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Review

A compendium of wheat germ: Separation, stabilization and food applications

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ABSTRACT

Background: Wheat germ is a precious by-product deriving from the milling industry, as it is a natural concentrated source of essential amino and fatty acids, minerals, vitamins, tocopherols, and phytosterols. However, the presence of high enzymatic activities together with a high content of unsaturated oil, induce a fast decrease in the nutritional value of wheat germ during storage and, consequently, strongly limit product's shelf-life.
Scope and approach: In recent decades, flour blends from raw or/and processed wheat germ received great interest from nutritional and technological perspectives. Nevertheless, the quality of the end-product strongly depended on the supplementation level, as well as the type and the severity of separation and stabilization techniques that wheat germ went through. Hence, in this review, the newest advances in wheat germ pre-handling approaches and food applications are discussed to provide relevant and updated information about its worthiness to be a part of the human diet.
Key findings and conclusions: To fully valorize and preserve the nutritious potential of wheat germ, effective pre-treatments of separation and stabilization are needed to guarantee its stability and suitability to meet food quality and safety standards. Such an underutilized ingredient might be a valuable fortifying component for a spectrum of foodstuffs.

1. State of the art of wheat germ

1.1. Wheat germ within the whole wheat

The whole wheat kernel is composed of three primary structures: endosperm, bran and germ.

Endosperm (80–85%) is mostly formed by starch and proteins and surrounded by several outer layers called "the aleurone". The aleurone is made up of living cells enclosing bioactive compounds, surrounded by thick cell walls composed of arabinoxylans and β-glucans, and some proteins (Y. M. Hemery et al., 2010).

Bran (13–17%) is formed by pericarp and testa. The testa is a hydrophobic tissue rich in lignin and characterized by the presence of lipidic compounds such as alkylresorcinols, present in a cuticle at the surface of this tissue (Y. M. Hemery et al., 2010). The pericarp lies in the outermost layers, which are composed of three layers, the epicarp, mesocarp, and endocarp (Yu et al., 2015).

Wheat germ (WG) (2–3%) contains the embryo and the scutellum, which are separated from the endosperm by the aleurone. The embryonic axis includes the radicle and plumule (Yu et al., 2015). The scutellum plays mainly the role of a storage organ. Also, it is the attachment organ between the pericarp and the embryo. Generally, most of the scutellum is discarded during wheat milling and the "recovered germ" is mainly the embryo.

1.2. Wheat germ: a precious milling co-product

Together with the bran, WG is considered the most important by-product of the dry milling industry. The world deposit of WG is estimated to be, annually, ca. 25,000,000 tons (Rizzello, Nionelli, Coda, De Angelis, & Gobbetti, 2010), which is an important milling co-product to valorize. WG has been shown to have important impact on human health (e.g. antioxidant, antihyperlipidemia, hypocolesterolemic, anticancer effects) (Ghafoor et al., 2017; Kumar et al., 2011; Mueller & Voigt, 2011). WG may, indeed, be considered the most nutritious part of wheat grain because it contains excellent amounts of nutrients such as proteins, unsaturated fatty acids, minerals, vitamins E and B, dietary fiber, essential amino acids, flavonoids and sterols (Niu, Jiang, Pan, & Pang, 2013; Sun, Zhang, Hu, Xing, & Zhuo, 2015; Zhu, Wang, & Guo, 2015) (See section III. Wheat germ chemical composition). At present,

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WG is mainly used as a feed, while human consumption is still limited and not fully explored (Rizzello, Cassone, Coda, & Gobbetti, 2011). An emerging market is WG oil, which is integrated in pharmaceuticals and cosmetic formulations or fertility agents (Gorusupudi & Baskaran, 2013; Niu et al., 2013). Defatted wheat germ (DWG) and wheat germ proteins are by-products of the production of wheat germ oil (Niu et al., 2013). DWG contains about 30% proteins (Sun et al., 2015). Defatted wheat germ protein (DWGP) has a quality comparable to the model value set by the FAO/WHO (Arshad, Anjum, & Zahoor, 2007) and to egg and milk proteins (Ge, Ni, Yan, Chen, & Cai, 2002). Hence, WG and its derivatives might be considered a valuable functional ingredient with high nutritional interest.

1.3. Reasons for removing wheat germ during milling: stability, quality and safety

The widespread utilization of WG is limited by the rapid development of rancidity after isolation from the kernel (Li et al., 2016). The mechanical treatment involved in wheat milling favors oil diffusion, and once the lipid fraction is exposed to the air, oxidation drastically increases (Geng, Harnly, & Chen, 2015; Gili, Palavecino, Cecilia Penci, Martinez, & Ribotta, 2017). The presence of unsaturated fats as well as hydrolytic and oxidative enzymes favor WG rapid degradation (Xu et al., 2013). Enzymes, lipoxygenase and lipase, deteriorate lipids molecules generating acidity and volatile compounds (Capitani, Mateo, & Nolasco, 2011; Sjövall, Virtalaine, Lapveteläinen, & Kallio, 2000). Therefore, once separated, WG shelf life is drastically shortened to a matter of few days, which is the major limitation to WG industrial applications (Sjövall et al., 2000; Srivastava, Sudha, Baskaran, & Leelavathi, 2006).

Removal of intact WG in conventional milling process before kernel grinding is practically impossible, especially in the case of soft wheat. WG can be gradually recovered after the first passage through the rolling mills, but, being mainly crushed, WG is subject to oxidation and rancidity phenomena. WG is, therefore, generally removed during milling of wheat kernels to increase the shelf life of flour and to prevent occurrence of a strong flavor from rancid oils in the flour (Geng et al., 2015). Therefore, WG presence in flour negatively affects its shelf-stability and usability (Rizzello, Nionelli, Coda, De Angelis et al., 2010), and the final products stability and sensory attributes (Sjövall et al., 2000).

Besides stability issues, WG contains some anti-nutritional components. Compared to refined flour, unprocessed WG comes with higher anti-nutrients (i.e. phytic acid, agglutinins) concentrations. Phytic acid complexes minerals important for human nutrition thereby limiting their bioavailability (Demir & Elgün, 2014; Gupta, Gangoliya, & Singh, 2015; Zajdel, Wilczok, Węglarz, & Dzierżewicz, 2013). Agglutinins, sugar binding proteins which increase intestinal permeability and might damage the gut lining, are also found in WG (Pellegrina et al., 2009; de Punder & Pruimboom, 2013). However, these anti-nutrients can be drastically reduced by WG stabilization (Matucci et al., 2004; de Punder & Pruimboom, 2013).

Being rich in fats, pesticide residues (e.g. organophosphorus insecticides, which are mainly used for wheat conservation) tend to remain associated with WG because they are lipophilic (high affinity to fats) (Uygun, Koksel, & Atli, 2005; Uygun, Senoz, & Koksel, 2008). Pesticides and insecticides are serious threats to both human health and the environment (Hossard, Guichard, Pelosi, & Makowski, 2017). Different approaches were developed to determine the quantities, and measuring the content of these harmful chemical molecules, that often exceed the legal limits (Rezaei, Damalas, & Abdollahzadeh, 2018). Therefore, food safety issues are another reason why the germ is removed and not fully exploited. However, the final concentration of these residues depends on several factors such as the cultivation area, the residual amount of pesticides in the soil, the duration of storage, and the processing (Uygun, Senoz, Öztürk, & Koksel, 2009; Uygun et al., 2008, 2005). The highest level of pesticide residues legally tolerated in WG is 0.02 mg/kg for cyfluthrin (RD) and 0.05 mg/kg for permethrin (European Food Safety Authority, 2016).

In recent years, increasing efforts are being made to valorize milling "wastes" thereby turning the fate of WG from waste to a highly valuable by-product. New strategies were developed to provide health-beneficial and low-cost ingredients for food-making. WG is a nutritious but unstable ingredient due to the action of oxidative and hydrolytic enzymes on unsaturated fatty acids. Consequently, adequate techniques are needed to prolong WG shelf-life and preserve its nutrients. This comprehensive review is designed to acquire deep insights into the recent advances dealing with WG separation and stabilization strategies, compositional traits, and food applications, through the use of scientifically-sound and reliable evidence.

2. Advances in wheat germ separation

WG separation might be performed throughout two main approaches: direct and gradual. Degermination is a direct approach, which might provide intact WG. As for the indirect approach, WG is gradually separated in the form of flakes, through the successive passages throughout the milling process.

2.1. Direct approach: degermination

The goal of the degerminator is to remove the germ without excessive grinding. Several types of degerminators have been patented (Table 1). Prior to degermination, a tempering phase of the grain is required to reach a moisture level ranging from 19% to 25%, depending on the degree of degermination. The degerminators first crush kernels from their thin edges to separate the germ and endosperm without damaging the germ. Afterward, endosperm undergoes successive passages of breaking and reduction to obtain a fine flour. Such a pretreatment has the advantage to reduce separation passages (purifiers to separate bran particles and germ from endosperm). In the mill industry, until now, degerminators are not used in wheat processing, and they are

Table 1
Degerminators patents.

Patent	Publication date	Applicant	Title
US4189503	19 Feb 1980	Cereal Enterprises, Inc.	Method of degerminating a kernel of grain by simultaneously compressing the edges of the kernel
US4301183	17 Nov 1981	Cereal Enterprises, Inc.	Method and apparatus for degerminating a grain kernel by impelling the kernels along a guide vane into an impact surface
US4365546	28 Dec 1982	Cereal Enterprisess, Inc.	Apparatus for degerminating a kernel by compressing the edges of the kernel
US5250313	5 Oct 1993	Cereal Enterprises, Inc.	Grain milling and degermination process
WO2003047366A1	12 Jun 2003	Satake Usa, Inc.	Corn degermination process
US6936294	30 Aug 2005	Satake Usa, Inc.	Corn degermination process
US6953165	11 Oct 2005	The Quaker Oats Company	Corn milling process
US7553507	30 Jun 2009	Satake Usa, Inc.	Corn debranning and degermination process
EP3124119A1	1 Feb 2017	Cereal Enterprises, Inc.	Degerminator