructans: origin and structure

Fructans are considered a soluble fibre and can be linear, cyclic, or branched molecules. They belong to the family of oligo- and polysaccharides consisting of chains of fructose units linked via β (2 → 1) bonds with a single D-glucosyl unit at the non-reducing end (Panchev et al., 2011). They are reserve products of plants and are found as carbohydrate stores in tubers, bulbs, roots and leaves of plants (Ahmed & Rashid, 2019; Rubel et al., 2021). The presence and distribution of fructans in plants is related to the species, their growth stage and environmental conditions (Branca et al., 2022; Kiss & Forgo, 2011; Raccuia & Melilli, 2010). There are two structural forms of fructans in nature, namely levans and inulin (Mudannayake et al., 2022). Levans have β-(2,6) linkages between fructofuranosyl units and branching at the β-(2,1) position while inulin has β-(2,1) linkages between fructofuranosyl units and branching at the β-(2, 6) location. Recently, five types of fructans with different structures have been described: inulin-type fructans (1-kestose), levan-type fructans (6-kestose), fructans of the inulin neoseries (neokestose), mixed-type levans (bifurcose) and fructans of the levan neoseries also called mixed-type levans (mixed-type F3 fructans) (Apolinário et al., 2014). They are selectively fermented by a limited number of bacteria in the large intestine, especially Bifidobacteria, which are rather sensitive to fructans degree of polymerization (Scott et al., 2014).

Inulin, which is used today as a functional ingredient (Afoakwah et al., 2015; Ahmed & Rashid, 2019), is distributed in >36,000 vegetables and herbs (Kokubun et al., 2018). It is obtained mainly from different parts of plants (bulbs, roots and tubers) belonging to the Asteraceae family, such as burdock roots (Mudannayake et al., 2022), chicory roots (*Cichorium intybus* L.), with inulin content of 11–20 g/100 g (Barkhatova et al., 2015; Shoaib et al., 2016), dahlia tubers (*Dahlia pinnata* Cav.) with an inulin content of 10–12 g/100 g (Diederichsen, 2010), (Shoaib et al., 2016), *Cynara cardunculus* roots containing 80 g/100 g (Raccuia et al., 2005; Melilli, Branca, et al., 2020), yacon (Scandurra et al., 2022) and Jerusalem artichoke tubers (*Helianthus tuberosus* L.) containing 10–22 g/100 g (Barclay et al., 2016; Barkhatova et al., 2015; Gupta & Chaturvedi, 2020; Rubel et al., 2021; Shoaib et al., 2016).

Inulin is not degraded by human digestive enzymes, and several beneficial physiological effects have been identified (Bach et al., 2013; Causey et al., 2000; Li et al., 2013), such as prebiotic activity (Biedrzycka & Bielecka, 2004; Ramnani et al., 2010; Taper & Roberfroid, 2002). Inulin is classified as soluble dietary fibre and is included in the total dietary fibre content, with a daily intake value ranging from 1 to 15 g/day (Bonnema et al., 2010; Judprasong et al., 2011; Khuenpet et al., 2017; Ripoll et al., 2010). It is necessary to avoid exceeding the recommended doses of dietary fibre, because it can lead to intestinal disorders or flatulence resulting from microbial fermentation in the intestine (Hiel et al., 2019).

Inulin-type fructans are also functional food ingredients, with various applications including pharmaceuticals and food (Barclay et al., 2016). Inulin has been identified as a safe and important substance by the Food and Drug Administration (FDA) thanks to its numerous properties such as biodegradability, high molecular flexibility, easy availability, biocompatibility, non-reactogenicity, and non-toxicity (Afinjuomo et al., 2019; Usman et al., 2021). The extraction of inulin from plant raw materials involves two methods; first, the extraction of the raw syrup and subsequent purification (Raccuia & Melilli, 2010). More modern methods that lead to a purified final product with a higher inulin yield and lower energy consumption employ advanced technologies such as ultrasound, supercritical carbon dioxide, pulsed electric field and simultaneous ultrasound/microwave (Popoola-Akinola et al., 2022; Lou et al., 2009).

A specific group of carbohydrates (FODMAPs, an acronym for Fermentable Oligosaccharides Disaccharides Monosaccharides And Polyols) is insufficiently absorbed by the intestine and is rapidly fermented by the microbiota with the production of gas and endoluminal osmotic water accumulation. FODMAPs are short-chain dietary carbohydrates and consist of galactooligosaccharides such as raffinose and stachyose, fructans such as inulin, lactose and polyols such as sorbitol and mannitol, which are mainly present in cereals, vegetables, fruits and dairy products (Ispiryan et al., 2020; Murray et al., 2014).

Foods such as onions, garlic, Jerusalem artichokes, legumes, apples and pears represent the main source of FODMAPs. Wheat and wheat-based products, although they have a low FODMAPs content, represent the main source of supply due to their high daily consumption (Fraberger et al., 2018; Muir et al., 2009; Verspreet et al., 2015).

FODMAPs have simultaneously been associated with beneficial and negative health effects. FODMAPs such as fructans are insufficiently absorbed by the intestine and are rapidly fermented by the microbiota with the production of gas and endoluminal osmotic water. Consequently, they can trigger symptoms of irritable bowel syndrome (IBS) such as bloating, diarrhea, constipation and abdominal pain in some individuals due to the production of gas through the fermentation of FODMAPs by gut bacteria (De Giorgio et al., 2016). Among the beneficial effects of β-fructan fibre on the entire microbiota is the production of SCFAs (short-chain fatty acids, including acetate, propionate, butyrate). Data from the literature have linked intestinal acetate levels with the secretion of inflammatory factors such as THP-1 macrophages of IL-1 β. Conversely, propionate and butyrate were negatively correlated with the secretion of IL-1 β by THP-1 macrophages in response to FOS fermentation. The amount of fibre remaining in the intestinal fermentation supernatants was also assessed, demonstrating almost complete degradation of inulin (Armstrong et al., 2023). Due to recent studies carried out on FODMAPs, it was essential to produce foods enriched with low FODMAPs dietary fibre ingredients.

3. Degree of polymerization of fructans

Inulin-type fructans are divided into two classes as fructooligosaccharides (FOS) and inulin, based on their degree of polymerization (DP) The degree of polymerization of FOS and inulin ranges from 3 to 10 (low DP) and 11 to 65 (high DP) respectively (Kumar et al., 2016)

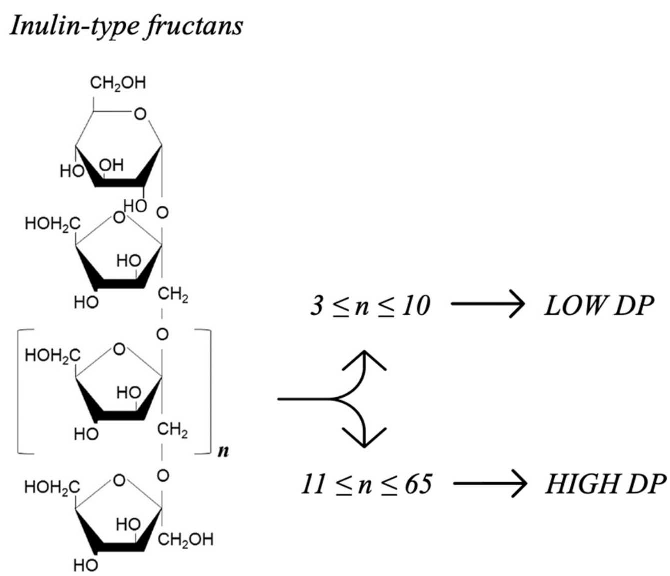

Fig. 1. Different degrees of polymerization of inulin-type fructans.

(Fig. 1) influence the functionality of inulin including solubility, thermostability, and prebiotic activity. Inulin with a low degree of polymerization (3−10) is usually fermented quickly in the proximal colon, and has a higher solubility and sweetness (Singh et al., 2020). Inulin with long DP (about 60 fructose units), found in *Cynara cardunculus* roots (Raccuia & Melilli, 2010), is more thermostable resistant to intestinal fermentation, and more viscous compared to low polymerization. More branched and long DP inulin polymers tend to form three-dimensional gels in water with a creamy white structure and a spreadable, fat-like consistency (Fu et al., 2019). The physicochemical and functional properties and industrial application of inulin depend on its degree of polymerization. Short-chain inulin (DP $<$ 10) has been used mainly as a low-calorie sweetener, long-chain inulin (DP $>$ 23) being less soluble, leads to more viscous suspensions and is used to improve rheological properties and sensory aspects of food products, for example, it has been used as a fat substitute in reduced-fat products (Özer, 2019).

4. Chemical structure and prebiotic effects of inulin

Inulin polysaccharides, due to the β-configurations of anomeric C2 in fructose monomers, are considered non-digestible carbohydrates (not breakable by human digestive enzymes). Inulin-type fructans are modified by the intestinal microbiota in the final portion of the ileum, improving the functionality of the digestive system, and preventing metabolic syndromes, inflammatory diseases, and infections by stimulating the immune system (Man et al., 2021). The addition of inulin to the diet has shown immunomodulatory effects for the prevention of metabolic disorders (Fernandes et al., 2017). Inulin-type fructans reduce energy intake and induce the production of interleukin (IL)-22 (Zou et al., 2018), reduce the absorption of carbohydrates and lipids at the gastrointestinal level (Kumar et al., 2016), decrease glucose and insulin tolerance (van der Beek et al., 2018), blood pressure (Hess et al., 2020) and serum plasminogen activator-1 (Parnell et al., 2017). Melilli, Pagliaro, et al. (2020) showed in their studies that long-chain inulin has pronounced beneficial effects on the colonic microbiota.

Inulin can also regulate and improve the structure of the intestinal microbiota, stimulate the proliferation of beneficial bacteria and reduce harmful ones, with a positive effect on intestinal health and anti-inflammatory action. Similarly, inulin is fermented to produce SCFA by colonic bacteria to maintain intestinal homeostasis (Tawfick et al., 2022). The modulation of the intestine by the microflora can lead to various beneficial effects, such as resistance to human pathogenic bacteria, reduction of the risk of cancer and decrease in the concentration of ammonia and blood lipids (Popoola-Akinola et al., 2022).

A study reported by Hughes et al. suggests that inulin-type fructans have a prebiotic and bifidogenic effect on the intestinal microbiota and promote the growth and activity of other bacteria such as *Bifidobacterium, Lactobacillus* and *Faecalibacterium prausnitzii*. These effects on the gut microbiota contribute to human health benefits, and they are based on improved intestinal barrier function, improved laxation, increased insulin sensitivity, decreased blood triglycerides and an improved lipid profile, improved absorption of calcium and magnesium and a greater feeling of satiety and increased insulin sensitivity (Hughes et al., 2022). The gastrointestinal microbiota is important for the growth and functioning of the immune system and modulates inflammatory processes both in situ and systemically through intestinal permeability and through the action on dendritic cells and T and B immune cells (Blander et al., 2017; Kelly & Mulder, 2012). It has been studied as insulin-type fructans, they reduce intestinal and systemic inflammation by increasing the production of SCFA and the abundance of *Bifidobacterium* and *Lactobacillus* (Hughes et al., 2022). Parnell et al. (2017) showed a decrease in the proinflammatory plasminogen activator inhibitor-1 (PAI-1), positively associated with inflammatory states and insulin resistance, following the consumption of oligofructose (21 g/day).

5. Application of inulin in the food industry

Nowadays, there is a growing demand for inulin due to its extensive use in food fortification and the production of beverages, dietary supplements, animal feeds and pharmaceuticals. The interest in inulin as a functional food is increasing due to its potential beneficial effect on human health mainly related to the degree of polymerization and ramifications (Melilli, Pagliaro, et al., 2020; Garbetta et al., 2020). Inulin is widely applied in the food industry today: it has been used as a low-calorie sweetener, fat replacer in dairy products, non-digestible fibre and prebiotic (Melilli et al., 2021; Melilli, Branca, et al., 2020; Mensink et al., 2015). In addition to its beneficial nutritional effects, inulin can be used as a rheological modifier in food formulation due to its very good water holding capacity, due to its white color and characteristic powder similar to flour or starch and good gel consistency properties (Gao et al., 2016; Kuntz et al., 2013).

Since inulin provides about 30–50 % of the sweetening power of sucrose and above all has a lower caloric value (1–2 kcal/g), it can be used as a substitute or in combination with other sweeteners (such as aspartame and acesulfame) in food products (Ahmed & Rashid, 2019). It has also been demonstrated that the addition of inulin in bakery products allows not only the replacement of sugar but also an increase in the fibre content and an improvement in rheological properties. Highly polymerized inulin can be used in food products to improve organoleptic and rheological characteristics, such as the stability of foams and emulsions. In particular, it has been highlighted that inulin deriving from Jerusalem artichoke can be used as a bioactive ingredient in dairy products (yogurt and cheese), baked products (cakes, biscuits, and bread), sausages and drinks (Alibekov et al., 2021; Gupta & Chaturvedi, 2020; Khuenpet et al., 2017). Inulin has also been included in sweets to define them as “high fibre” products for the prevention of dysphagia. The fortified products provided greater firmness, flexibility, consistency and cohesion than any hydrocolloid used, evidenced by the back extrusion test (Cartagena et al., 2024).

The rheological properties of some inulin-fortified baked goods have been studied. According to some studies, fortification of durum wheat flour with inulin can prolong stability time and quality and decrease water absorption and bread volume. Poinot et al. (2010) found that inulin could reduce bread baking time without any impact on quality and Gallagher et al. (2003) studied the inclusion of inulin in the biscuit dough and found an improvement in the quality and shelf life of the biscuits. Biscuits fortified with Jerusalem artichoke powder showed a high acceptability rate, with a lower energy content than traditional biscuits made from wheat flour (Díaz et al., 2019). Krystyjan et al. (2015) highlighted that the addition of 10 % inulin could cause visco-elastic changes in doughs. He et al. (2015) evaluated the degree of recrystallization of starch during the cooling process of starch paste, especially the recrystallization and rearrangement level of amylose molecules. This phenomenon could be related to the presence of small sugars in inulin, which positively influence the inhibition of starch retrogradation or the formation of a layer around the starch particles, which limits the rearrangement molecular structure of the amylose in the dough. According to Luo et al. (2017), retrogradation of starch depends on the degree of recrystallization of amylopectin. Their study shows that retrogradation enthalpy values decreased with the addition of inulin, probably due to the presence mainly of sugars with lower molecular weights, such as fructose, sucrose and trehalose, which can delay retrogradation and recrystallization of the starch.

Meat, an essential food for human nutrition, has a high fat and protein content. To make it a less harmful substance, functional ingredient, such as indigestible polysaccharides, can be added in meat products such as burgers (Bis-Souza et al., 2018; El Zeny et al., 2019), sausages (Berizi et al., 2017; Choi et al., 2016; de Souza Paglarini et al., 2021; Ferjančič et al., 2021; Glisic et al., 2019; Keenan et al., 2014; Méndez-Zamora et al., 2015; Prapasuwannakul, 2018), ham (dos Santos Silva et al., 2019), patties (Guedes-Oliveira et al., 2019) and minced meat (Furlán et al., 2014). Inulin in meat products helps retain water, reduce cooking losses and maintain juiciness. One factor that reduces the shelf life and quality of meat is lipid rancidity, caused by a high amount of unsaturated fatty acids and oxidizing agents present in meat. Meat processing also accelerates the lipid oxidation process by releasing membrane phospholipids. This problem can be reduced by the addition of indigestible antioxidant polysaccharides, complex parts of polysaccharides linked together by a β-1,4-glycosidic bond that cannot be digested by humans, that include lignocellulose (cellulose, hemicellulose, lignin, and pectin), dietary fibre (gum, resistant starch, agar) and inulin (Popoola-Akinola et al., 2022). Furthermore, an improvement in water and oil retention, emulsion stabilization and an increase in antimicrobial and anti-inflammatory activities in meat was highlighted thanks to the addition of dietary fibre from plant by-products (Goñi & Hervert-Hernández, 2011).

Non-digestible polysaccharides can also be exploited for the fortification of dairy products as prebiotics (non-vital constituents of foods metabolized by gastrointestinal bacteria modulating the well-being of the human intestine). A study was conducted on the fortification of powdered milk with inulin and dextrin which was seen to improve blood risk factors in diabetic patients such as glycemic control and insulin resistance, but also reduce blood pressure (Cao et al., 2021). The degree of polymerization influences the properties of dairy products such as sweetness, prebiotic activities and degree of digestibility (Olawoye et al., 2020). Pimentel et al. (2013) added inulin to low-fat yogurt as a fat substitute and observed the presence of microcrystals that formed a pleasant and creamy consistency, better than full-fat yogurt. The suitability of long-chain inulin as a fat substitute in dairy products is due to its stability, lower solubility and high viscosity compared to native inulin. Babenyshev et al. (2020) applied Jerusalem artichoke extract in the purification process of cheese whey to reduce the protein content; polysaccharides can complex proteins and separate them by sedimentation as an alternative method to ultrafiltration. Guo et al. (2018) indicated that Jerusalem artichoke powder improved the nutritional value but also the sensory characteristics and microbial counts of low-fat yogurt. The addition of Jerusalem artichoke powder favored the growth of lactic acid bacteria and probiotic cultures in yogurt and fermented milk, respectively increasing the viscosity and antioxidant activity compared to the control sample (Amal, 2009; Kusuma et al., 2009; Park et al., 2019). Alibekov et al. (2021) produced ricotta fortified with inulin derived from the artichoke which presented acceptable physico-chemical properties, both in terms of consistency, color and smell, with a delicate taste. Guimarães et al. added inulin with different degrees of polymerization to prebiotic whey-based drinks. It has been highlighted that the higher the degree of polymerization of inulin, the greater the physical stability of the drink (Guimarães et al., 2018). In addition to the prebiotic action of indigestible polysaccharides, they can be added to dairy products to modify the technological characteristics of the food. De Castro et al. (2009) have studied a modification of the rheological properties (pseudoplastic behavior and consistency index) of whole fermented milk added to non-digestible fibres. A decrease in milk viscosity has been highlighted due to a lower hydrodynamic volume of milk proteins. Fortification of dairy products with fibre is also important to extend shelf life due to increased water absorption (Mohamed et al., 2014).

In the recent years, hydrophobically modified inulin (HMI) and the properties of short-chain fatty acids (SCFAs) inulin esters have gained attention due to their features. HMI has been used to stabilize real food dispersion formulations, which have been observed to be safe because inulin is generally recognized as safe (GRAS), while the SCFAs inulin esters, can regulate the human gut microbiota and increase the biological half-life of SCFAs in the human body, due to the biotransformation of beneficial metabolites and increase the beneficial metabolites in the gut microbiota (Usman et al., 2021).

6. Health based evidence for functional bread fortified with inulin with different DP

Breadmaking is a dynamic process with continuous physicochemical, microbiological and biochemical changes induced by the mechanical–thermal action and the activity of the yeast and lactic acid bacteria together with the activity of the endogenous enzymes. Mixing involves mechanically and hydration-induced alterations, whereas during proofing, enzymes are mainly implicated and changes related to temperature increase occur during baking. Starch and proteins, undergo the most dramatic changes during the breadmaking process. The gluten proteins are largely responsible for the rheology of wheat flour dough, structural formation during mixing and gas holding, whereas the role of starch is mainly implicated in final textural properties and product stability after baking (Rosell, 2016).

In the baking sector and the production of cereal-based foods, fibre, and in particular inulin, has become a reality as a functional ingredient to be added, with a prebiotic effect widely used especially in the production of bread (Ktenioudaki & Gallagher, 2012). The inclusion of inulin as soluble dietary fibres needs to be studied. Since the technological properties of bread, which are crucial for consumer acceptance, are highly influenced by the formulation, the effects of inulin on the technological properties of bread are a crucial step. Furthermore, since inulin's health-promoting effects are attributed to its regular and specific consumption in intact form, the factors affecting its stability during bread processing needs to be investigated.

Already 20 years ago, Morris and Morris (2012) revised the literature about the effect of inulin and fructo-oligosaccharide (FOS) supplementation on the textural, rheological and sensory properties of bread. Table 1 reports the main impact of inulin or FOS fortification in bread on dough rheology and bread quality as determined instrumentally and from the sensory point of view.

It was found that the effect of inulin/FOS substitution on the textural and sensory properties depended on the type of prebiotic added, flour type, substitution level, degree of polymerization and prebiotic addition (e.g., powder or gel). In all cases, technical challenges were apparent in terms of dough machinability resulting in end product quality slightly lower than that of the control. The main inulin/FOS impacts reported were lower bread loaf volumes, increased crumb hardness and darker crust. On the contrary, inulin appears to integrate well into the gluten network, it also dilutes it resulting in lower gas retention ability. A darker color and increase in aroma compounds characteristic of the Maillard reaction were attributed to a larger number of reducing ends.

Table 1
Summary of published results on the impact of inulin or fructo-oligosaccharide (FOS) fortification in bread on dough rheology and bread quality as determined instrumentally and sensorally [modified from Morris and Morris (2012)].

	Collar et al. (2007)	Rosell et al. (2010)	Filipovic et al. (2010)	Poinot et al. (2010)	Meyer and Peters (2009)	Karolini-Skaradzinska et al. (2007)	Mandala et al. (2009)	O'brien et al. (2003)	Peressini and Sensidoni (2009)	Korus et al. (2006)	Mujoo and Ng (2003)	Frutos et al. (2008)	Praznik et al. (2002)	Wang et al. (2002)	Hager et al. (2011)	Brasil et al. (2011)
	a	a	a	a	a	a	a	b	a	b	d	e	e	a	a	b
Doughts																
Water absorption		−			−	−		−/=	−					−	−	
Dough development						+			+					=		
Dough stability		=	−		+	+			+					+		
Resistance to deform.	=					+/−								+		
Elasticity									+					−	−	
Extensibility	=					=/+								=		
Stickiness	=															
Breads																
Loaf volume			=/−		−	−	=/−	=/−	−	+*	−	−	=/+	−	=	−
Yield of bread							+			=/+*			+			
Moisture content							=/+		−			+	=/+	−	−	=/+
Hardness–firmness				+			+	+	+	−*	+	+		+	+	
Cohesiveness										−*		−		=		
Springiness										−*				=		
Chewiness												+		=		
Elasticity							+					+				
Color				+			=		+	+*		+			+	
Loaf volume			=/−		−	−	=/−	=/−	−	+*	−	−	=/+	−	=	−
Sensory																
Score cards			=/−							=/−*			=/−			=/−
Consumer acceptance												=/−				

* Compared to gluten free bread. (+): increase in parameter with the addition of prebiotic. For color, (+): darker color. For dough development and stability: (+) longer times. (=): no significant difference reported. (−): decrease in parameter with addition of prebiotic. For water absorption, (−): water absorption decreased with inulin addition. a Breads made with added inulin; b Inulin added as fat replacer; c Inulin or FOS added in gluten free bread; d Bread made with immature wheat meal rich in fructo-oligosaccharides: e Breads made with artichoke fibres.

Those, in turn, may be partly due to inulin/FOS degradation upon baking as there is evidence that both yeast invertase and dry heat degrade inulin.

However, the stability of inulin depends on the components of the formulation, the type of fermentation and the cooking process. In various works, the addition of inulin to bread and bakery products has been evaluated. In Franck's work (Franck, 2002) the role of inulin and oligofructose is highlighted, which can be used both for their nutritional and technological properties and better organoleptic quality. The use of these as a fibre supplement can in fact lead to better taste and rheological characteristics (Franck & Coussement, 1997). If also added to baked goods and cereals, it can represent not only a significant supplement compared to classic dietary fibre, but can also give greater crunchiness to snacks and increase their shelf life, also acting as prebiotic ingredients that stimulate the growth of beneficial intestinal bacteria (Walter, 1999). Furthermore, the addition of inulin to baked products allows for the replacement of sugar and the enrichment of fibre.

When a food product is fortified with fibre, it extends the duration of its palatability and its shelf-life; furthermore, bread rich in fibre is excellent for marketing as it has important nutritional functions. Fibre-rich products, such as wheat or oat bran, have been used to replace wheat flour in bread making (Popoola-Akinola et al., 2022). One of the key reasons for supplementing with dietary fibre is that it produces a wide variety of flavors making products more palatable (Olawoye & Gbadamosi, 2020a; Olawoye & Gbadamosi, 2020b).

Therefore, inulin is also an ideal ingredient to produce low-calorie foods. Also, Mohammadi et al. (2023) studied the incorporation of inulin in bread. Also, in their work, the addition of inulin to bread improved its technological properties, both in classic and gluten-free bread. Considering the importance of bread in human nutrition and the need for its fortification to reduce and limit the use of gluten, they wanted to study the inclusion of inulin as soluble dietary fibre. The effects of inulin replacement in bread formulation, such as texture and color, specific volume, water absorption, and stale point, were analyzed. They highlighted the characteristic of inulin-type fructans of reducing staleness and maintaining the freshness of gluten-free and gluten-containing bread thanks to their hydrophilic properties; it can prevent the formation and recrystallization of ice crystals and avoid damaging the proteins during the dough-freezing process. They showed increased stability of long-chain inulin, probably attributed to the presence of simple sugars and low pH. Another study was carried out by Kou et al. (2019) to analyze the effects of inulin with different degrees of polymerization on the properties of steamed bread made from soft flour. Here too, the type and level of inulin replacement had a significant impact on the quality of the steamed bread. The addition of inulin contributed to the softness and delicious taste and increased the staling rate of fresh steamed bread by interacting with starch via hydrogen bonds and altering the distribution of water between proteins and starch. The addition of inulin significantly increased the height and specific volume of steamed bread, and decreased its hardness, cohesion, and chewiness, but had no significant influence on elasticity. It also influenced the color, which was lighter, and the consistency was softer.

Many studies have recently focused on gluten-free or low-gluten foods. In the work of Morreale et al. (2019), the ability of inulin to improve the nutritional quality of gluten-free bread and perform prebiotic activity in breads produced with rice flour and fortified with 10 % inulin was studied. Furthermore, dietary fibre such as fructans can also lead to some technological advantages in gluten-free baking, due to their hydrocolloid properties. In particular, previous studies have investigated how the addition of inulin can increase water retention and volume of bread and reduce the hardness of the crumb of gluten-free bread. However, the result of the study highlighted how low DP inulin is partially degraded during the process, which affects both the final fructan content in the bread and the potential structuring capacity during bread making. This decrease may be caused by the use of yeast with normal invertase activity. It is therefore advisable to use yeast with low invertase activity to effectively enrich gluten-free bread with inulin, but particular attention should be paid to the selection of the type of inulin due to its influence on the technological properties of bread. A final inulin content of 3 % was highlighted in the loaves initially fortified at 3 %.

Another aspect that has been evaluated following the enrichment of bread and baked goods with inulin is the final volume. In several works the addition of this fibre led to a decrease in the volume of bread (Meyer & Peters, 2009; O'brien et al., 2003). In the work of Brasil et al. (2011), when 6 % or 10 % inulin was added as a fat substitute, a significant decrease in bread volume was observed. An addition of 3 % inulin from chicory to bread resulted in a notable decrease in bread volume: 906–733 ml (Wang et al., 2002). The addition of 1–4 % inulin led to a progressive decrease in bread volume (Karolini-Skaradzinska et al., 2007). Another important aspect is the water content and humidity rate, which contribute to the technological and rheological characteristics of baked products, including the hardness of the product (He & Hoseney, 1990). In the work of Wang et al. (2002) the hardness of the crumb measured by TPA (Texture Profile Analysis) was increased by the addition of 3 % inulin in bread and confirmed for bread prepared with 3 % and 5 % of inulin from Poinot et al. (2010). Bread containing inulin has been described (Mandala et al., 2009) as having "an elastic crumb, a soft crust and a relatively low specific volume". In the work of Mandala et al., however, no significant difference in crust color was observed due to the addition of 3 % inulin; the moisture content in the center of the crumb was also assessed and found to be the same as the control bread, although the inulin bread had a wetter outer layer. The addition of fibre also reported a change in color of the final product. In fact, a darker color of the rind was highlighted for all levels of addition (2.5 %; 5 %; 7.5 % and 10 %) and for two types of inulin (Hager et al., 2011; Poinot et al., 2010). Darker colors and an increase in crumb hardness (TPA) were reported by Frutos et al., which prepared a bread with the addition of 3–12 % artichoke fibre which increased moisture content and was explained by a greater number of reducing ends involved in a Maillard reaction (Frutos et al., 2008). An increase in crumb moisture has also been reported for bread prepared with 8 % and 10 % fructo-oligosaccharides (Raftilose P95) (Praznik et al., 2002).

The type of inulin is critical in the resulting hardness, with a greater increase observed with long-chain than short-chain inulin in bread. The shorter chain inulin therefore appears to have an even darker color since they have more low molecular weight fructans (Peressini & Sensidoni, 2009). Praznik et al. (2002) fortified wheat and rye bread with Jerusalem artichoke powder and studied how the loss of fructan content by hydrolysis during dough development and the baking process depends on the degree of polymerization: bread prepared with low DP inulin had a higher fructose content than bread formulated with high DP inulin. Radovanovic et al. (2014) also developed wheat bread fortified with Jerusalem artichoke powder and highlighted optimal nutritional and caloric values, with a low glycemic index.

Melilli et al. reported the possibility of obtaining bread from quinoa flour, added by inulin, to improve the rheological characteristics of quinoa doughs. Flours were obtained from two quinoa cultivars "Titicaca" and "Puno", added with 2.5 % of inulin (high DP ≤100) extracted and purified from roots of *Cynara cardunculus* and, compared with flours added with 2.5 % of commercial inulin (low DP <20). The farinographic and alveographic parameters of doughs were measured against a control. The dough enriched with high DP inulin has the highest development time but also the highest stability compared to the control and the dough with low DP inulin. The addition of both types of inulin resulted in a decrease in the tenacity of the dough. "L" (extensibility of the dough) by adding low DP inulin did not change, while significant differences were found in the doughs added with inulin extracted from *Cynara cardunculus*, improving the curves obtained during alveograph analyses. This study showed a general improvement of the farinographic and alveographic indices due to the addition of high DP inulin to the quinoa flours. These first results gave useful information to improve/develop new quality products for celiac consumers, considering the enrichment of quinoa doughs with higher concentrations of high DP inulin from cardoon, or mixing quinoa with other gluten-free flours (Melilli et al., 2019).

7. Effect of different DP on technological and nutritional characteristics of Inulin enriched pasta

Pasta has a primary role in human nutrition, thanks to its complex carbohydrate content. It is a staple food eaten daily or weekly that constitutes a dominant moiety of the diet in many countries. Furthermore, dried pasta is a convenient product with a long shelf-life that can well preserve the phytochemicals present for a long period (Oliviero & Fogliano, 2016). Despite being considered a traditional product, pasta (and the pasta sector in a broader sense) has been able to evolve over the years to meet the needs of the market that has expanded from Italy throughout the world through the improvement of production efficiency, on the one hand, and the enhancement of product quality from hygienic, sensory and nutritional and nutraceuticals stand points on the other.

The healthy effect of inulin could be combined with low glycemic food to obtain functional food. Among cereal-based products, due to its compact structure characterized by a very dense protein network that traps the starch granules and protects them from the hydrolytic activity of digestive enzymes, pasta is defined as a low or medium glycemic index food. The slow digestion of pasta induces a gradual increase in blood glucose levels and a consequent slow release of insulin; these potential beneficial effects are particularly appreciated for the health of both healthy and diabetic consumers (Augustin et al., 2002; Brennan & Tudorica, 2008; Foschia et al., 2015).

In this context, the healthy effect of inulin could be combined with the low glycemic value of pasta to obtain a functional food, because the starch-inulin interactions could further slowdown starch digestion and thus lower the glycemic response.

Several studies have shown that enrichment with inulin modifies the structure of pasta, compromising its acceptability by consumers and its nutritional aspects (Bustos et al., 2011; Padalino et al., 2017), and partially reviewed by Yazici et al. (2023). In general, pasta produced with inulin addition concerns mainly durum wheat semolina, while very few works reported data obtained with whole or semi-whole semolina.

The first paper analyzing the chemical and sensorial properties of spaghetti made from whole durum wheat semolina added with inulin at different degrees of polymerization (extracted from cardoon roots with a high DP <100 and chicory with a low DP <20) (Fig. 2) at two different concentrations (2–4 %) was conducted by Padalino et al. (2017) in a pasta pilot plant.

In general, the increase in the quantity of inulin resulted in a decline in sensorial quality even if the molecular weight of inulin played a key role on the acceptability of the pasta. This effect can be directly ascribed to the probable entanglements created by the high molecular weight inulin which generally improved the characteristics of the pasta. Regarding the chemical composition, the sample enriched with 4 % cardoon inulin showed a higher total dietary fibre content and a lower content of available carbohydrates compared to control samples. Furthermore, starch digestibility decreases significantly with increased inulin. Specifically, spaghetti supplemented with high DP inulin from the cardoon roots showed lower starch digestibility than samples with low DP inulin from chicory. This result is attributed to the fact that chicory inulin can have a greater disintegrating effect on the starch-gluten matrix, thus compromising its cohesive encapsulating layer. In conclusion, the DP of inulin significantly influenced its interactions with the gluten matrix during the formation of the pasta and consequently, the inulin extracted from the roots of the thistle allowed to create a final

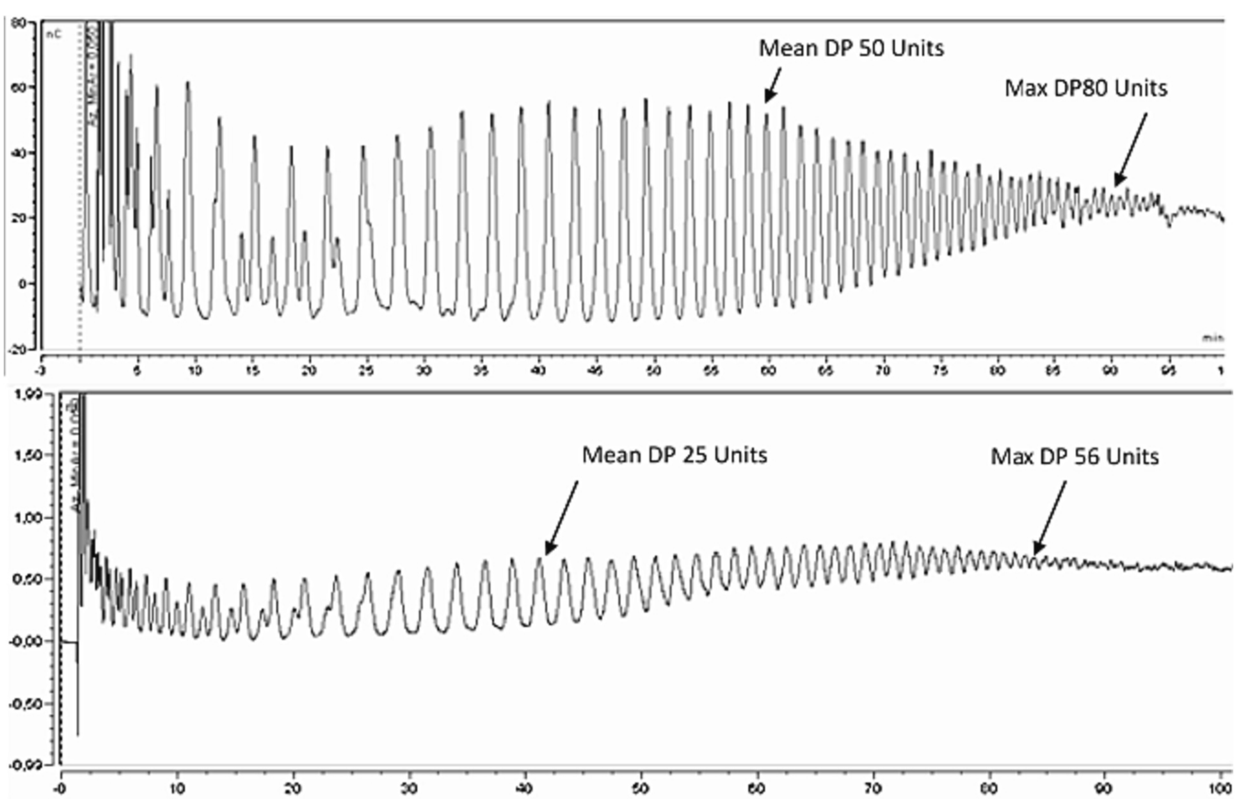

Fig. 2. - Inulin profiles from cardoon roots (CRI)(up) and from commercial inulin (CHI)(down). Solutions of both inulin have been prepared dissolving 1 g in 100 ml of hot water. Solutions have been 10 fold diluted before injection in HPAEC. Mean DP = (F − f − 0.525S)/(G − g − 0.525S) where F, G, are the total fructose and glucose after acid-hydrolysis and f, g and s the reducing free sugars fructose, glucose and sucrose before the acid-hydrolysis, respectively.

pasta that was very interesting from a nutritional point of view, and also acceptable for sensory properties and cooking quality (Padalino et al., 2017).

The work confirm data obtained by Liu et al. (2016), that investigated by scanning electron microscopy the effects of three types of inulin with different degrees of polymerization on the structure of protein component of wheat dough (gluten, gliadin and glutenin) (Fig. 3). Besides, Luo et al. (2017) observed that the gelatinization and retrogradation properties of wheat starch were largely dependent on degree of polymerization and inulin content.

Another work, the effects of the different DPs and 4 wholemeal durum wheat cultivars on the quality, chemical composition and glycemic index (GI) of spaghetti were studied (Garbetta et al., 2020). Four ancient Sicilian durum wheat cultivars were used to produce inulin-enriched spaghetti. In particular, 4 % inulin with two different DPs was used, inulin from cardoon roots with a high DP and commercial inulin from chicory with a low DP. Inulin enrichment produced spaghetti characterized by an OQS (Overall Quality Score) value within the acceptability threshold (>5) and higher for spaghetti fortified with higher DP inulin. Among the cultivars, Timilia was the one that maintained the OQS scores after the addition of inulin. Inulin cooking loss in spaghetti samples was mainly related to the durum wheat cultivars used with an increase in chicory inulin-enriched spaghetti compared to the control sample. Instead, the DP did not affect the inulin amount in the cultivar considered and the glycemic index values of cooked spaghetti, with the exception of cv. Timilia. Timilia spaghetti enriched with 4 % cardoon inulin showed a significant reduction in the glycemic index value compared to control pasta. Furthermore, the results have shown that there is an effect of DP on inulin release during digestion process regardless the cultivar of wholemeal durum wheat used. In the digestive tract, the release of low DP inulin in aqueous fraction was higher than high DP inulin in all the cultivars studied, while the in the solid fraction of the digested spaghetti a greater quantity of cardoon inulin was detected, thus making a greater amount of this soluble fibre available for fermentation by the intestinal microflora. In summary, the sensory characteristics of pasta were influenced by the molecular weight of inulin and its interactions with the gluten matrix during pasta. The effects of the different inulin DPs on the technological properties of spaghetti were also influenced by the choice of durum wheat cultivars. The development of pasta produced using ancient Sicilian whole grains and enriched with a high dietary fibre content would be a good way to increase fibre intake and reduce the glycemic index of pasta and the development of gluten sensitivity (Garbetta et al., 2020).

Further research, using higher percentage of long DP inulin substitution (8 %), extracted from *Cynara cardunculus* roots and *Helianthus tuberosus* L (topinambur) tubers, compared with low DP inulin from *Chicory intybus* showed that the addition of low polymerization inulin reduced the OQS from 6.47 to 5.84 vs control (100 % durum wheat

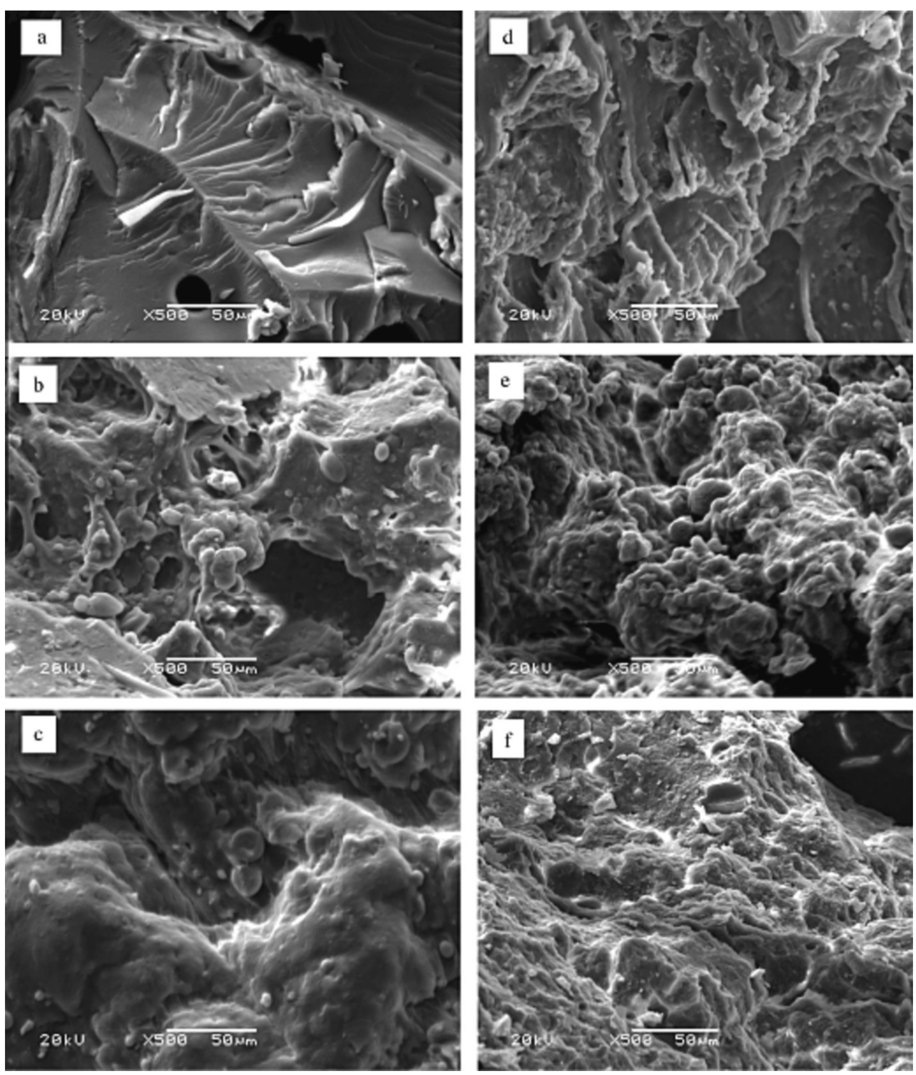

Fig. 3. - SEM images of the microstructure of proteins before and after cross-linking with inulin. (a) Gliadin, (b) glutenin, (c) gluten, (d) HPX-gliadin, (e) HPX-glutenin, (f) HPX-gluten (Liu et al., 2016).

spaghetti), while statistically no differences were recorded between control and spaghetti fortified with high polymerization inulin (6.09). Samples with high DP inulin have a higher overall quality (Fig. 3), because pasta showed a decline in adhesiveness and bulkiness as compared to the spaghetti with low DP inulin (Sillitti, 2018). The elasticity was positively influenced by the fortification of spaghetti with high polymerization inulin. The addition of inulin improved or maintained the elasticity, firmness, bulk, tack, color, odor and OQS scores (Table 2).

The cooking loss in spaghetti samples has been studied and the data obtained show an increase in cooking loss in spaghetti samples added with low DP inulin. It is possible that some of the low DP inulin may leach out of the pasta during cooking, which would contribute to cooking loss, as also reported by Roberfroid (2005) and Foschia et al. (2015).

In all the above-mentioned works, pasta were produced using a lab pilot plant and the conditions described in Padalino et al. (2017).

Data reported by Aravind et al. (2012) demonstrated that samples enriched with high molecular weight inulin (high degree of polymerization) showed no changes in swelling index, pasta water absorption, cooking loss and texture compared to control samples. Inulin with lower molecular weight (low degree of polymerization), presented a greater negative impact on pasta consistency, cooking loss and sensorial acceptability. Overall, the impact of the incorporation of higher molecular weight inulin on the technological, organoleptic and sensorial properties was minimal. Furthermore, the reduction in starch digestion caused by the incorporation of highly polymerized inulin into the pasta was due to the production of a protein-fibrous matrix as a physical barrier to the starch-degrading enzymes, therefore it is the best one for improving the glycemic index of pasta with minimal impact on the technological and sensorial properties of pasta.

Spaghetti fortified with high polymerization inulin showed a significant decrease in swelling index and water absorption compared to the control sample, probably due to the competitive activity of inulin with the starch for water when cooking pasta (Garbetta et al., 2020).

Cooking quality results may be related to the amount of fructose found in the water after the cooking process (Fig. 4). The spaghetti samples fortified with low DP inulin retained less inulin than the samples fortified with high DP inulin.

The glycemic index values for control and spaghetti enriched with 4 % inulin at different DPs have been discussed in the literature (Garbetta et al., 2020). The glycemic index values of control spaghetti ranged from 63 to 75 in relation to the whole durum wheat cultivar used for the preparation of the pasta (Garbetta et al., 2020).

In fortified spaghetti, high DP inulin significantly reduced the glycemic index value compared to control pasta with a percentage decrease of 6.6 %. Contrasting were the results of Brennan and Tudorica, who, through a laboratory assay, found that pasta enriched with different percentages of inulin with low chicory DP (from 2.5 % to 10 %) did not show a reduction in glycemic index compared to control. In the article, pasta enriched with 10 % low DP inulin induced a decrease only in the

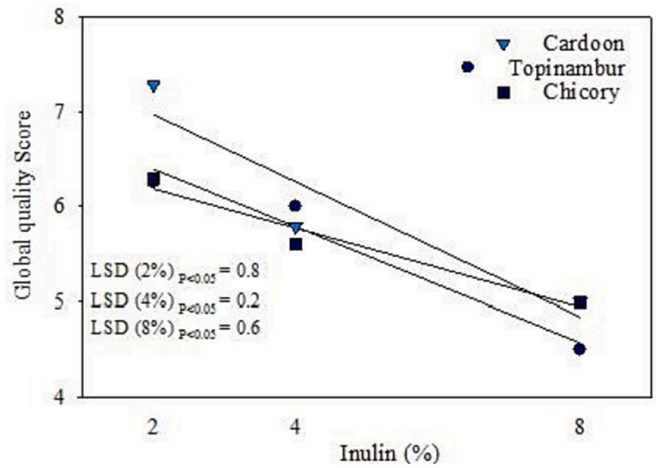

Fig. 4. Global quality score of dry spaghetti produced with different types and concentrations of inulin.

hydrolysis index values; analyzing the microstructure of inulin-enriched pasta by means of SEM micrographs, they highlighted that cooked pasta containing inulin appeared to have internal structures similar to control pasta not related to the enrichment percentage (2.5 % or 10 %) (Brennan & Tudorica, 2008). Although the overall concept of low glycemic index pasta must be contextualized with the raw materials (soft or durum wheat, refined or wholemeal, their origin), with the technological process used to produce it and with the experimental conditions (e.g. sample size, characteristics and eating patterns of the enrolled subjects and daily variability) (Di Francesco et al., 2020; Pandolfo et al., 2021).

Postprandial serum glucose upsurge control is one of the efficient means of management of postprandial hyperglycaemia, which is associated with starch hydrolases, such as amyloglucosidase and α-amylase. To lessen and control long term postprandial plasma glucose spikes, inhibition of the activities of α-amylase and amyloglucosidase can delay starch digestion, triggering reduction in the rate of glucose absorption, and consequently lessening serum glucose rise. Clinically, synthetic inhibitors are commonly used with a number of side effects such as severe gastrointestinal complications including flatulence, diarrhea distention and liver disorder. Therefore, it is urgent to discover alternative new and safer natural inhibitors. This has heightened interests focusing on natural α-amylase and amyloglucosidase inhibitors from plant source including dietary fibre, polyphenolic compounds and flavonoids and to develop new tools for α-amylase inhibition (John Nsor-Atindana et al., 2019).

Starch from pasta is digested slowly, thus reducing post-prandial glycemia, a risk factor for type 2 diabetes.

In a study by Zou et al. the role of proteinaceous amylase inhibitors contained in wheat proteins, and how these slow starch digestion was examined. Endogenous α-amylase/trypsin inhibitors play a role in

Table 2
- Sensorial properties of dry cooked spaghetti samples. Different letters indicate differences among types of pasta $P < 0.05$.

Sample	Elasticity	Firmness	Fibrous	Bulkiness	Adhesiveness	Color	Odor	Taste	Overall quality
On average of concentration									
CTRL	6.0 a	6.8 a	5.8 a	7.2 a	6.0 a	7.5 a	8.0 a	7.3 a	7.0 a
Topinambur	5.6 a	5.9 b	5.7 a	5.5 b	5.2 b	6.7 a	7.3 a	6.0 c	5.6 b
Cardoon	5.8 a	5.9 b	5.5 a	5.8 b	5.6 ab	7.2 a	7.5 a	6.5 ab	6.0 b
Chicorium	6.0 a	5.9 b	5.7 a	5.4 b	5.5 ab	6.9 a	7.4 a	6.9 ab	5.6 b
On average of plant type									
CTRL	6.0 b	6.8 a	5.8 ab	7.2 a	6.0 a	7.5 a	8.0 a	7.3 a	7.0 a
2	6.8 a	6.6 ab	6.3 a	6.0 b	5.8 a	7.2 a	7.5 a	7.0 a	6.6 a
4	5.9 b	6.1 b	5.2 b	5.8 b	5.5 a	6.8 a	7.4 a	7.0 a	5.8 b
8	4.8 c	5.1 c	5.3 b	5.0 c	4.9 b	6.8 a	7.3 a	5.4 b	4.8 c

slowing starch digestion by interacting with α-amylase as it enters the gluten network traps the starch, causing the enzyme to be immobilized on the gluten network, so that the digestion of the starch is inhibited. Furthermore, they are also able to resist denaturation at high temperatures. This study therefore demonstrates how the slow digestion of pasta is due not only to the fact that the gluten network acts as a physical barrier that inhibits the accessibility of enzymes, but also that a greater effect is due to inhibition by endogenous enzymes present in the pasta (Zou et al., 2019).

In Cardullo et al.'s work, (Cardullo et al., 2022) the effects on the inhibition of α-amylase in pasta produced using whole-meal flours of two ancient native Sicilian varieties fortified at two different substitution levels (2 and 4 %) and two type of inulin with different DP were evaluated. The potential hypoglycemic effect of pasta produced with ancient durum wheat flours and inulin was evaluated through the inhibition of α-amylase. This enzyme catalyzes the breaking of the α-(1,4)-D-glycosidic bonds of starch and glycogen, producing maltose and other oligosaccharides resulting in a rapid increase in postprandial blood glucose level (Kaur et al., 2021). Alpha-amylase inhibitors have been studied for their potential use as therapeutic agents for the treatment of diabetes and obesity; in fact, the inhibition of α-amylase can reduce the absorption of carbohydrates and therefore decrease blood sugar and body weight (Kaur et al., 2021), (Zeng et al., 2020), (Bonsu et al., 2011).

The enzymatic activity was linked to the local varieties used, and by replacing inulin in the flours, it allowed high percentages of α-amylase inhibition to be obtained, also confirming the data previously obtained on the glycemic index for spaghetti produced with wheat Timilia added from cardoon long-chain inulin (Garbetta et al., 2020), and for the starch digestibility of spaghetti supplemented with high DP inulin, which was found to be lower than that of samples with low DP inulin (Padalino et al., 2017). In particular, the in vitro results of α-amylase inhibition highlighted a reduction of the enzymatic activity in a dose-dependent manner with the presence of inulin in the pasta samples. Previous findings have highlighted that soluble fibre, such as inulin-type fructans, can have a hypoglycemic effect (Bonsu et al., 2011). The study supports these data as a lowering of α-amylase IC50 values was observed with an increase in the % of inulin contained in the pasta. Furthermore, kinetic studies have confirmed the hypoglycemic effect of fructan-based fibre.

Since non-digestible long-chain oligosaccharides are typically less (or more slowly) biodegradable than shorter-chain inulin compounds, fermentation will take longer than oligofructose fermentation, which results in greater degradation of residual carbohydrates in the compartments of the distal colon. A slower degradation of fructo-oligosaccharides with a higher DP is reflected in a degradation of oligo fructose in the more distal compartments of the colon with positive effects on the intestinal microbiota.

8. Conclusions

This review has summarized the main physiological functions of inulin, including the prebiotic effect, metabolism regulator, antioxidant, prevention of diseases (such as diabetes and obesity, constipation, celiac disease, Crohn's disease, inflammatory bowel disease, ulcerative colitis and colon cancer) and anti-inflammatory effect. In recent years, consumer awareness of the importance of diet and health has grown. For this reason, there is a growth in the demand for foods low in fat and sugar, with further beneficial effects for health. Numerous studies demonstrate the health-promoting roles played by inulin, a polysaccharide consisting of a mixture of polymers of chains of different lengths with biological and technological properties (flexibility, availability, biodegradability, biocompatibility and low toxicity).

The healthy effect of inulin on glycemic index of fortified pasta was reported. The rheological and sensory properties, glycemic index, release of inulin and inhibitory effects of the inulin on the activity of α-amylase of fortified spaghetti added with inulin at two degrees of polymerization were also evaluated. Molecular weight of inulin played a key role in the acceptability of the pasta. In fact, fortified spaghetti with inulin with a high degree of polymerization did not changes in swelling index, pasta water absorption, cooking loss and firmness compared to the control samples. The inhibition of α-amylase was studied, and this is directly proportional to the percentage of inulin substitution in the pasta samples.

In bakery products, bread processing conditions can influence the structural integrity of inulin and thus affect its technological efficiency. In general, adding inulin to bread improved its technological properties. Inulin-type fructans reduce the staling rate and maintain the freshness of gluten-free and gluten-containing bread due to their hydrophilic properties. Furthermore, the effect of formulation components, fermentation, and baking process on the stability of inulin revealed that short-chain inulin had less stability than long-chain inulin. This could be attributed to the presence of simple sugars (which are more accessible to yeasts) as well as low pH. On the other side, due to the high content of reducing sugars in the structure of inulin, short-chain inulin increases the Millard reaction rate and forms a more attractive crust color. Overall, it can be concluded that inulin is almost stable under acidic conditions, but is highly susceptible to degradation by heating at low pH levels.

In conclusion, inulin has rheological and technological characteristics that can be really exploited in various food fields (bakery, meat and dairy products) to obtain healthy and functional foods with lower glycemic index and higher total dietary fibre content.

CRediT authorship contribution statement

Maria Grazia Melilli: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Carla Buzzanca:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Vita Di Stefano:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgments

The authors would like to thank the "National Biodiversity Future Center" (CUP B73C22000790001): 'Biodiversity', financed under the National Recovery and Resilience Plan (NRRP), the project "ON Foods - Research and innovation network on food and nutrition Sustainability, Safety and Security - Working ON Foods", project PE00000003, concession decree n. 1550/2022, CUP D93C22000890001, National Recovery and Resilience Plan, mission 4, component 2, investment 1.3, call n. 341/2022 of Italian Ministry of University and Research funded by the European Union - NextGenerationEU and CNR project FOE-2021 NutrAge - code DBA.AD005.225.

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