Invited Review

Technological, nutritional and sensory properties of pasta fortified with agro-industrial by-products: a review

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Summary Reducing food waste is a priority to move towards more sustainable food systems. Since agro-food by-products are often rich in healthy compounds, such as fibre, phytochemicals, protein, fatty acids, vitamins and minerals, the waste valorisation could move through their transformation into ingredients useful for the formulation of functional foods. Pasta is a staple food widely consumed all over the world representing an optimal carrier for nutrients delivery. The incorporation of ingredients of a high added value obtained by agro-industrial by-products in pasta can improve its nutritional value and provides several health benefits. At the same time, the inclusion of new ingredients could modify the physical, chemical and textural properties determining the change of the organoleptic characteristics of fortified pasta, affecting its acceptability. Thus, the preparation of new pasta formulations with high nutritional properties, good technological and sensory characteristics represents a challenge for the food industry.

Keywords Agro-industrial by-product, bioactive compounds, circular economy, fibre, pasta, phytochemicals, polyphenols.

Introduction

Pasta is a widely consumed food (IPO, 2021) and is a good source of carbohydrates but generally lacks of proteins and the complete range of amino acids, as well as functional bioactive compounds. Despite its increasing popularity, constant demands by consumers for a healthier lifestyle have encouraged food scientists and industrial producers to overcome the traditional boundaries for pasta making, researching new and different ingredients for pasta manufacture. For this matter, World Health Organization (WHO) and Food and Drug Administration (FDA) consider the fortification of pasta with high added value ingredients of great nutritional importance as pasta can be an appropriate carrier for healthy compounds. Moreover, the promotion of health, well-being and sustainable lifestyles, and waste management are some goals of the United Nations for the Agenda 2030, and such issues represent a hard challenge for the United Nation (ONU, 2015). The waste generated from the food supply chain, including the agro-industrial by-product, represents around 30% of the total food globally produced (FAO & SiK, 2011). These 'leftovers' (e.g. vegetable or fruit pomaces) are often rich in healthy compounds, such as fibre, phytochemicals, protein, fatty acids, vitamins and minerals and can be converted into ingredients with high added value useful for pasta fortification (Padalino *et al.*, 2017; Padalino et al., 2019; Sobata, *et al.* 2020). As traditional semolina wheat pasta is rather poor in physiological active compounds, many studies are involved with the increasing of pasta nutritional value. Several researchers have investigated the partial replacement of durum wheat flour with ingredients obtained from agro-industrial by-products to obtained new pasta formulation (Foschia *et al.*, 2013; Padalino *et al.*, 2017; Desai *et al.*, 2018; Desai *et al.*, 2019; Simonato *et al.*, 2019).

Moreover, the consumer demand for healthy food products rich in bioactive compounds with beneficial effects on human health is growing (Porto Dalla Costa *et al.*, 2016). Plant-derived by-products, including the husk, bran, seed, stem, leaf and peel residues, are important sources of dietary fibre with healthy bioactive compounds and sometimes technological benefits (Padalino *et al.*, 2017; Simonato *et al.*, 2020). In

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particular, foods fortified with dietary fibre often result in healthier products due to their ability to decrease the blood glucose and cholesterol levels, regularise bowel transit, enhance colonic fermentation, thus promoting colon health, improve the feeling of satiety and contribute the energy intake reduction (Foschia *et al.*, 2013; Simonato *et al.*, 2019). For these reasons, the recommended fibre intake for adults should be 25–30 g/day (Jane, McKay & Pal, 2019) and the fortification of staple foods, such as pasta, with by-products (Porto Dalla Costa *et al.*, 2016; Kim *et al.*, 2017; Padalino *et al.*, 2017; Simonato *et al.*, 2019; Tolve *et al.*, 2020) is of great interest in the formulation of innovative and healthy products. Additionally, many bioactive compounds in fruits and vegetables, such as carotenoids, polyphenols, are well known for their antioxidant and anti-inflammatory properties (Rigacci, 2015). Many studies have reported their beneficial effect against chronic diseases from oxidative stress, such as cardiovascular and neurodegenerative pathologies, diabetes and cancer (Gorzynik-Debicka *et al.*, 2018). It should also be underlined that the food by-products may be rich in minerals, vitamins, fatty acids and proteins, which can contribute significantly to the increase in pasta nutritional value (Kowalczewski *et al.*, 2015; Porto Dalla Costa *et al.*, 2016; Pan, Liu & Shiau, 2018; Kamble *et al.*, 2019). Finally, the agro-industrial by-products conversion into useful ingredients for the food industry works in the transition towards a circular economy (Galanakis, 2015), which is the process that would turn goods that are at the end of their service life into resources for others, closing loops in industrial ecosystems and minimising wastes (Minson, 2020).

The present review aims to provide an overview of the recently published articles from the year 2014 to 2021 (Table 1) focused on the use of agro-food industry by-products as ingredients in pasta fortification and to highlight their possible effect on the technological, nutritional and sensory properties.

By-product pretreatments

Agro-food industrial by-products are generally perishable being characterised by high moisture, so it is pivotal to improve their shelf life with preliminary treatments (Bas-Bellver *et al.*, 2020). Sample pretreatment through refrigeration and freezing could be applied to extend the storage time; however, the energy, the space required and the still high moisture content make them not practical and economically feasible (Guaita *et al.*, 2021). The other practicable solutions are based on moisture reduction, providing a longer storage period and reducing storage space and transportation. In general, by-products undergo a drying process by conventional hot-air, low-temperature or microwave to reduce moisture before powdering to allow their incorporation in foods (Melini *et al.*, 2020).

To satisfy the necessity of preserving healthy bioactive compounds, often sensitive to oxidation and high temperatures, low-temperature treatments are preferred as described for grape pomace (30–35°C for 48 h), orange and watermelon by-products (50–55°C for 24 h) and soy okara (70°C for 12 h; Crizel *et al.*, 2015; Marinelli *et al.*, 2015; Pan, Liu & Shiau, 2018).

Padalino *et al.* (2017) applied sun-drying to reduce the moisture content of tomato skin, but this treatment is time-consuming and could have a detrimental effect on bioactive compounds due to oxygen and UV light exposure (Guaita *et al.*, 2021). Alternatively, freeze-drying can be used to reduce the moisture of the by-products as performed by Simonato *et al.* (2019) for olive pomace and by Lončarić *et al.* (2014) for apple peel. However, different authors observed that for grape pomace, the drying treatment gave a better result in terms of retaining bioactive compounds content (García-Lomillo & González-SanJosé, 2017; Tolve *et al.*, 2020).

Another indispensable pretreatment concerns the reduction of the particle size of by-products. This step is essential both for the sensorial and the technological properties of the fortified food product. It has been reported that the dietary fibre particle size optimisation was beneficial on the texture and the sensorial pasta properties (Sissons & Fellows, 2014). Smaller particles (<40 μm) resulted in a smoother surface as well as increased hardness and chewiness of cooked noodles (Niu *et al.*, 2014). For the fortification of pasta, the by-products particles size used was generally lower than 500 μm as for carrot pomace, olive pomace, grape pomace and coconut residue (Porto Dalla Costa *et al.*, 2016; Simonato *et al.*, 2019; Cedola *et al.*, 2020; Sykut-Domańska *et al.*, 2020; Tolve *et al.*, 2020). Only for the fortification of the pasta with barley spent grains and grape, pomegranate and Rosehip seeds powder, the particle size reported was <1000 μm (Koca *et al.*, 2018; Nocente *et al.*, 2019). The powdered by-product is generally stored away from oxygen and in the dark until analysed or used for pasta preparation.

Technological properties of by-product fortified pasta

The determination of the technological properties is of great importance to define pasta quality.

Proper pasta technological evaluation requires consideration of several factors including cooking and textural properties and pasta colour.

Generally, good pasta technological quality is guaranteed by the formation of a continuous network of coagulated gluten proteins, which entraps the starch

Table 1 Technological, nutritional and sensory properties of pasta fortified with agro-industrial by-products

Fortified pasta		Technological properties: Cooking properties	Texture	Colour	Nutritional and bioactive compounds	Sensory properties	References
Apple 10, 15%	Fettuccine	↓OCT ↑CL, WA	↓hardness ↓adhesiveness	↓L*, a* ↑b*	↑TPC, AC	↓consistency odour, taste ↓OA	Lončarić *et al.* (2014)
Artichoke 35%(v/w)	Orecchiette	ND	ND	↑ brown index ↓yellow and red indices	↑TPC, AC	NR	Pasqualone *et al.* (2017)
Barley spent grain 5, 10, 20%	Spaghetti	↓WA	↓firmness	↓L*, b* ↑a*	↑RS/TS, DF ↑β-glucan ↑AC	lower score in every attribute	Nocente *et al.* (2019)
Einkorn Brewers' spent grain (BSGE) Tritordeum (BSGT) 5, 10%	Macaroni shape	↑CL, OCT ↑WA	NR	NR	↑β-glucan ↑DF ↑protein ↑AC	↓stickiness BSGE 10% same OA compared with control pasta	Nocente *et al.* (2021)
Carrot 10, 20%	Noodles	↑CL	NR	↑a*, b*	↓carbohydrates ↓protein ↑DF ↑carotenoids ↑AC	ND	Porto Dalla Costa *et al.* (2016)
Carrot 2, 4, 6, 8, 10%	Tube type	↑CL	↓ firmness	↓L* ↑a*, b*	NR	NR	Gull, Prasad and Kumar (2015)
Celery root Sugar beet 5, 7.5, 10, 20%	NR	↓OCT ↑CL, WA	NR	NR	NR	↓grittiness ↓firmness ↑stickiness ↓OA	Minarovičová *et al.* (2018)
Chia 2.5, 5, 10%	Strings	↓OCT ↓CL	ND	↓L*, b* ↑a*	↑DF ↑ω3/ω6, TPC ↑AC	↓appearance ↓taste ↓firmness	Aranibar *et al.* (2018)
Coconut flour (CF) and coconut residue (RCO) 5, 10, 15, 20, 25%	Short form cut ribbon	↑OCT ↑CL	↓firmness (CF) ↑firmness (RCO)	↑ L*, ΔE	↑protein ↑lipids, DF ↓available carbohydrate	CF pasta had higher OA compared with RCO pasta	Sykut-Domańska *et al.*, 2020
Flaxseed 5, 8, 13, 17, 23%	Ribbon short form	↑OCT ↓CL	↓firmness	↓ L*, b* ↑ a*, ΔE	↑protein, fat ↑IDF, SDF, DF ↓carbohydrate	NR	Zarzycki *et al.* (2020)
Grape (G), pomegranate (P) and rosehip (R) seed 10, 20, 30%	Noodles	↓OCT	↓hardness (P and R) ↑G	↑L*, a* ↓b*	↑TPC, AC	↓flavour OA ↓chewiness (G and R)	Koca *et al.* (2018)
Grape marc NR	Spaghetti	↓CL ↓WA, SI	↓adhesiveness	NR	↑TPC, TFC ↑AC	↓OA ↓adhesiveness ↓ bulkiness	Marinelli *et al.* (2015)
Grape pomace 5, 10%	Spaghetti	↓OCT, SI ↑CL	↑firmness ↑adhesiveness	↓L*, b* ↑a*	↑SDS ↓RDS ↓RS, pGI ↑TPC, AC	↑wine aroma ↑acid aroma ↑astringency ↑grittiness	Tolve *et al.* (2020)
Grape pomace 3, 6, 9%	Fettuccini	NR	NR	NR	↑TPC, AC	↑appearance ↑colour, smell ↑taste	Gaita *et al.* (2020)
Kimchi 2, 4, 6%	Noodle	↑CL, SI	↓adhesiveness	↓L* ↓a*, b*	NR	↓hardness ↓springiness ↓ texture ↓flavour	Kim *et al.* (2017)
Mango 5, 10, 15%	Maccheroni	↓OCT ↑CL	↓hardness	↓L*, b* ↑a*, ΔE	↑calcium ↑ascorbic acid ↑AC	↓appearance ↓texture ↓taste, OA	Jalgaonkar, Jha, & Mahawar (2018)

Table 1 (*Continued*)

Fortified pasta		Technological properties: Cooking properties	Texture	Colour	Nutritional and bioactive compounds	Sensory properties	References
Okara 5, 10, 15%	Noodle	↓OCT ↑CL	↓extensibility ↓tensile strength	NR	↑TPC, TFC	↓colour ↓flavour ↓texture, OA	Pan, Liu, & Shiau (2018)
Okara 10, 20, 30, 40, 50%	Macaroni	↓OCT ↑CL	↑hardness ↓cohesiveness	NR	↑protein, fat ↑DF ↓carbohydrates ↓ pGI, ↑ TPC, AC	↓flavour ↓texture, taste ↓ OA	Kamble *et al.* (2019)
Olive 10%	Spaghetti	NR	NR	NR	↑ TPC	↓ colour, taste ↓ firmness ↓bulkiness ↓ OA	Cedola *et al.* (2020)
Olive pomace 5, 10%	Spaghetti	↓OCT ↑SI, WA ↑CL	↑firmness ↑adhesiveness	↓L*, b* ↑a*	↓TPC, AC ↓RDS, pGI ↑SDS, RS	NR	Simonato *et al.* (2019)
Onion skin 2.5, 5, 7.5%	NR	↓OCT, SI ↑CL	NR	↓L*, b* ↑a*	↑DF ↓moisture, fat ↓carbohydrates ↑TPC, AC ↑TFC	↓sensory scores	Michalak-Majewska *et al.* (2020)
Orange 2.5, 5, 7.5%	Fettuccini	↑CL	NR	↓L*	↑ash, DF ↑carotenoids	↓appearance ↓OA ↓aftertaste ↓taste	Crizel *et al.* (2015)
Potato FPJ 30% DPJ 1.7%	NR	↓ CL	↑ firmness ↑ total work shear	↓ L*, b* ↑ a*	N	↓all sensory scores in DPJ sample	Kowalczewski *et al.* (2015)
Tomato 10, 15%	Spaghetti	↓OCT, SI ↓WA ↑CL	↑adhesiveness ↑hardness	NR	↓protein ↓carbohydrates ↑DF, lycopene ↑β-carotene	↓OA, colour ↓bulkiness ↓taste ↓adhesiveness	Padalino *et al.* (2017)
Watermelon rind 5, 10, 15%	Noodles	↓CL	↓firmness ↓adhesiveness	↓a* ↑b*	↑fat, DF ↓protein ↑TPC	↓elasticity	Ho & Che Dahri (2016)

AC, antioxidant capacity; CL, cooking loss; DF, dietary fibre; DPJ, dried potato juice; FPJ, fresh potato juice; IDF, insoluble dietary fibre; ND, no significant differences; NR, data not reported; OA, overall acceptability; OCT, optimum cooking time; pGI, predicted glycaemic index; RDS, rapidly digestible starch; RS, resistant starch; SDF, soluble dietary fibre; SDS, slowly digestible starch; SI, swelling index; TFC, total flavonoid content; TPC, total phenol content; TS, total starch; WA, water absorption.

granules, limiting their swelling and leaching into the cooking water and leading to pasta with low cooking loss, water absorption and swelling index, high firmness but low adhesiveness (Bustos, Perez & Leon, 2015).

However, the compositions of the different by-products added in pasta formulation can affect the physical and textural pasta's properties as well as the colour (Desai et al., 2019; Rachman et al., 2020).

Cooking properties of by-product fortified pasta

Cooking properties which are used to assess the pasta quality are optimum cooking time, cooking loss, water absorption index and swelling index (Nilusha *et al.*, 2019). One of the first technological parameters evaluated after pasta production is usually the optimum cooking time (OCT), defined as the time necessary to observe the disappearance of the central core when pasta is gently squeezed between two glass slides. In most cases, OCT is seen to be reduced after pasta fortification. For instance, OCT was observed to be reduced in pasta with olive and grape pomace (Tolve *et al.*, 2020) and onion skin powder (Michalak-Majewska *et al.*, 2020), this reduction of OCT is probably due to the increase in dietary fibre (DF) content that alters the structure of pasta, accelerates water penetration and allows an early starch gelatinisation.

A similar result was obtained in pasta with okara powder (Pan, Liu & Shiau, 2018; Kamble *et al.*, 2019), partially deoiled chia flour (Aranibar *et al.*, 2018), grape and pomegranate seeds powder (Koca *et al.*, 2018), and apple and mango peel powder (Lončarić *et al.*, 2014; Jalgaonkar, Jha & Mahawar, 2018). Instead, Zarzycki *et al.* (2020), Sykut-Domańska *et al.* (2020) and Nocente *et al.* (2021) observed an increase in OCT in pasta fortified with deoiled flaxseed, coconut flours, and brewers' spent grain. The rise in the OCT might be due to the competitive hydration tendency between proteins in the flaxseed and coconut flours, starch and gluten protein which decreased the starch swelling (Pongpichaiudom & Songsermpong, 2018).

Another essential parameter to assess pasta quality is cooking loss (CL). CL is evaluated by the release of solids from pasta into cooking water (AACC, 2000), and low cooking loss identifies the high quality of pasta depending on the capability of the gluten network to retain the starch granules and bioactive compounds during cooking processes (Nilusha *et al.*, 2019).

The addition of non-starchy ingredients could weaken the gluten network causing a loss of solids during pasta cooking. A CL value of 8% is the technologically accepted limit for dry pasta (Dick & Youngs, 1988).

Generally, pasta fortified with by-products has been shown to exhibit an increased CL compared with control pasta. Indeed, many authors reported such effect of fibre addition in pasta formulation with the inclusion of carrot flour, onion skin, olive pomace, grape pomace, tomato skin, orange fibre, by-product from kimchi, celery root, brewers' spent grain, sugar beet and coconut (Lončarić *et al.*, 2014; Crizel *et al.*, 2015; Gull, Prasad & Kumar, 2015; Porto Dalla Costa *et al.*, 2016; Kim *et al.*, 2017; Padalino *et al.*, 2017; Koca *et al.*, 2018; Minarovičová *et al.*, 2018; Pan, Liu & Shiau, 2018; Kamble *et al.*, 2019; Simonato *et al.*, 2019, 2020; Michalak-Majewska *et al.*, 2020; Sykut-Domańska *et al.*, 2020; Nocente *et al.*, 2021). However, as reported by Porto Dalla Costa *et al.* (2016), the inclusion of egg to the pasta fortified with fibre might contribute to a more compact protein network and could prevent /reduce the solid loss.

Kowalczewski *et al.* (2015) reported a lower CL in pasta fortified with fresh potato juice than control pasta due to potato proteins which likely form a more cohesive matrix with gluten, binding tighter the starch fraction. Moreover, Marinelli *et al.* (2015) found lower CL in spaghetti with added grape marc aqueous extract and suggested that the antioxidant compounds of grape marc extract could have formed complexes with gluten protein resulting in a more consistent gluten network and fewer losses in cooking.

Ho & Che Dahri (2016) recorded the same effect within watermelon rind fortified noodles. The authors debated that watermelon fibres could have competed against starch for water absorption preventing the leaching of starch granules themselves and leading to lower adhesiveness as well. Aranibar *et al.* (2018) and Zarzycki *et al.* (2020) concluded similarly for deoiled chia and flaxseed flour fortified pasta, respectively. The amount of water absorbed (WA) by cooked to optimum pasta is associated with starch swelling and gelatinisation and is linked to the swelling index (SI), an indication of the protein matrix integrity. A weakened gluten network allows an increase of starch granules WA and a faster gelatinisation, causing a SI increase. Generally, a good quality pasta, without the inclusion of additional ingredients, has WA in the range of 150–200 g of water/100 g pasta and a SI of approximately 1.8 (Bustos, Perez & Leon, 2015). The inclusion of by-products, as new ingredients, affects both parameters, influencing pasta microstructure (Bustos, Perez & Leon, 2015). Several authors pointed out a decrement in SI proportional to the pasta fortification level primarily caused by DF inclusion (Tudorică, Kuri, & Brennan, 2002; Tolve *et al.*, 2020). As for CL, dietary fibres included in onion skin, tomato skin and grape pomace weaken the gluten network and compete with starch for water absorption, resulting in lower swelling starch (Padalino *et al.*, 2017; Michalak-Majewska *et al.*, 2020; Tolve *et al.*, 2020). Specifically, as shown by Padalino *et al.* (2017), Padalino *et al.* (2019), during cooking, due to unlimited water availability, the level of water absorption is reached faster in pasta fortified with by-products rich in fibres compared to the control pasta.

Simonato *et al.* (2019) and Kim *et al.* (2017) showed opposite results in pasta fortified with olive pomace and kimchi fibres, respectively. The authors explained their findings with the unravelling of gluten structure, due to the DF of by-product added, that cause a major exposure of starch to the boiling water increasing in SI.

However, WA increased in pasta fortified with apple peel powder, and celery root and sugar beet by-product. Lončarić *et al.* (2014) suggested that pectin and fibres in apple peel may cause an increase in water retention. Instead, Minarovičová *et al.* (2018) reported the rise of WA in celery root and sugar beet fortified pasta to the strong water binding capacity of DF added. Nocente *et al.* (2019) observed a reduction of WA in pasta added with barley spent grain, probably due to less WA in barley fibre in comparison with starch granules. Marinelli *et al.* (2015) obtained similar results in pasta fortified with grape marc.

Textural properties of by-product fortified pasta

The main parameters used to evaluate the pasta textural properties are firmness and adhesiveness. The most used method to assess the texture profile of cooked pasta is the Texture Profile Analysis that uses texture analyser. Typically, to mimic the chewing action the texture assesses sequence involves contacting cooked to optimum pasta samples, compressing them, going back to the original contact point and repeating a second time the entire cycle (Bustos, Perez & Leon, 2015). Firmness or hardness is defined as the force required to penetrate the pasta samples with teeth and represents the degree of resistance to the first bite (Marti, Pagani, and Seetharaman 2014).

Firmness decreased in barley spent grain pasta and flaxseed cake pasta due to the increasing addition of fibres components which weaken the gluten matrices (Zarzycki *et al*., 2020). The same trend was observed for mango peel flour (Jalgaonkar, Jha & Mahawar, 2018), apple peel flour (Lončarić *et al*., 2014), rosehip seed flour and pomegranate seed flour (Koca *et al*., 2018) inclusion in pasta sample.

Pasta with grape pomace (Tolve *et al*., 2021), coconut residue (Sykut-Domańska *et al*., 2020) and tomato peel flour (Padalino *et al*., 2017; Padalino *et al*., 2019) showed a higher firmness than control, probably to the stiff structure of DF particle in these functional ingredient added.

Tudorică, Kuri, & Brennan (2002) suggested a relation between pasta firmness and the hydration/gelatinisation of starch granules during the cooking process. As such, the decrease in firmness may be associated both with an increase in pasta starch gelatinisation and with a reduced quantity of starch in the fortified pasta.

Adhesiveness, defined as the negative peak force required to separate the probe of the texture analyser from the pasta sample surface, was reduced by the inclusion of apple peels powder, grape marc aqueous extract, and coconut and kimchi by-products (Lončarić *et al*., 2014; Marinelli *et al*., 2015; Kim *et al*., 2017; Sykut-Domańska *et al*., 2020) likely to the action of DF from added ingredients which promoted the breakdown of the gluten network (Tudorică, Kuri, & Brennan, 2002).

However, in pasta fortified with olive by-products, adhesiveness increased in relation to dietary fibre content. Authors sustained that the increase of firmness could be due to the increment of fibre content, while the high water absorption is responsible for the adhesiveness increase (Simonato *et al*., 2019). This different behaviour of rich in fibre by-products can be explained, among other things, in the different ratios of the fractions of soluble and insoluble fibre present in the ingredient added. Thus, the physicochemical nature of fibre added should be considered (Rakhesh, Fellows & Sissons, 2015).

Generally, soluble fibres, characterised by high hygroscopicity, compete with the starch and protein for water upon hydration bringing to a starch not perfectly enclosed within the protein matrix that may form a 'starchy' layer at the surface of the product, resulting in higher levels of adhesiveness. Moreover, the weakening of pasta gluten matrix due to high fibre ingredient addition would increase the adhesiveness of samples because of starch leaching (Tudorică, Kuri & Brennan, 2002).

Rakhesh *et al*. (2015) emphasised that different sources of fibres (such as inulin, guar gum) have a different impact on pasta textural properties. Moreover, the author concluded that the mechanisms by which fibres affect the textural properties of pasta probably depend on interactions among protein, starch and fibres at the microscopic and molecular levels.

Colour of by-product fortified pasta

One of the most important parameters that define pasta quality is the typical yellow colour given by the high carotenoid content of durum wheat semolina. Colour plays an extremely important role and has a very strong influence on the final choice of consumers. The addition of other ingredients could strongly modify the colour of the new pasta formulations (Bustos, Perez & Leon, 2015).

Colour is expressed as L* a* b* values referred to the CIELAB colour space. L* conveys the perceptual lightness, a* is the red/green value, and b* represents the blue/yellow value. In most cases, the L* value decreased after pasta fortification.

Tolve *et al*. (2020), Lončarić *et al*. (2014), Jalgaonkar *et al*. (2018) and Kim *et al*. (2017) observed a reduction in the lightness (L*) of pasta with the addition of grape pomace, apple peel powder, mango peel powder and DF from kimchi, respectively. Instead, an increase in L* value has been shown in pasta fortified with coconut flour and orange fibre (Crizel *et al*., 2015; Sykut-Domańska *et al*., 2020). The addition of partially deoiled chia flour, barley spent grain and flaxseed flour caused a reduction of L* and b* values and an increase in a* value (Aranibar *et al*., 2018; Nocente *et al*., 2019; Zarzycki *et al*., 2020). Similar results have been obtained by Kowalczewski *et al*. (2015), Gull *et al*. (2015), Michalak-Majewska *et al*. (2020) and Simonato *et al*. (2019).

Other researchers have reported that pasta fortified with grape pomace and mango peel powder showed an increase of a* and b* values (Jalgaonkar, Jha & Mahawar, 2018; Tolve *et al*., 2020). However, apple peel powder and watermelon rind powder addition caused a reduction of the same values (Lončarić *et al*., 2014; Ho & Che Dahri, 2016). It is clear that the addition of by-products to pasta must be assessed carefully in relation to colour changes and consumer acceptability; however, this may be also dependent upon variations in consumer perceptions across the world.

Nutritional aspect of by-product fortified pasta

The addition of olive, carrot, artichoke, kimchi, potato and onion residues in pasta production has been evaluated (Porto Dalla Costa *et al.*, 2016; Pasqualone *et al.*, 2017; Simonato *et al.*, 2019; Cedola *et al.*, 2020; Michalak-Majewska *et al.*, 2020). The olive oil chain leads to the production of different residues sortable in by-products (olive pomace and wastewater) and wastes (olive leaves and wood; Difonzo *et al.*, 2021). Olive pomace is rich in phenolic compounds, mainly identified in caffeic, vanillic and coumaric acids (Padalino *et al.* 2019), and DF is used for pasta fortification to obtain a functional product with higher nutritional properties. Simonato *et al.* (2019) developed spaghetti functionalised by replacing durum wheat semolina with 5–10% lyophilised olive pomace. The by-product inclusion significantly affected the pasta's total phenolic content and antioxidant capacity. Very interesting is the capacity of olive pomace to affect the starch digestibility with a decrease in RDS and an increase in SDS due to DF (48% w/w) and phenolic content. As explained by the authors, DF could compete with starch granule for water adsorption, limiting the starch gelatinisation instead the polyphenols may inhibit the α-amylase and α-glucosidase activities contributing to the decrease of starch digestion rate. Encouraging results in term of phenolic compound and antioxidant activity were obtained in the pasta fortification with olive mill wastewater, containing hydroxytyrosol, tyrosol, caffeic, p-coumaric, vanillic, syringic, gallic acids as well as luteolin, quercetin, cyanidin and verbascoside (Obied *et al.*, 2009; Cedola *et al.*, 2020). Nevertheless, the concentration of bioactive compounds resulted in lower olive mill wastewater compared with the olive pomace suggesting the fortification strongly depends on the type of by-product used (Cedola *et al.*, 2020). Moreover, the content of DF in olive pomace is of great interest.

Sykut-Domańska *et al.* (2020) evaluating the effect of pasta fortification with two different by-products from the coconut (coconut flour and coconut residue) showed that increasing the by-products inclusion, caused a progressive increase in pasta's ash, protein, lipid, total and insoluble DF. Nevertheless, the pasta supplemented with the coconut residue was higher in protein, total and insoluble DF contents than the pasta added with coconut flour.

Similarly, the addition of the 20% of dried and milled carrot pomace, consisting of peel, shavings and peduncles, in pasta significantly increased the total DF content and the antioxidant capacity of about 608 and 132%, respectively, and interesting is the 388% increase of retinol in the cooked pasta containing carrot flour compared with the pasta produced with the commercial β-carotene (Porto Dalla Costa *et al.*, 2016). A significant increase in antioxidant capacity and total phenolic compounds (TPC) was also obtained with the inclusion of apple peel powder. The highest increase in TPC (1.4 g of GAE/kg) and antioxidant capacity (0.8 mg gallic acid equivalents/100 g) was obtained with the inclusion of 15% of apple peel powder (Lončarić *et al.*, 2014). Moreover, a significant increase in carotenoids (lycopene and β-carotene) and DF (soluble and insoluble) was obtained by Padalino *et al.* (2017) replacing up to 15% of durum semolina in pasta with tomato peel flour. In the same way, Pasqualone *et al.* (2017) obtained a 64 and 49% enhancement in TPC and antioxidant capacity, respectively, after incorporating outer bracts, leaves and stems, representing the by-products of artichoke canning, in fresh pasta dough. Michalak-Majewska *et al.* (2020) improved the pasta nutritional properties using onion skin powder raising the pasta DF, ash, TPC, flavonoids content and antioxidant activity. The enhancement of pasta nutritional value was obtained also with the inclusion of the watermelon rind powder in pasta formulation: ash, DF, fat, carbohydrate and TPC of supplemented pasta improved progressively with the increasing level of replacement compared with the control. However, a decrease in the protein content was observed (Ho & Che Dahri, 2016). In addition to vegetables, fruit waste contains several bioactive compounds. Frequently, to reduce the deterioration and increase the shelf-life and handling, the fruit waste is turned into powder by removing the moisture (Murakonda & Dwivedi, 2021) and used as a functional ingredient for pasta fortification. For this purpose, the by-product obtained from orange juice production, being an interesting source of antioxidant compounds and carotenoids (Romero-Lopez *et al.*, 2011) is also used as a functional ingredient. The inclusion of orange by-products (from 2.5 to 7.5%) significantly increased the total DF, up to 50% in pasta. A similar increase was shown for the total carotenoid and polyphenols content (Crizel *et al.*, 2015). The residue of winemaking, named grape pomace, was used by Tolve *et al.* (2020) to substitute durum wheat semolina at 5 and 10% in pasta preparation. From a nutritional point of view, the fortification with grape pomace determined a significant increase in the phenolic compounds and antioxidant activity attributing to the presence of gallic, ferulic, coumaric, rosmarinic, caffeic acid as well as epicatechin, rutin, quercetin, kaempferol and resveratrol (Gaita *et al.*, 2020). Besides, due to the high DF concentration, pasta fortified with grape pomace benefits specific claims. Finally, pasta fortified with 10% of grape pomace resulted in an increase of SDS and a decrease in RDS with a positive effect on the predicted glycaemic index (pGI).

Despite legumes being rich in proteins, fibres, minerals, especially Fe, Zn and Ca, and bioactive compounds, including polyphenols (Dodevska *et al.*, 2013), to the best of our knowledge, soybean okara, the by-product of soymilk and tofu preparation, is the only legume by-product currently introduced as an ingredient for pasta fortification (Pan, Liu & Shiau, 2018; Kamble *et al.*, 2019). About 2.5 kg of fresh okara, also called soybean residue, bean curd residue or dreg are obtained from 1 kg of soybean soaking (Mateos-Aparicio, Mateos-Peinado & Rupérez, 2010). Soy okara's major constituent is DF (40–58%), followed by protein (15–33%) and fat (8–11%) rich mainly in oleic, palmitic, and linolenic acid. Other components with physiological and therapeutic functions include isoflavones (genistein and daidzein), lignans, phytosterols, saponins, phenols and phytates (Mateos-Aparicio, Mateos-Peinado & Rupérez, 2010; Li, Qiao & Lu, 2012). For the high nutritional value, semolina was replaced with okara from 10 to 50% (Kamble *et al.*, 2019) and the obtained fortified pasta increased in ash, protein and fibre content. The substitution of wheat flour with okara flour, at the rate of 50%, increased the phenolic content and the antioxidant activity by about 68% and 18%, respectively. Similarly, Pan *et al.* (2018) reported that the okara flour inclusion in pasta resulted high in flavonoid content. The incorporation of okara flour led to a significant reduction in RDS and increased the content of SDS, inducing a slow rate of starch hydrolysis, responsible for the low glycaemic index response. The fortification with the highest amount of okara flour reduced the pGI by about 45%. On the other hand, the increase in okara flour content led to a significant reduction in protein digestibility, ascribed to the antinutrients in okara flour, especially trypsin inhibitor that acts on the protein digestibility through the inhibition of proteolytic enzymes activity (Gilani, Xiao & Cockell, 2012).

Deoiled flour obtained after seed oil extraction is a by-product characterised by a high nutritional value. Pasta preparation with chia seed by-product, a good source of protein, DF, lipid and polyphenols (Aranibar *et al.*, 2018) improved the nutritional properties, increasing in DF, omega-3, protein and minerals as well as the antioxidant activity.

In the same way, the production of flaxseed oil gives rise to a by-product, the flaxseed cake, rich in omega-3 and omega-6 fatty acids and phenolic compounds (Pag *et al.*, 2014). The inclusion of flaxseed cake from 5 to 23% in pasta formulation significantly increased pasta ash, protein, fat and DF contents reducing, at the same time, the carbohydrate contents (Zarzycki *et al.*, 2020).

Brewers' spent grain (BSG), the major by-product of the brewing process, is mainly constituted of DF (30–50%) specifically cellulose, hemicellulose and lignin and protein (20–30%) with lysine that representing approximately 14% of the total protein (Lynch, Steffen & Arendt, 2016). Considering the nutritional and functional properties, BSG is a valuable ingredient for the fortification of pasta. Nocente *et al.* (2019) showed that the replacement of 10 and 20 g of BSG/100 g semolina significantly increased fibre content up to 135%, β-glucan up to 85% and total antioxidant capacity up to 19% compared with the control durum flour pasta. Moreover, an increase in the content of resistant starch in fortified pasta and an increment of 39% of the Resistant/Total Starch ratio was observed with the addition of 10g of BSG/100 g (Nocente *et al.*, 2019). Similarly, investigating the nutritional potential of pasta made of einkorn and tritordeum brewers' spent grain, Nocente *et al.* (2021) showed that BSG from both kinds of cereals resulted in pasta with notable increases in protein, TDF and glucan content.

Sensorial aspect of by-product fortified pasta

Appearance, colour and flavour represent some of the most important sensory attributes of pasta as well as elasticity, firmness, bulkiness and adhesiveness (Marinelli *et al.*, 2015). A trained sensory panel evaluated the sensory characteristics of fortified pasta using a quantitative and descriptive analysis, known as QDA. The analysis of the data obtained by QDA allows building a specific sensorial profile. However, a consumer test is necessary to assess the product-market potential (Kowalczewski *et al.*, 2015). In general, the variation of the sensorial profile is modest or not significant for most pasta products with a low/medium fortification level.

Sykut-Domańska *et al.* (2020) showed that coconut flour and coconut residue addition up to 15 and 10%, respectively, did not harm the pasta sensory profile according to surface appeal, colour, smell, taste, hardness, stickiness and overall acceptability. Tolve *et al.* (2020) reported that the inclusion of grape pomace significantly reduced specific pasta attribute, such as pasta aroma and colour, and, at the same time, increased wine aroma, acidity and astringency. Pasta fortified with onion skin, even if almost all the evaluated attributes reached the threshold of acceptability, with the inclusion level up to 5% significant pasta colour changes and taste deterioration were reported (Michalak-Majewska *et al.*, 2020).

Similarly, pasta containing 10% soy okara had a sensory score similar to control for flavour, taste, texture and overall acceptability. Up to this level, a significant reduction in the evaluated attributes was observed caused by the beany flavour of legume-based sources (Kamble *et al.*, 2019).

At high enrichment levels, sensory properties were ingredient- and dose-specific, giving to the reduction of sensorial pasta attributes, such as grain taste and pasta colour as reported for celery root and sugar beet inclusion. These by-products are characterised, in fact, by brown colour and pleasant vegetable flavour (Minarovičová *et al.*, 2018).

As already mentioned, from a sensorial point of view, particular attention must be paid when the by-product is added up to 15% and is rich in fibre as for tomato peels (Padalino *et al.*, 2017). The addition of a high quantity of fibre in pasta can reduce the elasticity, for the disruption of the protein-starch network and increase firmness, due to the water absorption of fibres (Tudorică, Kuri & Brennan, 2002).

A comparable response was observed by Cedola *et al.* (2020) that included olive paste and olive mill waste in pasta. The substitution of durum wheat semolina with the olive by-products significantly compromised pasta's profile in terms of elasticity, firmness and bulkiness, due to the gluten network strength, as well as adhesiveness and colour (Cedola *et al.*, 2020).

As reported by Crizel *et al.* (2015), the sensory evaluation of pasta enriched with orange by-product showed that levels of incorporation decreased the consumer's acceptance due to the modification of the taste and the aftertaste. The low scores for these attributes can be associated with the presence of bitter taste due to orange seed and peel used in the preparation of the fibre imputable, in turn, to the presence of bitter compounds such as naringin, nobiletin, quercetin and tangeretin (Drewnowski & Gomez-Carneros, 2000).

The consumer's sensory evaluation of pasta enriched with soy okara in form of powder revealed that the inclusion of up to 10% significantly reduced the scores that the consumers gave in terms of colour, flavour, texture and overall pasta acceptability. Instead, the inclusion of the 5% did not show any significant difference between those and the control. However, consumers showed a higher preference for the pasta obtained at 5 and 10% fortification level with the simultaneous inclusion of vital gluten, often used to improve deficiencies viscoelastic properties (Pan, Liu & Shiau, 2018).

The addition of carrot flour by-product did not affect the acceptability parameters (Porto Dalla Costa *et al.*, 2016).

In some case, the by-product inclusion can even improve pasta attribute as reported by Gaita *et al.* (2020) in terms of appearance, colour, smell, and taste to a level of 3 and 6% using grape pomace skin and by Ho & Che Dahri *et al.* (2016) concerning colour and overall acceptability for noodles incorporated with 10% watermelon rind. The increase of consumer's acceptability was instead reported by Kowalczewski *et al.* (2015) in a study on fortified pasta with potato juice when compared to the control sample.

Although controversial, the findings reported above show the centrality of the sensorial analysis in the development of a new formulation of pasta fortified with by-products. Based on the type of by-product and its sensory characteristics, considering the composition and concentration used, the product obtained could differ substantially from the control, meeting or not the consumer's expectations.

Conclusion

Pasta is a staple food rich in carbohydrates but lacks in proteins and bioactive compounds. Nevertheless, pasta fortified with high added value ingredients can represent an excellent carrier of nutrients. To this purpose, researchers proposed new pasta formulations exploiting the utilisation of ingredients derived from agro-industrial by-products. Indeed, many food wastes are rich in bioactive compounds able to improve pasta nutritional value and to meet the consumers' needs.

Nevertheless, fortification can affect the technological properties of pasta, mainly because the addition of new ingredients, especially rich in fibre, can alter the gluten matrix and consequently the pasta structure. So that it seems extremely important to a deep understanding of the effect of different fibre and the combination of soluble and insoluble fibre on the pasta texture and cooking properties. Moreover, it would be helpful for a deeper investigation from a microstructural viewpoint on the protein, starch and phenolic compound interactions on the textural and digestibility properties of pasta, also affecting the glycaemic index of the fortified product. New formulation pasta acceptability is generally good but strictly depends on the quantity of fortification added ingredient.

Finally, the innovative pasta recipe production utilising ingredients from industrial by-product is in the frame of sustainability and circular economy.

Conflict of interest

The authors declare that there is no conflict of interest.

Ethical approval

Ethics approval was not required for compiling and presenting this review.

Author contributions

Federico Bianchi: Writing-original draft (equal). **Roberta Tolve:** Writing-original draft (equal). **Giada Rainero:** Writing-original draft (equal). **Matteo Bordiga:** Writing-review & editing (equal). **Charles Brennan:** Writing-review & editing (equal). **Barbara Simonato:** Writing-review & editing (equal).

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Data availability statement

Data sharing is not applicable to this article as no new data were created or analysed in this study.

References

The paper described the impact of olive pomace and olive mill waste water addition in pasta. While the waste water slightly improved the antioxidant properties and the total phenolic compounds, the olive pomace considerably enhances the above-described properties. From the sensorial point of view, the olive pomace fortified pasta had less acceptability.

The manuscript reported the impact of okara addition in pasta. The outcome showed that the by-product increased the total phenols content and the antioxidant properties as well as the fibre quantity and reduced the glycaemic index of the fortified pasta.

The paper described the effects of spaghetti fortification with grape mark aqueous extract and showed that this winemaking by-product allowed an increase in total phenolic compounds, flavonoids and antioxidant capacity in fortified pasta. Good acceptability of pasta was described indicating that is possible to exploit this by-product to satisfy the consumers' healthy food demand.

The paper investigated the effect on the technological sensory and nutritional properties of carrot waste in fortified pasta. In particular, it was observed an increase in carotenoid, antioxidant capacity properties and fibres in enriched samples. The pasta had good sensory acceptability.

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