

Utilization of *Opuntia* as an alternative ingredient in value added bread and pasta products

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Abstract: Natural sources and healthy cereal-based food have recently received a lot of attention by both professionals and the common population for improving overall well-being. In this case, *Opuntia* cactus and *Opuntia* derivatives show high potential in the production of health-promoting cereal-based products. This study comprehensively reviews nutritional composition, health benefits of *Opuntia* spp. and its utilisation in the production of bread and pasta products. Moreover, the effect of this ingredient on the rheological properties of wheat dough and physical parameters as well as sensory properties of incorporated products is also discussed.

Keywords: bread, dough rheology, nopal, *Opuntia*, pasta, sensory attributes

Introduction

Due to increasing awareness and interest in health and various beneficial diets, the demand for value-added food continues to rise. Cereals and bakery products have the main importance in human nutrition, they are widely available and represent the main food source for humans. Bakery products are considered suitable medium for nutrients, particularly dietary fibre. Consequently, the bakery industry is one of the fastest growing food industries in the world (Biljwan et al., 2019; Codinã, 2022).

Incorporation of bakery products with plant materials offers opportunities to include beneficial components into the human diet. The positive effects of plant sources can be obtained from active components found in the entire plant, parts of the plant or plant materials, whether in the crude or processed state. Nowadays, there is increasing interest in *Opuntia* cactus, fruits, and cladodes, because of their high content of valuable bioactive compounds. Numerous studies have been focused on this topic (Das et al., 2012; Msaddak et al., 2017; Andreu et al., 2018; Rocchetti et al., 2018; Berrabah et al., 2019; Baniwal et al., 2021; Dubeux et al., 2021; Sciacca et al., 2021).

The genus *Opuntia* spp. includes more than 300 species of cacti. *Opuntia* is a tropical to subtropical plant belonging to the *Cactaceae* family, which originates in America. However, due to its high adaptability to different climatic conditions (drought, high temperatures, UV radiation), its production has expanded to Europe and Africa (Oniszczuk et al., 2020; Taşkin and Aksoylu, 2021). This genus appears to have its centre of genetic di-

versity in Mexico where it originates from and is still extensively produced. The other largest producers and suppliers of *Opuntia* spp. include Mediterranean countries, India, the USA, and South Africa (Taşkin and Aksoylu, 2021). Currently, Mexico and Italy are the main producer countries, accounting for approximately 70 % and 3.3 % of the global production on approximately 590 000 ha, respectively (Silva et al., 2021). Moreover, Mexico has the widest variation comprising at least 126 species with various degree of domestication (Wit and Fouché, 2021). It is confirmed that due to domestication, *Opuntia* spp. has improved in shape, colour, flavour, texture, and mucilage quality and quantity (Díaz et al., 2017; López-Palacios et al., 2019).

Morphologically, the plant consists of root, vegetable part (cladodes or stems), fruit (peel, pulp, seeds), and flower. The fruit is also known as “cactus pear” or “prickly pear” in different growing areas (Stintzing and Carle, 2005; Amani et al., 2019). While the cactus is primarily produced for its edible fruit, several parts of the cactus (mainly seeds, cladodes, and flowers) are utilised in the food and cosmetic industry (Osuna-Martínez et al., 2014; Abbas et al., 2022).

Opuntia species globally produced include *Opuntia ficus-indica*, *Opuntia robusta*, *Opuntia streptocantha*, *Opuntia amyclaea*, *Opuntia megacantha*, *Opuntia hyptiacantha*, *Opuntia ratera*, *Opuntia engelmannii*, *Opuntia phaeacantha*, *Opuntia dillenii* cactus and *Opuntia lindheimeri* (Yahia and Sáenz, 2011). It was found that these species are a good source of natural bioactive compounds such as dietary fibre, polysaccharides, vitamins (A, B1, B2, and C), antioxidants (phenolic compounds), and minerals

(mainly Mg, Ca, K, Mn, and Fe). Many of these compounds have beneficial hypoglycemic, anti-inflammatory, and antimicrobial effects. Due to the potential health benefits of *Opuntia*, current studies are focused on incorporating different parts of this plant into various foods, including baked goods (Das et al., 2021; Silva et al., 2021; Taşkın and Aksoylu, 2021; Abbas et al., 2022). Currently, *Opuntia ficus-indica* is the most promoted and domesticated species worldwide for commercial production (Barba et al., 2017; Mazri, 2021). *Opuntia ficus-indica* is assumed to be a spineless species obtained from *Opuntia megacantha*, a native species from Mexico (Díaz et al., 2017; Mounir et al., 2020).

Chemical composition

The content of bioactive compounds, chemical composition, and the nutraceutical potential of *Opuntia* spp. depend on many factors, including production practices, region, climatic conditions, plant age, and maturation stage (Amaya-Cruz et al., 2019; Al Juhaimi et al., 2020; Pessoa et al., 2020; Taşkın and Aksoylu, 2021). Tab. 1 provides the chemical composition of different parts of the commonly grown species *Opuntia ficus-indica* (Cota-Sánchez, 2016; El-Beltagi et al., 2019; Mounir et al., 2020; Silva et al., 2021).

Cladodes

Opuntia cladodes represent the green stems of the plant (Ginestra et al., 2009; Magarelli et al., 2022). Proximate composition of cladodes from different *Opuntia* spp. has been evaluated by various authors, and the values are always variable (Astello-García et al., 2015; Díaz et al., 2017; Dubeux et al., 2021; Perucini-Avendaño et al., 2021; Hernández-Becerra et al., 2022). These variations can be attributed to different environmental conditions at the production site, as well as structural differences between

individual species (Angulo-Bejarano et al., 2014). Tab. 2 shows the chemical composition of cladodes from selected wild and domesticated *Opuntia* species (Astello-García et al., 2015; Díaz et al., 2017).

According to Díaz et al. (2017), De Santiago et al. (2018), and Rocchetti et al. (2018) water is the primary component of *Opuntia ficus-indica* cladodes (80–95 %), followed by carbohydrates (3–7 %), fibre (1–3 %), and proteins (0.5–1 %) (Díaz et al., 2017).

Studies by Figueroa-Pérez et al. (2018) and Perucini-Avendaño et al. (2021) have revealed that certain wild *Opuntia* species have higher protein content compared to most domesticated species. For example, *Opuntia robusta* can reach protein values in the range from 17.40 % to 19 %. Higher protein content has also been reported in young cladodes. Significant differences in the composition between young and mature cladodes was also discovered in the content of amino acids. In young cladodes, various amino acids like alanine, isoleucine, and asparagine were found, whereas mature cladodes have shown only threonine content (Díaz et al., 2017; Figueroa-Pérez et al., 2018; Perucini-Avendaño et al., 2021).

Carbohydrates present in cactus cladodes can be divided into two types, structural carbohydrates, and storage carbohydrates. Structural polysaccharides are mainly cellulose (21.6 %), hemicellulose (8.19 %), and lignin (36 %). They are part of the cladodes cell wall and contribute to dietary fibre. The main constituents of storage carbohydrates are monosaccharides (glucose, galactose, arabinose, rhamnose, fructose), galacturonic, and glucuronic acid (López-Palacios et al., 2016; Perucini-Avendaño et al., 2021). Carbohydrates also include mucilaginous components that contain polymers, such as chains of (1-4)-linked β -D-galacturonic acid and R(1-2)-linked L-rhamnose residues (Ginestra et al., 2009; Perucini-Avendaño et al., 2021).

Tab. 1. Nutritional composition (g/100 g) of *Opuntia ficus-indica* different parts (Cota-Sánchez, 2016; El-Beltagi et al., 2019; Elshehy et al., 2020; Mounir et al., 2020; Silva et al., 2021).

Component	<i>Opuntia ficus-indica</i> part			
	Pulp	Seed	Peel	Cladode
Water	84–94.40	18	90.30	87.01–94
Ash	0.24–4.03	10.37	0.29	1.08–2.97
Protein	0.08–1.60	3.67	0.14	0.30–1.39
Lipids	0.04–0.97	3.00–16.30	0.04–2.43	0.11–1.83
Total fibre	0.02–5.37	54.20 ^{DM}	0.65	2.70–4.14
Carbohydrates	92.50	–	–	5.63–8.52
Starch	4.55 ^{DM}	5.35 ^{DM}	7.12 ^{DM}	0.71 ^{DM}

DM – dry matter

Tab. 3 lists the mineral composition of *Opuntia* spp. cladodes (Jun et al., 2013; Astello-García et al., 2015; Díaz et al., 2017). Several studies have shown that, in general, K and Ca are present in higher concentration compared to other minerals (Jun et al., 2013; Astello-García et al., 2015; Díaz et al., 2017; Dubeux et al., 2021). Cladodes of some species (*Opuntia humifusa*) are characterised by even higher Ca content than cow milk (113–122 mg/100 g), some fruits, vegetables, and nuts. Examples include spinach (1151 mg/100 g), lettuce (703 mg/100 g), cabbage (511 mg/100 g), and broccoli (43 mg/100 g) (Ceballos et al., 2009; Astello-García et al., 2015; Kapadiya et al., 2016; Díaz et al., 2017; Lambrini et al., 2021). Cactus cladodes contain significant amounts of organic acids such as malic acid, citric acid, and succinic acid (Figueroa-Pérez et al., 2018; Wit and Fouché, 2021). Andreu et al. (2018) identified malic acid as the prevailing organic acid in cladodes (71.8 g/L).

Cladodes are characterised by low fat content (Elshehy et al., 2020). Rocchetti et al. (2018) and El-Safy (2013) documented that the amount of fat in *Opuntia ficus-indica* cladodes varies from 0.11 to 0.87 %. The most abundant fatty acids in cladodes are linoleic acid (C18:2) (25.84–53.77 %), pal-

mitic acid (C16:0) (15.02–26.54 %), and oleic acid (C18:1c9) (8.52–36.30 %). Previously, it was found that the content of linoleic acid in cladodes is similar to that in argan oil (29–41 %), but lower than that determined in soybean (53.3 %) and barley (51.2 %) (Abidi et al., 2009; El-Mostafa et al., 2014; Andreu-Coll et al., 2019; Gharby et al., 2021; Wit and Fouché, 2021).

Total phenolic content of *Opuntia* spp. varies and correlates with the domestication gradient of individual species (Díaz et al., 2017). The wild species *Opuntia streptacantha* show the highest concentration of phenolic compounds (Astello-García et al., 2015). The most frequently occurring phenolic compounds in *Opuntia* spp. (domesticated as well as wild species) include quercetin (90.5 µg/g), kaempferol (12.9–45.6 µg/g), and isorhamnetin (58.9–326.9 µg/g) (Díaz et al., 2017).

Fruits

Opuntia fruit consists of a juicy pulp (28–58 % of the fruit mass) with seeds (2–10 %), encompassed by a thick peel (37–67 %) (Mona and Nesreen, 2011; Barba et al., 2017). *Opuntia* fruits contain a large amount of water, approximately 84–93 % of the fresh mass. Monosaccharides, as well as dietary

Tab. 2. Chemical composition of wild and domesticated species of *Opuntia* spp. cladodes (Astello-García et al., 2015; Díaz et al., 2017).

Species	Composition (g/100 g)				Phenolic acids (mmol GA/g)	Flavonoids (mmol quercetin/g)
	Proteins	Fat	Crude Fibre	Ash		
<i>Opuntia streptacantha</i>	11.20	0.73	7.30	12.60	56.80	18
<i>Opuntia hyptiacantha</i>	11	0.80	6.50	15.10	33.40	17.10
<i>Opuntia megacantha</i>	10.70	0.69	6.50	13.60	44.70	16.80
<i>Opuntia albicarpa</i>	11.60	0.75	6.50	13.20	40.80	17.20
<i>Opuntia ficus-indica</i>	11.20	0.69	5.90	14.40	40.10	19.40
<i>Opuntia humifusa</i>	4.70	1.25	50.30	2	–	–

GA – gallic acid

Tab. 3. Mineral composition of wild and domesticated species of *Opuntia* spp. cladodes (Jun et al., 2013; Astello-García et al., 2015; Díaz et al., 2017).

Species	Minerals (mg/100 g of sample)					
	K	Ca	Na	P	Fe	Mn
<i>Opuntia streptacantha</i>	2213	667	70	0.09	2.90	16.50
<i>Opuntia hyptiacantha</i>	2690	740	87	0.09	3.90	9.80
<i>Opuntia megacantha</i>	1960	683	137	0.08	5.10	13.30
<i>Opuntia albicarpa</i>	1956	647	77	0.09	0.70	24.10
<i>Opuntia ficus-indica</i>	2403	627	63	0.09	8.60	13.80
<i>Opuntia humifusa</i>	1269	1968	–	1110	–	1411

fibre (about 50 % of dry matter in total) are the main components of dry matter. Proteins accounting for about 8.30 % of dry matter and lipid content are negligible (0.09–0.7 %) (Feugang et al., 2006; De Wit et al., 2010).

In general, the fruit pulp shows lower protein and dietary fibre content than seeds and peel. The highest amounts of dietary fibre, protein and lipids were found in seeds (54.2 %, 11.8 % and 6.77 %, respectively) (Silva et al., 2021).

Minerals, sugars, and organic acids

Opuntia fruit pulp is considered a good source of minerals, especially Ca (12.8–59 mg/100 g), K (90–220 mg/100 g), and Mg (16.1–98.4 mg/100 g). Seeds are rich in minerals (Mg, P, K, Zn, Cu) and sulphur amino acids (Feugang et al., 2006; Özcan et al., 2011; Jana, 2012). Relatively high total sugar content (12–17 %) and low acidity render sweet but sometimes bland taste to the fruit. Sugar composition in the fruit pulp is very simple, consisting of glucose and fructose in virtually equal amounts, while the organic acid pattern is dominated by citric acid ranging from 1.60 to 3.20 g/L in peel and pulp (Feugang et al., 2006; De Wit et al., 2010; García et al., 2020).

Vitamins, carotenes, and amino acids

Vitamins are nutritionally important constituents of the *Opuntia* fruit. Beta-carotene and fat-soluble vitamin E – tocopherols were found in the lipid fraction of both cactus fruit pulp and seeds. Vitamin E homologues isoforms gamma-tocopherol (3.3 g/100 g) and delta-tocopherol (0.05 g/100 g) are the main components of the pulp and seed oils, respectively, representing approximately 80 % of the total vitamin E content (Jana, 2012; Berrabah et al., 2019; Oniszczuk et al., 2020). Eventually, only trace amounts of ascorbic acid, vitamin B6, vitamin B1, niacin, riboflavin, and pantothenic acid have been found in fruit pulp (Feugang et al., 2006; Medina et al., 2007; Berrabah et al., 2019; Oniszczuk et al., 2020). Several authors found that *Opuntia* contains a substantial number of amino acids, especially two predominant amino acids: proline (1265.2 mg/L) and taurine (434.3 mg/L), followed by serine (174.5 mg/L) (Feugang et al., 2006; Slimen et al., 2016; Berrabah et al., 2019; Oniszczuk et al., 2020).

Lipids

Fruit pulp contains lower amounts of oil (0.1–1.0 %), representing approximately 8.70 g of total lipid content per 1 kg of pulp dry weight compared to 98.8 g of total lipid content per 1 kg of seeds (Feugang et al., 2006). The major representative of fatty acids is linoleic acid with a content range

from 20.19–53.85 %. Other abundant compounds are oleic and palmitic acids (Andreu-Coll et al., 2019).

The peel fraction contains 36.8 g of lipids per 1 kg (Feugang et al., 2006). In this case, the major fatty acids are linoleic acid ranging from 39.58–52.02 %, followed by oleic (6.83–30.99 %) and palmitic (21.53–32.06 %) acids. The next most common compounds are linoleic acid (18.70–21.88 %) and stearic acid (1.74–3.76 %) (Feugang et al., 2006; Andreu-Coll et al., 2019).

Phenolic compounds

High antioxidant activity of *Opuntia* fruit pulp and peel is attributed to its content of polyphenols and betalains. Betalains present in the epidermis give the *Opuntia* fruit a colour ranging from yellow to purple (betaxanthins: orange and yellow and betacyanins: blue and red). These pigments are derivatives of betalamic acid (Khatabi et al., 2016; Ciriminna et al., 2019; Oniszczuk et al., 2020). Oniszczuk et al. (2020) reported high free radical scavenging potential of DPPH (99.7 %) and total phenolic content of 14.9 mg GAE/g dry weight in *Opuntia* fruits. Fruit is considered a good source of flavonols, of which quercetine (58.7 %) was detected as predominant, followed by isorhamnetin (31.7 %), luteolin (11.5 %), and kaempferol (11 %) (Barba et al., 2017). Furthermore, *Opuntia* fruits are also a rich source of free phenolic acids (57.96 µg/g of dry matter), especially benzoic and cinnamic acid derivatives (Ramírez-Moreno et al., 2017; Oniszczuk et al., 2020; Taşkın and Aksoylu, 2021).

Health benefits

Despite the enormous amount of synthetic substances used today, there is a growing trend to use natural compounds to prevent and manage chronic diseases. In addition, their promising effects are supported by scientific studies and evidence as possible therapeutics under certain conditions (Hashem et al., 2020; Abd-Elhakim and Al-Sagheer, 2021).

Opuntia spp. has been used for centuries in traditional medicine due to their beneficial health properties in chronic diseases, particularly obesity, diabetes, cardiovascular diseases, and cancer (Aragona et al., 2018; Abd-Elhakim and Al-Sagheer, 2021). Recent scientific studies, both *in vitro* and *in vivo*, have demonstrated the pharmacological potential of *Opuntia* spp., indicating the need for further research (El-Mostafa et al., 2014; Madrigal-Santillán et al., 2022). Several authors described different parts of *Opuntia ficus-indica* (cladodes, fruit pulp, peel, and seeds) and their extracts have

been characterised by various favourable biological activities (Abd-Elhakim and Al-Sagheer, 2021); in particular, its cholesterol-lowering, anti-ulcer, anti-inflammatory, cardioprotective, antidiabetic, neuroprotective, hepatoprotective, and wound healing effect (Milán-Noris et al., 2016; Aruwa et al., 2018; Abbas et al., 2022).

The antihyperglycemic effect of *Opuntia* spp. is related to its high fibre content (Díaz et al., 2017; Gouws et al., 2019b; Rbia and Smiti, 2019; Kashif et al., 2022). Deldicque et al. (2013) and Aragona et al. (2018) reported that oral intake of *Opuntia ficus-indica* (cladodes, flower extracts) contributes to insulin release in serum, so the extract can reduce blood glucose. Aragona et al. (2018) and Gouws et al. (2019b) documented that *Opuntia* fibre can slow the rate of intestinal absorption of glucose.

Recently, *Opuntia* spp. has been confirmed to play an important role in the prevention of cardiovascular diseases (Osuna-Martínez et al., 2014; Daniloski et al., 2022; Madrigal-Santillán et al., 2022). Antiatherogenic properties of cacti can be attributed to its high content of substances with antioxidant potential. *Opuntia* species contain mostly flavonoids, with significant amounts of quercetin followed by isorhamnetin, luteolin, and kaempferol, which can decrease lipid peroxidation and help prevent or slow down the development of atherosclerosis (Osuna-Martínez et al., 2014; Díaz et al., 2017). Although antioxidants are able to block lipid peroxidation, their lipid lowering properties are not completely clarified (Abd-Elhakim and Al-Sagheer, 2021).

According to the World Health Organization, cancer is classified as the second main cause of death. The fruit of *Opuntia* spp. is indicated as a promising natural source of functional substances for the development of novel chemotherapeutic agents. The anticancer activity of fruits is mostly connected to bioactive polysaccharides composed of rhamnose, arabinose, and glucose, which induce cell apoptosis or cell cycle arrest in different types of cancer cells (Abdulazeem et al., 2018; El-Beltagi et al., 2019; Dalila et al., 2021).

Abdulazeem et al. (2018) showed the cytotoxic effects of different parts of *Opuntia* on cancerous cell lines. *In vitro* tests have shown that the *Opuntia* fruit extract inhibits the proliferation of ovarian, cervical, and bladder cancer cell lines (Abdulazeem et al., 2018; Dalila et al., 2021; Madrigal-Santillán et al., 2022). Based on the previously described reports, it can be summarised that the *Opuntia* plant represents a safe and promising available alternative drug, which could lead to new research in cancer therapy (Abou-Elella and Ali, 2014; Dalila et al., 2021; Madrigal-Santillán et al., 2022).

On the other hand, a few cases reporting allergic contact dermatitis with *Opuntia* fruit have also been published (Yoon et al., 2004; García-Menaya et al., 2009). The small glochids (hair-like or short prickles) from this crop cause dermatological problems by physical penetration into the skin (Otang et al., 2014). Patients developed an erythematous plaque with exudation followed by itching. The skin lesions improved after application of topical and systemic corticosteroids (Yoon et al., 2004; García-Menaya et al., 2009; Otang et al., 2014).

***Opuntia* as a potential ingredient of cereal based products**

Several parts of *Opuntia* spp., such as seeds, stems, pear pulp, peel, and mucilage are potential ingredients in breadmaking or in other cereal products. These raw materials are usually applied in powdered form (Gül, 2021).

During processing, plant material collected from plantations is washed with distilled water and disinfected in order to eliminate microorganisms (Contreras-Padilla et al., 2016; Di Bella et al., 2022).

After that, fruits are cleaned with a brush to remove prickles and dirty particles. Peels are manually removed by a knife and cut into slices, seeds are separated from the pulp by sieving and processed individually (El-Shahat et al., 2019; Abou-Zaid et al., 2022).

Vegetative parts, i.e., cladodes are cleaned and cut longitudinally or into cubes (Moreno-Álvarez et al., 2009; Msaddak et al., 2017).

In the next step, individual parts of pre-treated *Opuntia* plant (cladodes, fruit peel, and seed) are processed by drying using various drying methods: sun drying (Nharingo and Moyo, 2016; Rebah and Siddeeg, 2017; Reda and Atsbha, 2019; Albergamo et al., 2022), convection drying (45–60°C) (Touil et al., 2014; Cruz-Rubio et al., 2020; Di Bella et al., 2022) or freeze-drying (–18°C) (Gouws et al., 2019a; Romero et al., 2021) until the required moisture content is reached (4–8 %) (Cruz-Rubio et al., 2020).

Seeds obtained from the fruit pulp can be roasted after drying. This procedure improves sensory acceptance of seed products (Ali et al., 2020; Gül, 2021).

Special by-product derived from *Opuntia* spp. is cactus mucilage. It is a slimy polysaccharide substance that appears right after cutting or crushing the cladode cuticle (Hussain et al., 2022a). Mucilage is a promising hydrocolloid because of its ability to retain large amounts of water and create gels (Rodríguez-González et al., 2014; Sepúlveda et al., 2007). Preparation of mucilage extract includes



Fig. 1. Flow chart of processing different parts of *Opuntia ficus-indica* into cladodes, seeds and mucilage powders (Contreras-Padilla et al., 2016; Dick et al., 2019; Reda and Atsbha, 2019; Ali et al., 2020; Dick et al., 2020; Nabil et al., 2020; Chaloulos et al., 2021; Sciacca et al., 2021).

several steps; first, cladodes are crushed to obtain pulp that is homogenised, heated, precipitated, and filtered to get the mucilage extract. The prepared product can be processed by drying to obtain mucilage powder (Dick et al., 2019; Dick et al., 2020). Dried material from various parts of *Opuntia* plant is usually ground and sieved to obtain the powder (Ali et al., 2020; Gül, 2021). Powder particle sizes vary from 80 to 500 µm (Moreno-Álvarez et al., 2009; Chahdoura et al., 2018; Rayan et al., 2018; Anchondo-Trejo et al., 2020; Arias-Rico et al., 2020; Parafati et al., 2020).

Previously it was stated that the drying method significantly affects the composition of final powders. The most preferred method of drying in commercial production of *Opuntia* powder is convention drying. This is the most economical method, especially if it is done using a solar drier, which is optimally suited to the dry and hot regions where *Opuntia* spp. is produced. However, a big disadvantage of this method is thermal degradation of bioactive compounds and the subsequent change in the quality profile of the plant material (Ali et al., 2020; Barba et al., 2020; Cruz-Rubio et al., 2020). According to Ali et al. (2020), temperature used during drying should not reach 60 °C. The mucilage quality is the most affected by temperature as mucilage proteins and polysaccharides undergo partial denaturation at high temperatures (León-Martínez et al., 2011; Barba et al., 2020; Cruz-Rubio et al., 2020).

Opuntia ficus-indica commonly known as nopal cactus, is the most widespread and commercially important cactus used in powder form; also, most published studies focus on this species (Dick et al., 2019; Reda and Atsbha, 2019; Dick et al., 2020; Gül, 2021). A detailed diagram of the individual parts of nopal cactus processing into powdered form is shown in Fig. 1. (Contreras-Padilla et al., 2016; Dick et al., 2019; Reda and Atsbha, 2019; Ali et al., 2020; Dick et al., 2020; Nabil et al., 2020; Chaloulos et al., 2021; Sciacca et al., 2021).

Incorporation of *Opuntia* into cereal-based food products

Recently, attempts to incorporate *Opuntia* spp. into various cereal-based foods, predominantly bread, pasta, cakes, and gluten-free products have been made to improve their nutritional quality. Most published studies focus on the production of bakery products by partially substituting wheat flour with *Opuntia* powders (Guevara-Arauza et al., 2015; Anwar and Sallam, 2016; Mata et al., 2016; Jotangiya and Samani, 2017; Rayan et al., 2018; Liguori et al., 2020; Gül, 2021). The significant number of po-

tentially active nutrients (dietary fibre, proteins, phenolic compounds) and their multifunctional (hydration, textural, stabilising and hydrocolloid) properties make edible parts of *Opuntia* spp. great candidates for the production of health-promoting cereal-based foods with reduced energy and carbohydrate levels (Jana, 2012; Msaddak et al., 2017; Ali et al., 2020).

Bread

Bread, commonly consumed food worldwide, is usually prepared by mixing simple ingredients such as wheat flour, water, salt, and yeast. It is characterised by low antioxidant potential and therefore enrichment with bioactive compounds could increase its nutritional quality (Dziki et al., 2014; Msaddak et al., 2017). The addition of *Opuntia* spp. derivatives could produce bread containing higher proportions of protein, fibre, and phenolic compounds, as well as increase oxidative stability of bread (Ali et al., 2020; Gül, 2021).

Several studies have reported that many parts of *Opuntia* spp. such as cactus peel fruits, cladodes, seeds and fresh mucilage have great potential to be used in breadmaking (Anwar and Sallam, 2016; Ali et al., 2020; Gül, 2021; Sciacca et al., 2021). However, cladodes are the most common parts of the cactus that are used in the production of bread (Moreno-Álvarez et al., 2009; De Wit et al., 2015; Msaddak et al., 2017; Gül, 2021; Sciacca et al., 2021).

Rheological parameters of dough

Rheological behaviour of dough is very important because it has significant effect on baking characteristics, mechanical properties of the dough and quality of final products (Mirsaeedghazi et al., 2008; Culetu et al., 2021).

Farinograph water absorption (WA) represents the amount of water required to produce a dough of optimum consistency depending on the content of wheat gluten in the flour (Linlaud et al., 2009; Hussin et al., 2022). It is well known that the addition of non-protein components modifies WA of flour (Wang et al., 2016; Hussin et al., 2022).

Moreno-Álvarez et al. (2009) and Sciacca et al. (2021) have concluded that incorporation of cladode powder to wheat or durum wheat flour at different levels (5–20 %) significantly increased WA. This can be explained by higher water holding capacity of cladode powder attributed to the presence of a large amount of dietary fibre (Msaddak et al., 2015; Taşkın and Aksoylu, 2021). Similar results have also been reported for flour mixtures based on plant materials with high fibre content, such as pumpkin, carrot, hemp (Moreno-Álvarez et al., 2006; Turksoy and Özkaya, 2011; Shahzad, 2012).

In the fibre structure, hydroxyl groups which absorb a significant quantity of water by hydrogen bonding are present (Moreno-Álvarez et al., 2009; Gül, 2021).

During dough mixing, water hydrates flour components and dough is developed (Lauková et al., 2016). Dough development time (DDT) is the time required for the dough to reach its optimal consistency during mixing (Hussain et al., 2022a). Several researchers have documented that the increase in the level (3–15 %) of cladode powder in dough resulted in prolongation of DDT (Sciacca et al., 2021; Hussain et al., 2022a, 2022b). Elhassaneen et al. (2022) suggested that this effect can be caused by the formation of a gluten-fibre complex inhibiting the protein hydration and gluten structure development.

The addition of *Opuntia* cladodes to wheat dough also influences dough stability (DS) (indication of dough strength) and elasticity (ability to bounce back once dough is stretched) (Nassar et al., 2008; Ayadi et al., 2009; Patel and Chakrabarti-Bell, 2013; Sciacca et al., 2021). De Wit et al. (2015) and Moreno-Álvarez et al. (2009) documented that inclusion of 5–20 % of cladode powder into wheat dough decreased DS. This effect is attributed to the higher dietary fibre content; wheat-cladode mixtures produce weak flour (Moreno-Álvarez et al., 2009; Gül, 2021).

The effect of *Opuntia* addition on rheological properties of dough can also be analysed by the alveographic test (Msaddak et al., 2017; Mironeasa and Mironeasa, 2019; Sciacca et al., 2021). Glutenin and gliadin, two components that make up gluten, give the dough toughness and extensibility (Sciacca et al., 2021). The alveographic parameter P (tenacity) indicates the maximum overpressure required to blow a dough bubble (Codină et al., 2019). This parameter is connected with the gluten quantity and quality and also its ability to absorb water (Msaddak et al., 2017). According to Ayadi et al. (2009) and Sciacca et al. (2021), P parameter increases with the increasing addition of cladodes powder (10–20 %), which is probably due to poor gluten hydration. The L index (dough extensibility) indicates the ability of gluten to hold gas (Msaddak et al., 2017). Several studies have concluded that the L value decreases with partial substitution (from 5 % to 20 %) of wheat flour or durum wheat semolina with cladode powder (Ayadi et al., 2009; Msaddak et al., 2017; Mironeasa and Mironeasa, 2019; Bouazizi et al., 2020). Thus, the action of the cladode powder on both these parameters (P and L) leads to the P/L configuration ratio (dough balance between tenacity and extensibility) increase with the increasing amount of cladode powder (Ayadi

et al., 2009; Bouazizi et al., 2020). Similar results were described by Borchani et al. (2011) and Bchir et al. (2014) in alveographic parameters of dough incorporated with different levels of apple, pear, and date flesh fibre concentrate. These findings can be attributed to the high water-holding capacity of cladode powder (Msaddak et al., 2017). The deformation energy (W), the index of dough strength, increased with the increasing addition of cladode powder (5–20 %) (Ayadi et al., 2009; Msaddak et al., 2017; Bouazizi et al., 2020), probably due to the high fibre content in cladodes. The fibre structure contains a large number of hydroxyl groups, which enable more interactions with water through hydrogen bonding (Ayadi et al., 2009; Sciacca et al., 2021).

Physical parameters of enriched bread

Several studies have shown that incorporation of *Opuntia* to bread significantly affects its physical characteristics such as volume, specific volume, hardness, and colour (De Wit et al., 2015; Ali et al., 2020; Gül, 2021; Sciacca et al., 2021; Hussain et al., 2022a).

The volume of bread is a result of the gas-holding capacity of the dough, which is created during fermentation (Hussain et al., 2022a). It was determined that the incorporation of 4–10 % of *Opuntia* seed powder reduces the volume and specific volume of bread (Ali et al., 2020). A similar trend was also observed when up to 17 % of cladode powder were added to wheat bread (De Wit et al., 2015). This effect is attributed to the interactions between insoluble fibre and gluten, which leads to a decrease in the gas-holding capacity (Gómez et al., 2003; Msaddak et al., 2017).

Bread hardness describes the resistance of bread to pressure (Budžaki et al., 2014). The replacement of wheat flour with cladode powder can cause an increase in bread hardness with the increasing concentration of the substitute (2–17 %) (Ayadi et al., 2009; De Wit et al., 2015; Sciacca et al., 2021). The fibre in *Opuntia* powder can interfere with gluten network which leads to weaker gluten structure and more crumbly and brittle bread texture, which contributes to increased bread hardness (De Wit et al., 2015; Gül, 2021).

Golden brown crust and creamy white bread crumb are the most important appealing factors to indicate the quality of a bakery product to consumers (Kurek and Wyrwicz, 2015). The incorporation of *Opuntia* cladode powder into the bread affects the colour parameters L*, a*, and b* of bread, whereas L* represents the lightness of bread, a* represents the red-green spectrum, and b* represents the yellow-blue spectrum (Brühl

Tab. 4. The impact of *Opuntia* addition on the sensory characteristics of bread (Álvarez et al., 2009; De Wit et al., 2015; Msaddak et al., 2017; Reda and Atsbha; 2019; Ali et al., 2020; Liguori et al., 2020).

Part of Cactus	<i>Opuntia</i> spp.	Substitution levels/%	Effect on final product	References
Roasted seed powder (RPPS)	<i>Opuntia ficus-indica</i>	0/2/4/6/8/10	Sensory properties were not sufficiently affected at substitution levels up to 6 %. Higher substitution levels: ↓ colour scores because of darker colour of RPPS powder due to the presence of natural pigments (carotenoids, flavonoids, and chlorophyll) ↓ texture score due to high amount of dietary fibres.	De Wit et al. (2019) Ali et al. (2020)
Seed powder	<i>Opuntia ficus-indica</i>	0/5/10/15/20/25	Substitution of <i>Opuntia</i> seeds up to 15 % showed no negative effect on sensory acceptability. ↑ aroma scores for all samples probably caused by the presence of volatile organic matter (hexanal and 2-methylpropanal) from <i>Opuntia</i> seeds.	Reda and Atsbha (2019) Nounah et al. (2020)
Stem powder (cladodes)	<i>Opuntia boldinghii</i> <i>Britton et Rose</i>	0/5/10/15/20	Wheat flour substitution up to the 10 % level without negative effect on sensory acceptability. Higher substitution levels: ↓ colour score due to the presence of chlorophyll pigments ↓ odour score caused by herbaceous flavour of terpenes present in cladode powder ↓ texture scores caused by cladode polysaccharides interaction with wheat flour proteins.	Moreno-Álvarez et al. (2009) Feng et al. (2011) Abd El-Moaty et al. (2020) Dick et al. (2020)
Cladode mucilage extract	<i>Opuntia ficus-indica</i>	Formula water replaced by mucilage	↑ scores in colour of the crust and odour intensity in contrast with control wheat sample probably due to interactions between antioxidant compounds and mucilage carbohydrates.	Liguori et al. (2020) Czajkowska-González et al. (2021)
Cladode powder	<i>Opuntia ficus-indica</i> and <i>Opuntia robusta</i>	0/2/4/6/8/10/17	Substitution of up to 8 % showed no negative effect on overall acceptability. Higher substitution levels: ↓ odour score due to the presence of betalain pigments, which in high concentration have typical earthy flavour.	De Wit et al. (2015) Awolu and Oladeji (2021)
Cladodes powder	<i>Opuntia ficus-indica</i>	0/2,5/5/7,5/10	Substitution of wheat flour up to the 5 % level without negative effect on sensory acceptability. Higher substitution levels: ↓ colour score as the powder is a rich source of chlorophyll ↓ textural hardness score induced by high fibre content, which weakens the gluten structure.	Msaddak et al. (2017)

and Unbehend, 2021). It has been observed that bread fortified with cladodes powder is darker than wheat bread. Bread with cladode powder is characterised with lower L* values of the crust and crumb than wheat bread. Additionally, the a* and b* values for both the crust and crumb of the enriched bread also decreased as the substitution level increased, indicating a shift from the initial yellowish colour to a greenish one (Gül, 2021; Sciacca et al., 2021). This can be attributed to the high concentration of chlorophyll and other pigments present in the cladodes powder (Msaddak et al., 2017). According to Gül (2021), these changes can also be linked with the presence of different dietary fibre fractions of *Opuntia ficus-indica*, which have different effects on the crust colour of bread. Darker crust and green colour of crumb is caused by nopal insoluble fibre fractions. With the addition of soluble fibre, no significant changes in either crust or crumb colour were observed (Guevara-Arauza et al., 2015). However, according to Liguori et al. (2020), the addition of *Opuntia ficus-indica* mucilage does not cause any changes in L* and a* values.

Sensory evaluation

Sensory evaluation is an important part of bread quality assessment, which leads to the development of new cereal based products (Elia, 2011). The impact of *Opuntia* addition on the sensory characteristics of bread is presented in Tab. 4. (Moreno-Álvarez et al., 2009; De Wit et al., 2015; Msaddak et al., 2017; Reda and Atsbha; 2019; Liguori et al., 2020; Ali et al., 2020). Incorporation of cladodes powder into bread was reported to influence consumer preferences. Thus, higher concentration of the incorporated cladodes powder decreased the trend in average scores for sensory attributes.

No significant differences were found with the incorporation of up to 3 % of cladode powder into wheat bread. Several studies concluded that bread fortified with 5 % and 10 % *Opuntia* cladode powder is best accepted in sensory evaluation (Moreno-Álvarez et al., 2009; Msaddak et al., 2017; Liguori et al., 2020; Gül, 2021). According to studies of Lassoued et al. (2008) and Msaddak et al. (2017), it can be assumed that the formulation with 5–15 % of cladode powder shows the highest values of colour, taste, and aroma in comparison with higher additions of cladode powder, whereas the formulation with 5 % cladode powder was most accepted in terms of texture. Higher addition levels (above 20 %) were unacceptable because of textural hardness of the final bread (Lassoued et al., 2008; Msaddak et al., 2017; Gül, 2021). The

observed changes in bread texture can be caused by either dilution of gluten proteins or interactions between polysaccharides from the cladodes and wheat flour proteins. The presence of fibrous materials in the cladode flour may also have contributed to this change in texture properties by affecting the mixing properties of gluten (Ayadi et al. 2009; De Wit, 2015).

Pasta

Current strategy of the food industry is to incorporate fibre into conventional food formulations to improve their functional properties (Micale et al., 2017). Pasta is a globally consumed food and many studies are focused on innovation of wheat pasta using different sources of dietary fibre (Krishnan et al., 2012; Padalino et al., 2017; Madenci et al., 2018; Makhlouf et al., 2019; Oniszczyk et al., 2020).

In order to develop new functional pasta, several studies have focused on incorporation of *Opuntia ficus-indica* powder into wheat pasta (Micale et al., 2017, 2018; Attanzio et al., 2019; Oniszczyk et al., 2020; Palmieri et al., 2021). Cladodes and fruits are two parts of *Opuntia ficus-indica* used to enrich pasta (Micale et al., 2017, 2018; Attanzio et al., 2019; Oniszczyk et al., 2020; Palmieri et al., 2021). The addition of *Opuntia* powder to pasta can increase not only the fibre content but also the phenol level in the final products (Micale et al., 2017).

One of the most important factors in pasta quality assessment is optimal cooking time (time needed for the central core of a pasta strand to disappear after pasta is immersed in cooking water) (De Pilli et al., 2013; De la Peña et al., 2014; Attanzio et al., 2019). Previous studies concluded that the substitution of durum wheat flour with cladode powder at various levels (3–30 %) does not significantly affect the cooking time of pasta compared to wheat pasta (Biernacka et al., 2018; Attanzio et al., 2019; Vimercati et al., 2020). On the other hand, the swelling ability of pasta (indicator of water absorption during cooking) with a 10 % addition of cladode powder (1.73 g water/g dry pasta) has shown statistically significant differences compared to durum wheat pasta (2.11 g water/g dry pasta), which can be due to the ability of *Opuntia* cladode mucilage to encapsulate starch, slowing down its rate of swelling and increasing pasta firmness (Gutiérrez et al., 2018; Attanzio et al., 2019; Tashim et al., 2022).

Considering content and quality, protein evaluation is a fundamental cooking loss parameter (amount of solid substance that dissolves in water during cooking) and an indicator of pasta structural integrity during cooking (De la Peña et al.,

2014; Desai et al., 2018). Enrichment of pasta with 10 % and 20 % of cladode powder did not significantly change the cooking loss parameter in comparison with wheat pasta, which indicates that starch-protein matrix integrity is preserved during cooking. On the contrary, fortification of pasta with up to 30 % of *Opuntia* cladode powder showed a 15 % increase of the cooking loss (Attanzio et al., 2019), probably caused by disruption of the protein-starch matrix and unequal distribution of water in the pasta matrix due to competitive hydration of the fibre preventing starch swelling due to limited water availability (Tudorica et al., 2002; Foschia et al., 2017; Attanzio et al., 2019). Thus, more solid substances leak into cooking water (Simonato et al., 2019).

It was stated that pasta incorporated with up to 30 % of cladode powder showed good sensory acceptance. Higher addition of the powder in pasta resulted in slightly bitter aftertaste of the product (Micale et al., 2017, 2018; Attanzio et al., 2019; Park et al., 2021). Furthermore, Sepúlveda et al. (2013) and Dick et al. (2020) reported that the taste and aroma of cereal-based foods prepared with cladode powder can be negatively affected by such addition due to its herbaceous flavour. Sensory characteristics are mostly affected by powders derived from the cladodes with epidermis (peel), where the most chlorophyll is found.

Moreover, it was documented that an addition of *Opuntia* cladodes powder affects the colour of pasta products, as increased addition level of cladode powder leads to greener colour (Micale et al., 2017; Attanzio et al., 2019). Several authors deduced that this is caused by the presence of green pigments, particularly chlorophyll, in cladodes (El Mannoubi et al., 2009; Ramírez-Moreno et al., 2013; Biernacka et al., 2018; Attanzio et al., 2019).

Aiello et al. (2018) and Attanzio et al. (2019) indicated that pasta incorporated with *Opuntia* cladode powder at the 30 % level can participate in lowering blood cholesterol levels because it significantly reduces the bioavailability of sterols. These results were also confirmed by *in vitro* tests of Chong et al. (2014). In addition, pasta enriched with cladode powder can also be considered as beneficial for the prevention of age-related metabolic disorders, and hyperglycaemia, as well as for weight loss (Attanzio et al., 2019; Giglio et al., 2020; Sissons, 2022). Reduction of weight is probably linked with beneficial effect of soluble fibre (mainly pectin) on the reduction of appetite (Aiello et al., 2018; Attanzio et al., 2019).

Conclusion

Available literary research points out the importance of *Opuntia* and *Opuntia* derived products in human diet and nutrition as this plant is a rich source of bioactive substances such as dietary fibre, polysaccharides, vitamins, antioxidants (phenolic compounds), and minerals. This study presents nutritional composition and health benefits of the *Opuntia* plant and shows the possibility of its application as a potential ingredient for the production of selected cereal-based products like bread and pasta. Other important areas discussed include the effects of *Opuntia* on the rheological properties of dough, physical parameters of bread and pasta, and the sensory characteristics of these products. Given the increasing interest of consumers for value-added foods, incorporating cactus plants and cactus derived products into cereal-based food formulations is indeed a noteworthy innovation.

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