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Finding wholegrain pasta quality: what are the challenges and opportunities?

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Abstract

This review approaches the challenges and opportunities regarding wholegrain pasta's quality. Bibliometric maps were created to help visualize wholegrain pasta studies' main themes and chronology. Most research findings have focused on digestibility and nutritional enhancement, although concerns such as raw materials and processing conditions require further investigation. The main challenges are regulatory harmonization and developing quality standards to evaluate and produce wholegrain pasta. Thus, further research is necessary to overcome these challenges and improve technological and sensory quality of wholegrain pasta.

Keywords: processing; milling techniques; cereal science; nutrition; food technology; fibers.

Practical Application: Overview of the main challenges for better-quality wholegrain pasta applying bibliometric maps.

1 INTRODUCTION

Wholegrain pasta (WGP) consumption has increased globally since research findings and nutritional recommendations associate the intake of wholegrain cereals with direct health benefits (Guo et al., 2022). These effects are mainly related to the components of the bran layer, such as fibers, antioxidants, and minerals (Baky et al., 2024; Okarter & Liu, 2010; Slavin, 2004).

The fibers are carbohydrate polymers that are not digested or absorbed in the small intestine of the human gastrointestinal tract. However, fiber ingestion is essential for health, and daily intake is recommended by consuming fruits, vegetables, and wholegrains.

According to its characteristics, dietary fiber can be classified into soluble and insoluble fractions. Insoluble fiber is bulky, resistant to enzymatic degradation, and related to intestinal transit regulation and satiety. It is also helpful in controlling the glycemic index after meals. Due to its role in intestinal health, it prevents constipation and colorectal cancer occurrence (Baky et al., 2024; Castro et al., 2018) and reduces the risk of chronic non-communicable diseases (Jonnalagadda et al., 2011). In contrast, soluble fibers, such as beta-glucans, pectin, and mucilage, have a gelling capacity and are fermentable by benefic microorganisms, responsible for short-chain fatty acid production and protective effects of the intestine (Baky et al., 2024). As indicated in the review study of Gong et al. (2019), whole wheat cereals did not significantly change the intestinal microbiome. However, the ingested ferulic acid—a compound found mainly in wheat bran fractions—increased the abundance of beneficial microorganisms, such as lactic acid bacteria (BAL) and *Bifidobacteria*, that could reduce intestinal inflammation.

Indeed, phenolic compounds in the human diet have potential health benefits due to their antioxidant and anti-inflammatory properties. Studies on wholegrain products have pointed out that phenolic acids and components derived from benzoic or cinnamic acid were predominant in wholegrain wheat flour (WWF) due to the presence of bran.

For example, in the study of Zaupa et al. (2014), analyzing the antioxidant phenolic acid content in durum wheat bran, ferulic acid was the main antioxidant (50.2–210.4 mg/100 g), followed by p-coumaric acid (3.4–8.7 mg/100 g), and sinapic acid (1.7–7.6 mg/100 g).

Phytosterols, which are substances related to health-promoting effects due to the reduction of total and low-density lipoprotein cholesterol levels (Salehi et al., 2021), are also present in grains such as wheat grains, identified and quantified as β-sitosterol, campesterol, stigmasterol, and brassicasterol (Bartłomiej et al., 2012).

Despite the mentioned studies regarding the nutritional benefits of wholegrain product consumption, most sensory studies with consumers highlight descriptors such as "brittle," "coarse," and "unpleasant flavor" for WGP (Manthey & Schorno, 2002; Marti et al., 2017). Moreover, instrumental assessments of cooking quality have shown that these products have a higher cooking loss after cooking, resulting in higher adhesiveness

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than semolina pasta. However, there is still scarce literature on the technological and sensory evaluation of WGP that could be useful for its quality improvement.

Quality is a multifactor concept that incorporates a product's chemical composition, physical structure, and relationship to safety, nutrition, and overall sensory perceptions. It also refers to a product's capacity to present desirable and expected attributes of color, texture, and flavor that could be measured and predicted (Cardello, 1995).

In this context, the present work aims to establish an overview of the challenges regarding WGP's quality and evaluate the opportunities for the best quality of these products.

2 STATE-OF-THE-ART OF WGP STUDIES

A bibliographic search was done using five databases: Web of Science, ScienceDirect, *Scopus*, *Scielo*, and *Google Scholar*. Studies published from 2011 through 2023 were selected using the following search terms: "wholegrain AND pasta," "wholemeal AND pasta," "whole wheat grain AND pasta," "whole wheat AND pasta," and "wholegrain pasta AND quality." Titles, abstracts, and keywords were searched. There was no restriction regarding the language of the papers.

For the elaboration of Figures 1 and 2, the Elsevier Scopus database was explored using the following search sequence: "wholegrain pasta" AND "food" AND "wheat flour" AND NOT "gluten-free." The articles were screened by reading the title and abstract, and all documents unrelated to the topic were excluded. All original articles that investigated and reported information on WGP from 2011 to 2023 were included. The information from the articles generated by the research was selected and exported in CSV format and later used to build bibliometric maps of the occurrence of terms using the VOSviewer v1.6.19 software (Leiden University, Netherlands).

Based on the inclusion and exclusion criteria, 29 articles were selected and used to create the bibliometric map. The occurrence network shown in Figure 1 was built considering a minimum of three occurrences of the keywords found in the selected publications. Figure 1 provides an overview of WGP research, showing that the most significant search terms are assigned in a network of clusters (each color represents a different cluster), where larger nodes represent more frequently used keywords. As a result of this analysis, 387 keywords were part of the occurrence network, resulting in 39 linked items and four distinct clusters.

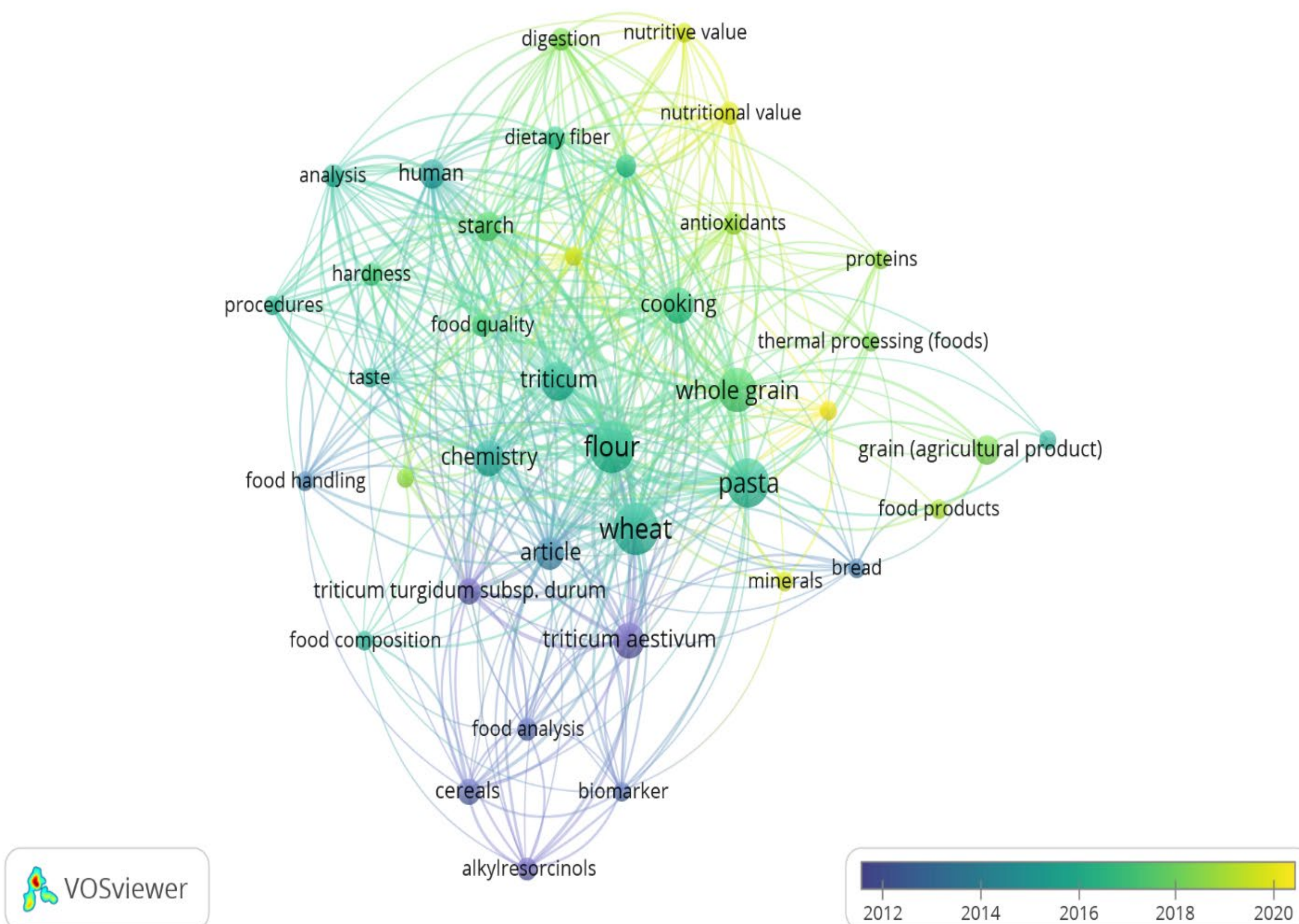

Figure 1. Keywords co-occurrence of wholegrain pasta (WGP) studies developed by VOSviewer v1.6.19.

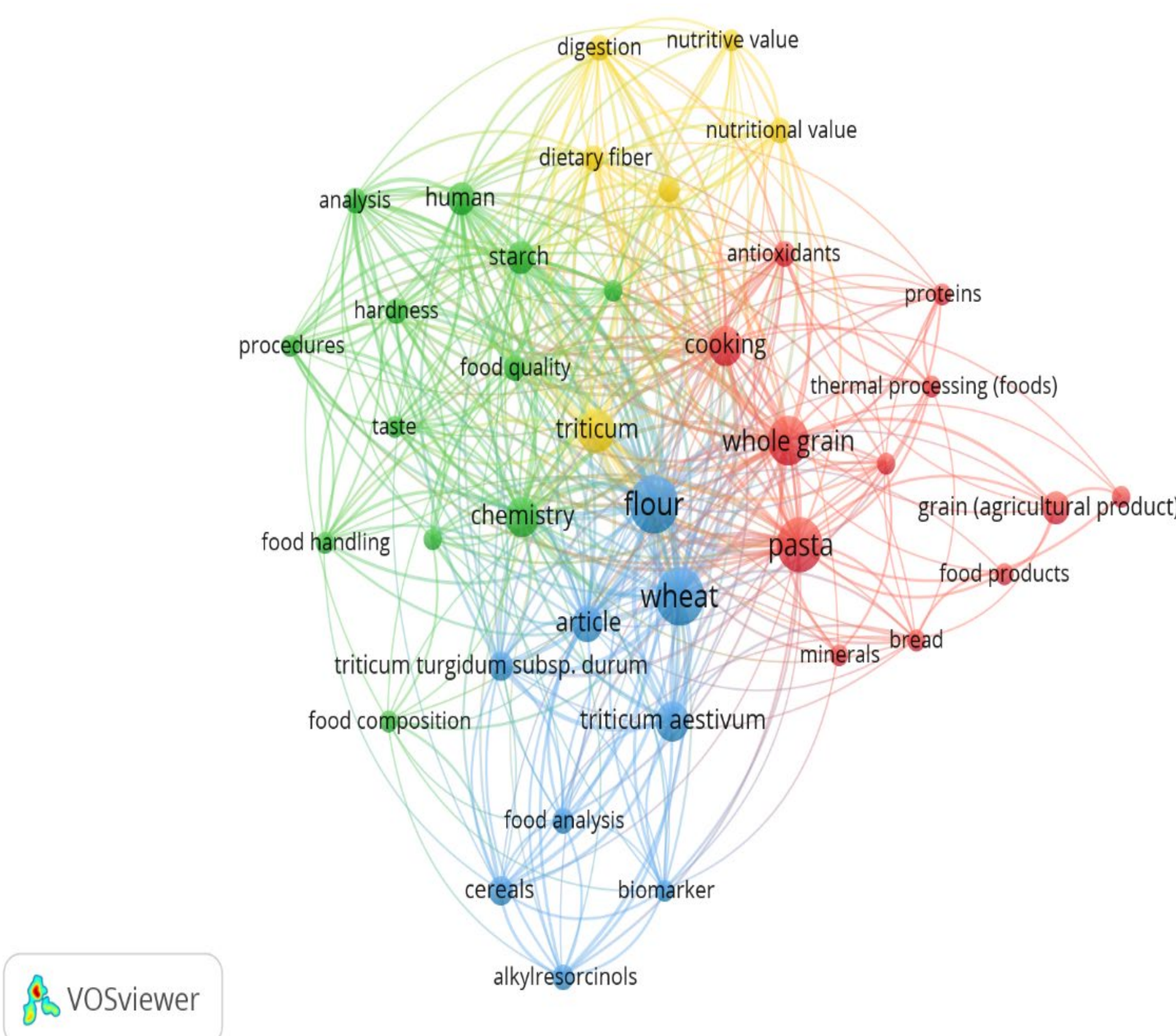

Figure 2. Keywords co-occurrence map and chronological classification of wholegrain pasta (WGP) studies developed by VOSviewer v1.6.19.

Figure 1 shows the chronology of WGP research. First, the studies were related to biomarkers of wheat types and food composition. In the latest studies, the interest of researchers has focused on aspects related to the nutritional value of pasta, digestibility, and levels of compounds with health benefits, such as antioxidants and dietary fibers.

In Figure 2, the largest cluster (red lines) is related to studies about cooking and food composition (antioxidants and mineral content). The second cluster (green) presented keywords mainly related to some of the most frequently used food analyses for pasta: hardness, chemistry characterization, and starch evaluation.

After evaluating the collected data, it was possible to identify challenges related to the processing and consumption of WGP, which will be detailed in the following sections.

3 CHALLENGES AND OPPORTUNITIES REGARDING WGP

3.1 Regulatory issues

Regulatory issues play a crucial role in the food industry, ensuring the safety and integrity of food products and establishing quality standards. Adhering to these standards guarantees that consumers receive products of consistent quality, taste, and nutritional value. Considering the WGP regulation, there is a global effort for consensual regulation, and many countries, such as Brazil and Malaysia, recently developed definitions for wholegrain products, as presented by Van der Kamp et al. (2022). Many efforts have been made to harmonize quality standards and composition, aiming to provide direction to the industry and comprehensive information to the consumer. Some examples of current definition standards are:

- For European Union countries, there is no legal definition of WGP. Regulation 1308/2013 only mentions that wholegrains are "grains from which only part of the end has been removed, irrespective of characteristics produced at each stage of milling";
- In Italy, "whole wheat semolina pasta" is obtained from hydration, formatting, and consequent drying of dough prepared exclusively with whole wheat semolina and water. The regulation presents pasta quality's composition and physical-chemical parameters, including WGP. The production of pasta with common wheat is not allowed (Italia, 2001);
- In Brazil (Brasil, 2022), "wholegrain products," including WGP, should contain at least 30% wholegrains, and this quantity should exceed the refined grain proportion. Also, the percentage of wholegrains in the product's composition should be mentioned on the nutritional label. The use of reconstituted WWF is allowed, but its quantities should ensure that all anatomical components of grain are present in the typical proportion that occurs in intact caryopsis. This flour will also be declared in the list of ingredients as reconstituted WWF, followed by the common name of the grain.
- The United States Food and Drug Administration (FDA), in Sec. 139.138 of the Code of Federal Regulations, points out some of the nomenclature and composition requirements for WGP but without a specific definition or quality standards. However, the FDA has standards and regulations for the use of claims such as "whole" or "wholegrain" on food labels (FDA, 2006). When a food is labeled "whole" or "wholegrain," it generally means that it contains all parts of the grain—the bran, endosperm, and germ. The FDA also has specific guidelines for using the "100% wholegrain" claim on food labels. This means that all the ingredients in the product are whole, without adding refined ingredients.

Wheat is the most recommended grain used as a raw material for pasta production (*Triticum* spp.). It is the second most important crop worldwide, and in 2022, more than 777 million tons of these cereals were harvested (FAO, 2023). Wheat is preferred for pasta making due to its ability to form a gluten matrix, which maintains structure during processing and cooking.

This cereal belongs to the grass family (*Poaceae*). Its edible part is oval or rounded, sized between 5 and 9 mm, and weighs between 35 and 50 mg. Its flour or derived ingredients, such as starch and protein isolates, are consumed in several food products, such as pasta, bread, cake, and biscuits, and they are also used as a thickener in creams, desserts, or sauces.

The global consensus and standards direct the selection of durum wheat semolina as the most appropriate raw material for pasta production. The durum wheat has an amber-colored kernel and significant gluten-forming protein content (Bresciani et al., 2022). Different from common wheat, which is widely cultivated worldwide, durum wheat is very restricted, representing 3–5% of global wheat production. It is cultivated in regions of the Mediterranean Basin and North America, and when milled, it results in semolina that could be used for pasta, bread, and couscous production (De Vita & Taranto, 2019).

Furthermore, WGP's challenges are linked to WWF regulation issues, as seen by the following definitions provided by several countries or international actions:

- According to the Code of Federal Regulations of the U.S. Food and Drug Administration (FDA, 2023), WWF is prepared by the milling of clean wheat, maintaining all the natural constituents of the grains, and more than 90% of this flour must pass through a 2.36-mm sieve, and not less than 50% must pass through an 850-µm sieve.
- In the Canada Food and Drug Regulation (2023), WWF must contain at least more than 95% of the constituents of the original grain. It also needs to present some quality parameters of composition: an ash content of not less than 1.25% (at dry basis, d.b.) and not more than 2.25%, and a maximum moisture content of 15%. For granulometry, the requirements are that not less than 90% pass through an nº eight sieve (2,380 µm) and not less than 50% through an nº 20 sieve (840 µm).
- The Argentine Food Code defines "wholegrain flour" as the product obtained by grinding the wholegrain of wheat, which, according to granulometry, can be classified as coarse, medium, or fine, and the maximum contents are 15.5 g/100 g for moisture and 2.3 g/100 g for ash (Código Alimentario Argentino, 2022).
- In Spanish legislation, WWF is the product resulting from the grinding of whole cereals by different processes, with one or more grinding stages during which the components of the grains are separated. The denomination is made with the name "whole flour" or "wholegrain flour," followed by the name of the cereal from which it comes. Bran flour is the product of mixing flour with bran from one or more cereals. Spanish legislation also defines micronized flour as one in which at least 95% of the particles pass through the sieve with the smallest granulometry, that is, with a particle size of less than 100 µ (España, 2016).
- According to the FDA (2023), WWF, or graham flour, could be defined as food prepared by grinding cleaned wheat, other than durum wheat and red durum wheat that presents the following granulometry characteristics: not less than 90% passed through a 2.36 mm sieve, and not less than 50% passed through an 850 µm sieve.
- In Brazil, according to Normative Instruction nº 8 of 2005 (Brasil, 2005), wheat flour is a product made with wheat grains or other species of wheat through crushing or milling from the complete processing of the clean grain with or without the germ. As for the quality standards for WGF, the standard presents criteria regarding the physical-chemical composition of this

product, which must present a maximum fatty acidity of 100 mg KOH/100 g, a maximum ash content of 2.5%, and a minimum protein content of 8%, without definitions about particle size distribution. The limit of losses is 2% of the grain or 10% of the bran.

The WWF regulation consequently affects the composition and labeling of wholegrain products, including WGP. It was observed that when there are definitions for these products, they differ according to national regulatory authorities, which can be difficult for the industry and confusing for consumers (van Der Kamp et al., 2014).

The WGP lacks studies on selecting the best suitable wheat varieties, which is a significant challenge. Most WGP studies make use of whole wheat semolina or WWF. Durum wheat (*Triticum turgidum* ssp. durum) is the most used wheat variety in WGP studies (Chillo et al., 2008; Ciccoritti et al., 2017; Suo et al., 2023; West et al., 2013b), followed by common wheat (*T riticum aestivum*) (Bock et al., 2015; Vignola et al., 2018; Wahanik et al., 2021).

Common wheat is used in pasta production in countries that do not produce durum wheat and do not have adequate equipment for milling this cereal. This lowers the high cost of imports and makes a more accessible product available to consumers. However, there is a lack of quality parameters for common wheat-based pasta, and other protein-rich ingredients, such as eggs and wheat gluten, are needed to meet consumer demand for flavor and color, given that durum semolina pasta has a yellow color and *al dente* firmness after cooking.

Wheat milling aims to reduce the particle size of wheat fragments and separate the starchy endosperm, which contains mainly starch and gluten-forming proteins, from the outer layers of the wheat kernel, including the bran and germ. The milling techniques and equipment have evolved, starting from grinding stones used to crush grains manually, improved using animal traction, wind, or water as mechanical energy, and in the Industrial Revolution introduced mechanized milling processes and enhanced the scale of production that significantly increased the milling capacity for wheat flour production and allowed the WF refining.

Technological investment in flour refining created new methods and equipment for flour and semolina production, such as the roll mills. In the roller milling process, the wheat grain passes through a series of corrugated and smooth rollers, causing the separation of endosperm, bran, and germ fractions.

However, in WWF, the presence of bran is desirable (Prabhasankar & Rao, 2001). The stone mill was the first equipment used for its production. It consists of passing the wheat grains between two stones, which causes grain fragmentation due to the compression, shear, and abrasion forces (Cappelli et al., 2020).

It is also possible to obtain WWF with the products from the roller milling methods after a subsequent mixture of bran and germ with endosperm flour within natural proportions. That could occur through two processes: recombination or reconstitution. In recombination, the grains are milled and sieved in the same way to produce the refined flour, but the fractions are remixed to produce WWF. For reconstitution, bran and flour not from the same batch could be mixed, maintaining the same proportions in the intact grain. This is usually done when the bran undergoes some post-grinding or heat treatment for stabilization by enzymatic inactivation. In this case, it is necessary to invest not only in the processes involving the bran but also in equipment for recombining the fractions (Doblado-Maldonado et al., 2012; Ross & Kongraksawech, 2018). When producing WWF in roller mills, some conditions differ from those used for stone milling. For example, conditioning is obtained by adding water to the grains to increase bran toughness and improve the separation between the endosperm and bran fractions, which is optional in stone mills.

The milling process has many variables that could influence the quality of pasta, such as particle size and damaged starch proportion. The fiber fragments of bran affect the water-holding capacity, dough hydration, and gluten-matrix development. On the contrary, damaged starch influences the pasta's cooking properties, affecting the cooking time and firmness. Thus, it is crucial to consider that the milling method should not increase above the temperature of WWF or cause excessive damage to starch fractions.

Each method will result in a distinct particle size distribution and composition, and raw material requirements exist for semolina for pasta production but not for WWF, which motivates more research. In the Bressiani et al. (2019) study, the authors evaluated the effect of the particle size of WWF on the thermo-mechanical properties of flour through Mixolab equipment. They found that particle size influences the functionality of the gluten network. In their studies, Deng et al. (2017) and Deng and Manthey (2019) explored single-pass and multipass milling systems for producing WWF blends intended for *spaghetti*. They found that blends of semolina with either fine or coarse bran led to firmer pasta after cooking, with minimal cooking loss.

Understanding the milling processes of the raw materials is essential for predicting WGP quality. Thus, given the valuable information that could be obtained and the diversity of wheat varieties and WWF obtention methods, more investment in WWF research for WGP production is still required.

For example, Cappelli et al. (2020) investigated the impact of stone milling parameters on the yield, productivity, and energy efficiency of milling common WWF. They found that preconditioning the wheat significantly influenced the rheological properties of the dough, particularly in the context of bread making. This insight suggests that the preconditioning stage should also be considered when processing WGP, hinting at potential benefits for pasta quality.

Aside from the raw materials, another opportunity for composition challenges is the use of other wheat varieties, as explored by the authors Suo et al. (2023), who evaluated WGP produced with pigmented and ancient wheat. The main advantages of these raw materials were increased phenolic content and antioxidants, which were associated with greater sensory acceptability compared to pasta formulated only with durum wheat semolina.

Cappelli et al. (2020) emphasize the importance of adopting sustainable practices in both the cultivation and processing phases of WWF production. This approach includes efforts to minimize the use of pesticides and fertilizers, promote responsible soil management, and reevaluate milling processes to improve energy efficiency to enhance the sustainability of WWF production.

3.2 Production processes of WGP

Pasta production begins with the hydration of the dry ingredients (flours or starches), followed by the formatting of the dough, which could be manual or toward the use of equipment such as cold extrusion, thermoplastic extrusion, or laminators. The obtained fresh pasta could also be dried by several methods for humidity removal—ambient temperatures, convection-air ovens, or pasta dryers with specific thermal ramps. Considering the diversity of WWF, different types of WGP could be made.

Table 1 summarizes information on the processing and characteristics of WGP studies reviewed in the literature. The WGP ingredients maintained clean label characteristics without using additives or ingredients such as eggs or vital gluten. The composition of WGP was predominantly based on durum wheat semolina, and all articles addressed the regulation of each country of study.

As observed in several studies, the methods for WGP production were not adapted, considering the differences caused by bran interference in the gluten matrix.

Considering the formats, the studies that evaluated long pastas were predominant. It is essential to highlight that the processing parameters, such as the quantity of water for pasta hydration, mixing time, and drying conditions, directly influence the pasta production process and are related to flour characteristics, especially considering WWF (Deng & Mantey, 2019). However, few studies have focused on the influence of processing conditions on WGP quality. For example, in the Bock et al. (2015) study about the quality and processing comparison between refined wheat flour pasta and WGP, the higher temperatures (> 80°C) encouraged the formation of a compact gluten network in refined pasta that contains a substantial number of hydrophobic interactions. In contrast, the same conditions result in a structured network in WGP, which is less driven by hydrophobic interactions. The authors also verified that low-temperature drying produces a gluten network with properties comparable to semolina pasta. Thus, more studies could be conducted to verify the real needs of WGP production or process adaptation.

3.3 Technological quality of WGP

The semolina pasta presents consolidated analysis parameters for its quality due to the development of standards for raw materials and pasta production, drying, and packaging.

However, for WGP, the same range of technological evolution was not observed, and the methods are adapted for data collection but still without clear parameters of desirable characteristics or defects.

Frequently, WGP is categorized as "darker" or "brittle" compared to semolina pasta, but without proper evaluation methods. Since WGP has no specifications for evaluating cooking quality, this is the main challenge in creating quality standards.

Considering the color analysis, the addition of bran modifies the color of the pasta, resulting in a darker (reduction of L* value), less yellowish (reduction of b* value), and reddish (an increase of a*) color (Vignola et al., 2018). These modifications occur due to the fractions from the pigmented pericarp layer present in the bran fraction. They could be influenced by aspects such as flour production method, final granulometry of WWF, flour composition, or oxidation degree of compounds of flour. Thus, the color evaluation of the WWF used as raw material for WGP could be an important parameter in evaluating the possible degradation of bran-colored compounds.

The cooking quality methods for pasta include weight increase, cooking loss, or water absorption. The bran's strong tendency to absorb water may result in the water competing with other flour components for hydration, such as starch and gluten, influencing the firmness of WGP (Roozendaal et al., 2012).

One of the most reported defects to WGP, as shown in Table 2, is related to the interruption of the gluten network and the impacts of the weakening of the gluten network or by-products derived from the bran or germ components. According to Vignola et al. (2018), the WGP may have a more fragile and brittle structure, with more significant starch leaching in the cooking water (loss of solids) and surface adhesiveness. The presence of the germ also affects the final texture of the WGPs, as the by-products generated by the lipoxygenases also interfere with the formation of cross-links in the gluten network, weakening it (Brandolini & Hidalgo, 2012).

The cooking loss is related to the lixiviation of components such as starch or soluble proteins during cooking, total cooking time, and textural properties, such as stickiness, firmness, hardness, or adhesiveness. The color comparison before and after cooking, or the presence of spots, is also used as a comparative quality method related to the raw material extraction rate and conservation of carotenoid content, especially for wheat semolina pasta.

Focusing on the new quality evaluation methods, in a study developed by Badaró et al. (2021), the authors evaluated the application of near-infrared hyperspectral imaging as a non-destructive method for identifying the fiber distribution in pasta based on semolina (*Triticum durum*) and bamboo fiber.

Other important aspects that could be better developed for WGP are related to food safety, from the evaluation of bioactive compounds and mycotoxins. In the study by Tibola et al. (2015), the authors evaluated the presence of deoxynivalenol (DON) and found that mycotoxin levels were superior in bran layers of wheat-milled fractions. As addressed in the review by Gómez et al. (2020) focused on whole grain breads, the contamination by residues of pesticides (herbicides applied pre-harvest), insecticides, and mycotoxins (mainly aflatoxin and deoxynivalenol – DON) can be found in greater quantities in wheat bran fractions, and consequently, in wholegrain foods. Mycotoxins indicate failures in grain processing, and the main

Table 1. Compiled from studies from 2017 to 2023 on the properties of wholegrain pasta.

Authors and country	Objective of the study	Ingredients	Samples	Processing conditions	Cooking loss (%)	OCT (min)	Water absorption (g/100 g)	Hardness (N)	Main findings
Marti et al. (2017) Italy	Characterize commercial wholegrain dry *spaghetti* samples representative of the Italian market from both molecular and electronic senses (electronic nose and electronic tongue)	Wholegrain organic durum wheat semolina, or wholegrain durum wheat semolina.	10 WGP	Industrial processing (conditions n.m.)	3.38–4.7	n.m.	107.8–155.2	n.e.	Quantification of higher ε-poly-L-lysine and furosine levels were correlated to heat damage, characterized by e-nose sensors as "more bitter" (3 of 10 samples). There was no significant difference between organic and conventional WGP
Vignola et al. (2018) Argentina	Developed dry WGP spaghetti with WWF of two wheat cultivars and produced two different types of wheat flour and evaluate the influence of flour particle size on cooking parameters and texture	WWF (*Triticum aestivum*) from two cultivars (Klein Guerrero and Baguette Premium), 0.1% salt	Two control pastas and four WGP	Labscale processing. Mixing and water are added to dry ingredients for 3 min to obtain a homogeneous dough, extruded (domestic pasta extruder) without vacuum. Drying program: 30 °C (30 min, without humidity control), 45 °C (17.5 h, 75% RU). Stored at room temperature	5.7–6.4	13.0–15.0	119.0–133.0	26.1–31.2	The WGP showed greater hardness and lower values of water absorption, swelling index, and optimal cooking time in comparison to control
Diantom et al. (2019) Italy	Identify analytical protocols to evaluate cooked pasta (dry *penne rigate*) quality with a multi-scale analysis of four commercial kinds of pasta	Pasta composition: Control pasta-durum wheat semolina (100%); WGP—wholegrain durum wheat semolina (100%); *veggie pasta*; *gluten-free pasta*	Four distinct pastas of the same brand (control, WGP, veggie, gluten-free)	Industrial processing (conditions n.m.)	n.e.	9.0	n.e.	7.6	Control and WGP had a more pronounced viscoelastic behavior, higher hardness, higher mobility of the more rigid protons than veggie and gluten-free pasta
Wójtowicz et al. (2020) Poland	Determine the effect of flour on the chemical composition, nutritional value, and quality properties of extrusion-cooked *spaghetti*	White wheat flour (*T. aestivum*), wholegrain wheat flour (n.e.), white spelt wheat flour, and wholegrain spelt flour	Four pastas (one to each flour)	Labscale processing. Mixture and hydration of ingredients (32% of moisture) for 15 min, resting of dough (30 min), extrusion in a single-screw extruder (screw speed of 100 rpm, 85 °C in section I, 105 °C in section II, 75 °C in the cooling section and 65 °C at the die plate). Drying at 40 °C until 7% of moisture. Storage at room temperature	11.9	6.0	222.6	6.7	WGPs showed the higher cooking loss and water-holding capacity, and were less firm than the other pasta
Wahanik et al. (2021) Brazil	Evaluate the use of natural-colored concentrates in WGP fresh *spaghetti*	Wholegrain wheat flour and refined wheat flour (*Triticum aestivum*) ratios—60:40, 70:30, and 65:35). 1.5% Yellow concentrate (safflower extract), 2% pink concentrate (cherry, purple sweet potato, apple, and radish extracts)	Twelve pastas (two response surface designs for each colored concentrate, and two control pasta (70% wholegrain flour and 30% refined wheat flour) with the inclusion of concentrates in 1, 1.5, or 2%	Labscale processing. Mixing and hydration of dry ingredients for 3 min to obtain homogeneous dough, extrusion (cold extruder, without vacuum). Stored at refrigeration (4°C)	3.6–4.5	3.5–4.0	93.0–106.8	n.e.	Yellow pasta (60:40 and 1% yellow concentrate) and pink pasta (70:30 and 1% pink concentrate) showed similar texture, weight gain, and cooking loss to the control pasta. The natural-colored concentrates inclusion contributed to the increase in antioxidant capacity
Suo et al. (2023) Italy, China	Evaluate consumer's acceptability, bioactive compounds, and antioxidant activity and physical quality of WGP (dry *Paccheri*) made with two different wheat varieties	Durum wheat semolina, durum whole wheat flour (Senatore Cappelli), pigmented durum whole wheat flour (Grano Mischio)	1 Control pasta 100% durum semolina, and 2 WGP	Industrial processing (conditions n.m.)	5.0–5.9	14.0	n.e.	31.5–35.3	The pigmented WGP presented the highest total phenolic content after cooking and showed no significative differences of control pasta for cooking loss and texture

n.e.: not evaluated; n.m.: not mentioned; WGP: wholegrain pasta; WWF: wholegrain wheat flour; OCT: optimal cooking time.

Table 2. Defects related to wholegrain pasta.

Defects	Related causes
Dark coloring and color change after cooking	Effect of staining outer bran layers, enzymatic browning
Fragile and brittle structure of cooked pasta	Interference of bran and germ in the formation of the gluten network; weakening of the protein network by the fibers and excessive leaching of amylose during cooking
Excessive adhesiveness and stickiness	Excessive leaching of amylose during cooking, forming a superficial layer of starch on the pasta
Residual bitter taste	Lipid oxidation (germ); 5-hydroxymethylfurfural aldehyde derivative; low molecular weight peptides; free phenolic acids (bran)
Presence of undesirable aftertaste ("grassy," "branny")	Compounds derived from lipid oxidation, the catalytic action of endogenous enzymes on compounds derived from bran and germ

challenge is establishing protocols for the main mycotoxins found in wheat and considering the mycotoxin presence as a criterion for WGP quality control.

As addressed in the review by Gómez et al. (2020). focused on whole grain breads, the contamination by residues of pesticides (herbicides applied pre-harvest), insecticides, and mycotoxins (mainly aflatoxin and deoxynivalenol — DON) can be found in greater quantities in wheat bran fractions, and consequently, in wholegrain foods.

3.4 Sensory acceptance of WGP

According to research by the International Food Information Council (IFIC, 2018), 80% of consumers recognize wholegrain food products as beneficial to health. However, as highlighted in the review study of Schaffer-Lequart et al. (2017), it is still a challenge to meet consumers' sensory expectations for tasteful and convenient wholegrain foods. The characteristics of the grains and the techniques used in processing affect these products' appearance, flavor, and texture (Ferruzzi et al., 2014).

Considering the appearance of WGP, the presence of bran causes a rough surface texture and a higher rate of breaks and defects due to the action of the fibers in the formation of the gluten network (Chen et al., 2015; Manthey & Schorno, 2002; Marti et al., 2017). Thus, regarding new milling methods, studies with bran micronization, such as ultracentrifugal milling (Khalid et al., 2017) and cryogenic milling methods (De Bondt et al., 2021), are being used for WWF and could be applied to WGP formulations.

The germ has a high lipid composition, predisposing the flour to oxidative rancidity and bitterness. The unsaturated oils are more susceptible to oxidation, and enzymes that degrade lipid compounds are inactive when wheat kernels are intact and dry. However, when plant tissue breaks down, oxidation reactions occur sequentially, starting with the hydrolysis of glycerides by lipases, phospholipases, and hydrolases. Afterward, these free polyunsaturated fatty acids could be oxidized by lipoxygenases, producing fatty acid hydroperoxides, which are later converted into aldehydes, ketoacids, and oxidized fatty acids, responsible for the residual flavors of rancidity and the bitter taste (Mandarino, 1994). Considering the opportunities for a better understanding of sensory acceptance, we also highlight the use of instrumental sensory analysis methods. For example, in a study by Marti et al. (2017), the authors applied sensory evaluation techniques associated with the quantitative and qualitative study of aromatic compounds, using equipment such as the electronic tongue (*E-Tongue*) and the electronic nose (*E-Nose*), to assess the influence of drying temperatures on the bitter taste intensity of commercial WGP. The authors found that the sensor could discriminate between the samples of WGP classified as "bitter" due to its furosine content as a marker of excessive heat damage. Thus, it could be a non-destructive analysis method for better quality of WGP.

In a study by West et al. (2013a), the authors found that despite the nutritional benefits associated with intact whole foods, they were darker in color, rougher, and firmer than refined ones. They could also develop odors and unwanted flavors that the consumer more easily perceives. The authors also studied the interference of the percentage of incorporation of WWF in the characteristics of flavor and texture of the WGP. The texture of the WGP was affected by incorporation, with the lowest values of firmness associated with the highest percentages of replacement. For the sensory analysis, it was observed that the bitterness increased in the same proportion as the incorporation of WWF. The sweetness decreased in the same proportion, and the tasters perceived odors such as grass and cereals.

The recommendation for semolina-based pasta is that the wheat semolina has at least 90% of its particle size between 150 and 340 μm (Rosentrater & Evers, 2018). However, those values were not established for WWF, and there is still the need for more studies regarding the granulometry evaluation for WGP production. In the study accomplished by Chen et al. (2011), the authors verified the influence of bran granulometry in wholegrain noodle-type pasta based on a Chinese wheat cultivar (Shannong 2, protein content of 12.5%) with the addition of three types of bran granulometry (coarse: 1.5–2 mm; medium: 0.43–1 mm; fine: 0.16–0.43 mm). The noodles received amounts between 10 and 20% of bran. The authors found that the increase in added bran reduced the scores attributed to the control's appearance, palatability, softness, and flavor (refined wheat flour), with the maximum addition of bran being 10%.

Despite the importance of sensory evaluation, the methods applied in studies were limited to either affective measurements or descriptive analysis by trained judges. In this sense, novel sensory evaluation techniques such as penalty analysis (a combination of affective and Just-About-Right methods) and Temporal Dominance of Sensations could be helpful for the establishment of quality standards for WGP. These methods could be correlated with sensory texture profiles and texture profile analysis (TPA) analyses to evaluate texture parameters of cooked WGP, such as hardness, cohesiveness, gumminess, elasticity, chewiness, and adhesiveness. They could also be explored for these pastas. Changes in the texture of pasta with different ingredients in the formulations and, mainly, in WGP with increased dietary fiber content. Pasta with fibers presents a decrease in firmness due to the interruptions caused by the fibrous fraction in the gluten network (Aravind et al., 2012; West et al., 2013b).

Regarding improving sensory acceptance opportunities, we identified that new WGP formulation studies using ingredients for better nutritional value and appearance, such as clear fibers, have an advantage due to their lower impact on the color and appearance of pasta (Ferreira et al., 2022). Also, natural colors and flavoring ingredients, such as turmeric, sweet potato, and carrots, could contribute to the best acceptance of WGP, as explored by Wahanik et al. (2021). As an example, Laureati et al. (2016) evaluated the impact of wheat bran on the sensory quality of kinds of pasta (based on durum wheat) and the effect of information on fiber enrichment on consumer acceptability and expectations. Fiber content labeling negatively impacted more than 20% of expected product quality. For pasta with 30% wheat bran, the fiber was sensorially perceived and compromised the acceptability of the product. For consumers who usually prefer wholegrain foods, higher levels of bran in WGP increased consumer expectations for a healthier product. In contrast, for non-consumers, expectations about the product's healthiness with 30% bran added did not offset the change in the taste of pasta.

It is important to highlight the importance of encouraging the consumption of wholegrain foods considering that most consumers do not have access to or are not in the habit of eating wholegrains.

4 CONCLUSION

The WGP are important sources of nutrients and compounds that promote health, but many challenges remain in understanding their sensory and cooking properties. The need for greater consensus on WGP identity and quality evaluation methods impacts the producing industries and consumers, highlighting the need for increased investment in these products' research. As a result, a better understanding of the characteristics of WGPs and the challenges associated with their increased dietary inclusion is required. According to the current research, the use of novel wheat varieties and nutritional and technological improvements to WGP are still required.

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