


Rye: Current state and future trends in research and applications

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ABSTRACT

After wheat, rye is the second most important raw material for bread and bakery products, and it is one of the most excellent sources of dietary fibres and bioactive compounds. Besides, rye is utilised in more and more other food products as well, such as breakfast cereals, porridges, pasta, snack products, etc. Interestingly, its production is decreasing worldwide, probably because of the expansion of other cereals (e.g. triticale), but also the effect of climate change can also play a role therein. However, there is no doubt that scientific research aimed at studying the possible health benefits and the potential of rye in the development of novel food products has intensified over the past decade.

The aim of our paper is to make a comprehensive review of the latest results on the compositional and technological properties of rye that fundamentally influence its utilisation for food purposes. Furthermore, this review aims to identify the current development directions and trends of rye products.

KEYWORDS

baking quality, novel products, nutritional value, rheological properties, rye

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1. INTRODUCTION

Rye (*Secale cereale* L.) has been cultivated since ancient times in Europe and is the second most important crop after wheat for production of bread and other bakery products. In botanical classification, rye belongs to the grass family Poaceae, the subfamily Pooideae, and the tribe Triticeae along with other cereals like wheat and barley. Most of the cultivated rye species are members of the genus *Secale*, and has probably evolved from a perennial grass (*Secale montanum*) that still grows wild in southern Europe (Arendt and Zannini, 2013; Sapirstein and Bushuk, 2016; Wrigley and Bushuk, 2017). Although rye is now cultivated worldwide, in terms of total production it is a minor cereal. The distribution of rye production differs from that of wheat, due to its demand for cooler growth temperatures and large differences in regional preferences for rye-based products (Poutanen et al., 2014; Wrigley and Bushuk, 2017). Europe provides more than 85% of the world's rye production (12.8 million tons, 2019), including the leading rye producing countries: Germany, Poland, Russia, Denmark, and Belarus. In the last decade (2009–2019), the world's rye production dropped significantly preceded even by the cultivation of triticale (14 million tons, 2019) (FAO, 2019). At the same time, the increasing research data on rye points out its relevance as an important raw material for healthy foods and its decisive role in developing novel products. Besides, our knowledge on its milling and technological properties are expanding as well, however, these data have been reviewed to a lesser extent yet.

Therefore, our review focuses on the one hand on the nutritionally important chemical composition and current health claims of rye, on the other hand on the most recent results on the techno-functional properties and quality testing of rye and on its potentials for product development.

2. COMPOSITION AND HEALTH EFFECTS

The chemical composition of rye shows similarities with other cereals (e.g. wheat, barley, and triticale), however, it can be characterised by higher fibre (especially pentosan) content regarding both the whole grain and endosperm, which is considered as the main nutritional benefit of rye (Shewry et al., 2013; Poutanen et al., 2014; Békés and Wrigley, 2015; Sapirstein and Bushuk, 2016) accompanied with its high content of bioactive compounds (Jonsson et al., 2018).

2.1. Macro- and micronutrient composition

Protein content of rye can vary in a wide range (8–15%) depending mainly on growth conditions (Kučerová, 2009; Sapirstein and Bushuk, 2016; Laidig et al., 2017). However, the higher influence of genotype compared to environmental effect has been also reported (Hansen et al., 2004; Kunkulberga et al., 2017). Albumins are the main proteins of rye, accounting for 29–40% of the total protein content. Globulins make up 8–11%, while the storage proteins of rye (so called secalins), the prolamins and glutelins, make up 17–19% and 9–15% of the total protein content, respectively. About 21–30% of the proteins are unextractable based on Osborne fractionation. The amino acid composition of rye proteins is slightly better than that of wheat due to its higher lysine content, but it is limiting in tryptophan and isoleucine (Chen and Bushuk, 1970; Hulse and Laing, 1974; Békés and Wrigley, 2015; Redant et al., 2017).



The most evident carbohydrate component of rye is starch, similarly to other cereals. The starch content of the rye grain ranges from 55 to 65%, which is little lower than that of wheat (63–72%) and higher than that of barley (50–64%) (Poutanen et al., 2014; Sapirstein and Bushuk, 2016). Rye starches, like those of wheat and barley, are composed of large (A-type, 60–90%) and small (B-type, 10–40%) granules with diameters of 23–40 μm and less than 10 μm , respectively. Amylose content of rye starches varies between 22 and 26% in general (Stoddard, 1999; Verwimp et al., 2004; Gomand et al., 2011; Grossmann and Koehler, 2016), however, higher value (30.1%) has also been reported (Klassen and Hill, 1971). The lipid content of rye is similar to that of wheat (2–3%) (Sapirstein and Bushuk, 2016), also fatty acid composition shows similarities having linoleic acid (18.9–59.3%) as a major component (Kan, 2015; Bağcı et al., 2019).

Mineral and vitamin composition of rye resembles to that of other cereals (Table 1). Cereals are considered as good sources of phosphorus, potassium, and magnesium, as well as B vitamins (thiamin, riboflavin, niacin, pantothenic acid, and pyridoxine) and folate. Compared to other cereals, rye has higher iron, zinc, manganese, and copper contents, generally. Furthermore, rye is good source of α -tocopherol similarly to wheat, however, oat can be characterised by the highest vitamin E content (Frølich et al., 2013; Sapirstein and Bushuk, 2016; Bağcı et al., 2019).

2.2. Rye: valuable source of dietary fibres and bioactive compounds

Non-starch polysaccharides (NSP) along with lignin make up the dietary fibre content of rye, which is the highest among the cereals (Table 2) ranging between 15 and 25% (Nyström et al., 2008; Shewry et al., 2013; Poutanen et al., 2014; Sapirstein and Bushuk, 2016). The most important NSP component of rye is arabinoxylan (AX), which is a cell wall polysaccharide consisting of a backbone of (1 \rightarrow 4)- β -D-xylo-pyranosyl residues mainly substituted with α -L-arabino-furanosyl residues to varying degrees at the O-2 position, the O-3 position, or both (Knudsen and Lærke, 2010). Ferulic acid is additionally attached to arabinosyl units of the polymer chain via ester linkages (Bender et al., 2017). Total and extractable AX content of the rye grain ranges from 7.5 to 11.5% and from 2.1 to 4.0%, respectively (Hansen et al., 2004; Andersson et al., 2009). In the HEALTHGRAIN variety screen study, total AX content of the bran and flour fractions was 12.1–14.8% and 3.1–4.3%, respectively (Nyström et al., 2008; Shewry et al., 2013). Rye also contains 1.5–3% β -glucan (Andersson et al., 2009; Poutanen et al., 2014) and 3.6–6.6% fructan (Karppinen et al., 2003; Andersson et al., 2009; Ispiryan et al., 2020).

Rye grain is also rich in various phytochemicals such as phenolic acids (491–1,082 mg kg^{-1}), tocots (44–67 mg kg^{-1}), phytosterols (707–1,420 mg kg^{-1}), lignans (25–67 mg kg^{-1}), and alkyl-resorcinols (663–1,231 mg kg^{-1}), and besides, several other bioactive compounds have also been identified in rye such as flavonoids (46 mg kg^{-1}), anthocyanins (3.6 mg kg^{-1}), anthocyanidins (1.8 mg kg^{-1}), benzoxazinoids (75–95 mg kg^{-1}), and phenolamides (Nyström et al., 2008; Andersson et al., 2014; Pihlava et al., 2018; Kulichová et al., 2019).

2.3. Health benefits and possible adverse effects of rye consumption

Currently there is one health claim authorised by EU according to the positive scientific opinion issued by the European Food Safety Authority (EFSA) Panel on Dietetic Products Nutrition and Allergies (NDA) (2014). This claim states the beneficial physiological effects of rye fibre on bowel function, provided that sufficient amount is consumed.



Table 1. Mineral and vitamin contents of rye compared to other cereals

	Rye	Wheat	Barley	Triticale	Oat
<i>Minerals (mg kg⁻¹)</i>					
P	1,806–4,220	1,500–5,400	2,700–3,600	3,210–3,850	4,510–5,020
K	3,480–6,148	2,900–6,200	3,190–4,400	4,660–4,700	3,890–4,250
Ca	157–1,447	370–1,220	400–2,700	350–400	500–590
Mg	920–1,602	900–2,900	660–1,800	1,100–1,530	1,220–1,580
Fe	27–129	28–42	30–76	26–37	43–47
Zn	21–52	19–32	14–23	25–27	29–37
Mn	20–75	5–49	13–22	26	41–45
Cu	3–13	4–7	3–4	3	3–5
<i>Vitamins (mg kg⁻¹)</i>					
Thiamin	4.0–4.6	5.0–12	2.0–2.6	3.8–9.8	5.0–8.0
Riboflavin	1.8–1.9	1.0–3.1	0.9–1.0	1.3	1.0–1.4
Niacin	12–15	41–64	45–50	29	9.6–16
Pantothenic acid	10	7.7–9.1	3.5	6.5–8.8	13.4
Pyridoxine	3.0–3.4	3.0–4.7	3.0–3.2	4.0	2.0–2.4
Folate	0.48–0.52	0.35–0.56	0.19–0.25	0.7	0.45–0.60
α -Tocopherol	10–12	5–12	3.4–4.0	9.0	8.0–18
<i>References</i>	Michela and Lorenz (1976); Welch (2011); Frølich et al. (2013); Sapirstein and Bushuk (2016); Zhu (2018); Bağcı et al. (2019); Bie et al. (2020)				

Table 2. Dietary fibre content and composition of rye grain compared to other cereals (% in dry matter basis)

	Rye	Wheat	Barley (hulled)	Triticale	Oat (hulled)
Total dietary fibre	15.0–25.0	10.0–17.0	8.0–16.2	7.5–16.0	11.8–19.1
Soluble dietary fibre	2.5	3.6	4.1	2.6–3.2	3.5–12.3
Insoluble dietary fibre	13.2	9.4–12.0	12.1	11.4–12.0	6.8–8.3
Total arabinoxylan	6.0–11.5	5.6–0.2.6	5.2	4.1–7.5	1.1–2.0
Water extractable arabinoxylan	1.05–4.0	0.6–1.0	1.1–1.4	0.21–0.44	0.15–0.18
Cellulose	2.9	2.4–2.5	1.9	1.7–2.5	1.3
β -glucan	0.7–3.0	0.5–1.1	3.2–4.6	0.5–2.1	3.9–7.1
Fructan	3.6–6.6	1.3	1.6	1.6–2.9	1.4
Arabinogalactan	0.9–1.0	0.89–1.09	0.71–0.97	0.14–0.23	0.01
Klason lignin	1.1	0.8–1.9	0.7	1.4–3.2	1.4–5.9
<i>References</i>	Karpinen et al. (2003); Nyström et al. (2008); Andersson et al. (2009); Göllner et al. (2011); Rakha et al. (2011); Saeed et al. (2011); Doehlert et al. (2013); Shewry et al. (2008, 2013); Frølich et al. (2013); Knudsen (2014); Piironen and Lampi (2014); Poutanen et al. (2014); Chibbar et al. (2016); Fraš et al. (2016); Sapirstein and Bushuk (2016); Aprudu and Banu (2017); Langó et al. (2017, 2018); Zhu (2018) Biel et al. (2020); Cetiner et al. (2020); Ispiryan et al. (2020); Liu et al. (2020)				



Several studies have been focusing on the potential health effects of rye and rye-based products, and the clinical studies and findings until 2018 have been reviewed comprehensively by several authors (Afzal et al., 2013; Arens, 2015; Jonsson et al., 2018).

The main objectives of most clinical trials have been the investigation of the role of rye consumption in the prevention of cardiovascular disease, type 2 diabetes, and certain cancers (mainly colorectal cancer). Furthermore, the impact of rye consumption on gut health, hormone secretions, and blood glucose levels, as well as on LDL cholesterol concentration has also been studied comprehensively. However, there are several studies, which refute the effect of rye product consumption e.g. on blood glucose and insulin level (Leinonen et al., 2000; Juntunen et al., 2002) or on the concentrations of biomarkers of inflammation and cardiovascular disease (Mhd Omar et al., 2020). The main reason of controversial results might be the limitations of clinical trials, such as their high cost and usually small sample size. However, when comparing the results of clinical trials, the characteristics of the investigated dietary fibres and bioactive compounds, the type of the involved food matrices (i.e. white, mixed, or whole grain products, etc.), and the eating habits of the test persons should be also taken into account. In the case of other mentioned health benefits, there is not enough scientific evidence for establishing cause and effect relationships yet.

However, in some individuals, rye consumption might have also adverse effects. Since rye also contain gluten homologous proteins, its consumption is not allowed in case of celiac disease (Malalgoda and Simsek, 2017). Rye based products (especially wholemeal or bran-rich, non-fermented) might contain significant amount of fructan, which is the most prominent FODMAP (fermentable oligosaccharides, disaccharides, monosaccharides, and polyols) component of the grain. It concentrates in the bran fraction (6.6 g/100 g), but also refined light flours can contain around 3 g/100 g fructan (Karppinen et al., 2003; Pejcz et al., 2020). FODMAPs that were not digested and absorbed in the small intestine are easily fermentable by enteric microflora, which triggers symptoms of the irritable bowel syndrome (IBS). The IBS affect around 7–21% of people in the world including gastrointestinal disorders such as chronic recurring flatulence, pain perceptible in the abdomen, and changes in defecation rhythm (Pejcz et al., 2020).

3. INVESTIGATION OF TECHNO-FUNCTIONAL PROPERTIES

3.1. Grain quality and milling properties

Grain quality assessment for rye is basically similar to that for wheat, however, there are some quality aspects of especially great importance such as grain soundness (lack of sprouting), test weight, and presence of ergot bodies (Wrigley and Bushuk, 2017).

The rye grain milling process is similar to that of wheat, although, some important differences exist between them, such as the shorter tempering period and the application of corrugated rolls instead of smooth rolls for reduction in the case of rye. Rye flour also needs larger sifting surface to avoid clumps. These can be explained by the softer endosperm of rye compared to wheat (Arendt and Zannini, 2013). The extraction rate of rye flour is usually lower than that of wheat, because it is difficult to separate the endosperm from the seed coat, especially in grain with a higher content of non-starch polysaccharides (Warechowska et al., 2019). Rye flours are generally classified on the basis of ash content, and their number varies nation to nation. As an



example, in Germany, eight flour grades can be distinguished having ash contents ranging from 0.9% to above 1.8% (Arendt and Zannini, 2013; Sapirstein and Bushuk, 2016).

3.2. Technological properties of rye flours

A broad range of testing methods has been established to predict end-product quality of flours (Tömösközi and Békés, 2016). As in wheat baking performance is influenced to a great extent by its protein (gluten) and starch fractions, specific (rapid) methods are designed to measure protein (or gluten) quantity and quality and starch quality. Similarly to wheat, the end-product quality of rye flours is affected by the storage proteins, starch, and non-starch polysaccharides. However, the carbohydrate fraction as well as α -amylase activity play a more important role in formation of functional properties. Therefore, the aim of existing methods is mainly to describe dough making and gel forming properties of these components (Lindhauer, 2014; Laidig et al., 2017).

It should be mentioned that no standardised procedure for laboratorial rye flour production has been developed yet, like in the case of wheat, therefore, the investigated samples can vary greatly in ash content and particle size distribution. Furthermore, in many cases, the type of rye milling products is not clarified in the articles, making the comparison of literature data and drawing general conclusions more difficult.

3.2.1. Dough-forming properties. To measure dough properties, empirical and fundamental rheological methods are usually applied. Based on the results of standard Farinograph and Mixolab measurements, mixing properties of rye doughs made from white (ash content of 0.5–0.7%) and from fibre-rich or wholemeal flour (ash content of 1.0–1.8%) differ greatly from their wheat counterparts, and they can be characterised generally by shorter development time and stability, as well as higher degree of softening (Munteanu et al., 2015; Bucsellà et al., 2016; Aprodu and Banu, 2017; Ponomareva et al., 2018).

The functionality of individual rye constituents (proteins, starch, and non-starch polysaccharides) and their interactions on dough properties have been investigated comprehensively in the last ten years. It is generally accepted that rye storage proteins are not able to form as strong viscoelastic network as wheat gluten proteins, which is explained by the basically different protein composition and lower protein content of rye (Meeus et al., 2020). However, increased protein aggregation can be achieved in rye dough (flour type 1,150) by using transglutaminase (TG) resulting in a more stable and elastic protein network, referring to the structure building potential of rye proteins (Beck et al., 2011; Grossmann et al., 2016). Based on a fractionation-reconstitution study of rye flour (type 1,150), it was assumed that especially non-gluten proteins (albumins) might play a role in the functionality of rye proteins (Grossmann and Koehler, 2016).

Starch is the main component of rye grain and flour and has a great impact on rye dough behaviour accompanied with amylase activity. Starch granules of different rye flours can be characterised by a higher level of enzymatic and mechanical damage, as well as higher swelling ability compared to wheat starch resulting a softer, stickier dough (Buxsa et al., 2010; Deleu et al., 2020; Sluková et al., 2021).

Among non-starch polysaccharides, pentosans, mainly arabinoxylans (AXs), affect rye dough behaviour to a great extent depending on their solubility, molecular weight, and cross-linking ability. AXs (especially water extractable fractions) are able to form highly viscous



solutions in water, therefore, they are the main contributor to the high viscosity of rye dough (Buksa et al., 2013; Buksa, 2016). Fundamental rheological studies of reconstituted rye dough showed that water unextractable AXs increase, while water extractable AXs decrease dough elasticity (Grossmann and Koehler, 2016). Other studies reported the possible hindering effect of AXs on protein interactions in rye model dough systems. Based on CLSM (confocal laser scanning microscopy) images it was confirmed that proteins were less dispersed and were surrounded by AX network in rye dough, especially at AX concentrations corresponding to commercial rye flours (5–7.5%). However, no stretched protein fibrils were detected in rye dough at 0% AX addition, which further confirms the weak network formation ability of rye proteins (Döring et al., 2015). The functionality of rye AXs can be investigated by enzymatic treatments. It has been shown that the encapsulation of proteins by AX can be reduced by the addition of xylanase (Grossmann et al., 2016; Döring et al., 2017). The treatment of rye dough by pentosanase enzymes resulted in improved extensibility, which was explained by the fact that hydration capacity of pentosans has been reduced due to hydrolysis, and the water could be absorbed by proteins and other components of the flour (David et al., 2019).

Most recent studies on rye dough liquor air-water interfaces showed that lipids hinder proteins to form strong viscoelastic films (Janssen et al., 2020a), while arabinoxylans strengthen the film, acting presumably as a secondary stabilising layer (Janssen et al., 2020b).

In conclusion, the findings about the role of rye constituents in dough formation are sometimes controversial and not fully understood yet, indicating that further research works are needed in this field.

3.2.2. Pasting and thermomechanical properties. In rye quality testing, investigation of carbohydrate-dependent traits such as swelling, pasting, and retrogradation dominate. Furthermore, rye is susceptible to pre-harvest sprouting, therefore, the measurement of α -amylase activity and properties related to it have a great importance as well. The determination of Falling Number or Stirring Number are the most general procedures to determine the amyolytic status of rye grain and flours (Wrigley and Bushuk, 2017), while more information on rye flour functionality can be obtained with viscosymetric methods such as Amylograph (Hansen et al., 2004) or Rapid Visco Analyser tests (Gómez et al., 2009). Since viscous properties highly affect bread properties, amylograph measurements and the determination of falling number are usually applied to predict baking performance (Laidig et al., 2017). However, according to recent studies, these methods seemed to be less sufficient for estimating wholemeal bread properties (Stępniewska et al., 2019) and the baking quality of modern rye cultivars (Lindhauer, 2014). A relatively new testing method, the Mixolab is used for the examination of thermomechanical properties in dough matrices instead of slurry, modelling the conditions during bread baking more accurately (Dubat, 2010).

Viscous properties of white (ash content: 0.5–0.7%) and wholegrain rye flours measured by the most common testing methods are summarised and compared to wheat flours in Table 3.

It is well-known that rye flours can be characterised by lower Falling Number values than wheat flours, due to the weaker sprout resistance and, therefore, higher amylase activity of the grains (Wrigley and Bushuk, 2017). According to literature data, the viscosity of white and wholemeal rye flour pastes is usually lower than that of corresponding wheat flours including peak viscosity, hot paste viscosity, and final viscosity. Regarding thermomechanical properties,



Table 3. Pasting properties of rye and wheat flours determined by different methods

Method/Parameter	RF	WRF	WF	WWF	References
<i>Falling Number</i> (s)	102–277	130–305	110–679	395	Dencic et al. (2013); Bucsell et al. (2016); Kunkulberga et al. (2017); Ponomareva et al. (2018); Stępniewska et al. (2018); Warechowska et al. (2019); Bánfalvi et al. (2020)
<i>RVA</i>					
<i>PV</i> (cP)	606	497–1,084	1,042–3,563	1,738	Ragae and Abdel-Aal (2006); Bucsell et al. (2016); Bánfalvi et al. (2020); Yuan et al. (2021)
<i>Tr</i> (cP)	63	95–757	353–2,719	950	
<i>FV</i> (cP)	115	179–1,770	902–4,579	2,045	
<i>Amylograph</i>					
<i>PV</i> (BU)	175–945	29–951	90–1,725	450–720	Salmenkallio-Marttila and Hovinen (2005); Pojić et al. (2013); Ponomareva et al. (2018); Saied Hussein et al. (2018); Stępniewska et al. (2018); Warechowska et al. (2019)
<i>Mixolab</i>					
<i>C3</i> (Nm)	1.39–2.65	1.45–1.76	1.40–2.80	1.75	Iuliana Banu et al. (2011); Bucsell et al. (2016); Aprodu and Banu (2017); Bánfalvi et al. (2020)
<i>C4</i> (Nm)	0.27–1.43	0.32–0.76	0.90–2.17	1.18	
<i>C5</i> (Nm)	0.41–2.48	0.51–1.32	1.36–3.61	1.87	

RF: rye flour; WRF: wholemeal rye flour; WF: wheat flour; WWF: wholemeal wheat flour; PV: peak viscosity; Tr: trough; FV: final viscosity.

rye doughs show similar gelatinisation (C3 torque) properties to wheat doughs, but they can be characterised by higher breakdown (C4 torque) and lower degree of retrogradation (C5 torque).

The differences in pasting behaviour can be explained by several reasons. As mentioned before, rye starch shows a higher level of enzymatic and mechanical damage compared to wheat starch (Sluková et al., 2021). Besides, a comparative study (Gomand et al., 2011) on isolated rye and wheat starches showed that rye starch had higher relative crystallinity, lower gelatinisation and pasting temperatures, lower peak and breakdown viscosities, higher setback, and a lower tendency to retrograde. These can be explained by the structural differences (different chain length distribution profile) of rye and wheat amylopectin and amylose. The slower retrogradation of rye flours can be also related to their pentosan content and composition (Stępniewska et al., 2018). Besides, higher amounts of soluble fibre in white and wholemeal rye flours compared to wheat flours can limit starch swelling and cause higher gelatinisation temperature of rye starch (Aprodu and Banu, 2017).

3.2.3. Baking quality of rye. Bread and other baked products are the main foods produced from rye (Sapirstein and Bushuk, 2016), therefore, the determination of baking quality is similarly important as in the case of wheat. Although baking tests are time-consuming and



labour-intensive procedures, end-product quality can be determined directly only by these procedures. Rye breads can be very different in shape, colour, flavour, and texture and are also often mixed with wheat flour (Arendt and Zannini, 2013; Sapirstein and Bushuk, 2016). This might be one possible reason why bread making tests for rye are less advanced on the international level compared to wheat bread making, and only a general guidance (ISO, 1985) is available currently. In rye producing countries, there are their own national standard methods for testing baking performance of rye. For example, in Germany, there are different standard protocols (Meißner and AGF, 2016) for performing baking tests specifically from rye flours. There are methods for yeast-leavened bread, sourdough bread, and bread acidified with lactic acid as well as for bread baked with or without baking pan. In Hungary the lactic acid method is used for making test breads from rye (MSZ: 6369/8, 1988). When surveying the literature, the applied methodologies for analysing baking performance of rye flours show great variability (Table 4). What they have in common is that conventional “soft” breads are produced and usually wholemeal rye flours are investigated.

Generally, baking of rye bread differs considerably from that of wheat bread, since rye dough is usually sticky, difficult to handle, and capable of very low gas retention resulting in low-volume bread with a coarse crumb (Katina et al., 2014; Sapirstein and Bushuk, 2016).

The role of proteins in rye bread quality is less evident yet, although they are important for the typical flavour and taste of rye sourdough bread (Deleu et al., 2020). Based on some studies, however, high protein content is usually less beneficial for breadmaking (Stępniewska et al., 2019).

Starch properties such as amylose content, swelling capacity, and, consequently, solubility and pasting temperature are of high importance in rye bread quality during and after baking (Bukša et al., 2010). A-type starch transforms after baking into hydrated crystalline forms during storage. The relative crystallinity of starch in rye sourdough bread is lower and increases more slowly than in wheat bread (Mihhalevski et al., 2012), which can be traced back to the differences in starch properties discussed in 3.2.2.

Several research works confirmed that rye bread quality (e.g. volume) is highly influenced by the proportion of water extractable to total pentosans. The analysis of industrial high extraction rye flours showed that bread with a higher volume was generally obtained from rye flours characterised by lower protein, pentosans, and water-insoluble pentosans contents and a higher percentage of water-soluble pentosans content (Stępniewska et al., 2019). In another study, rye flours of poor baking quality showed a higher ratio of insoluble-to-soluble non-starch polysaccharides (NSPs) than those of medium or good quality, confirming that composition and structure of NSPs play an important role in final bread quality. The role of water extractable rye arabinoxylans with varying molar mass and molecular characteristics was investigated in model breads prepared from fractionated and reconstituted wholemeal rye flours (Bukša et al., 2016). It was found that the amounts of AXs leading to positive changes were limited, because their excessive addition caused an increase in water content of the dough, and in consequence high adhesiveness of the crumb (or excessive dilution of dough), which led to deterioration of bread quality.

More information can be obtained when the effect of flour constituents is studied together so their relationship can be revealed. Arabinoxylan-protein complexes in model rye bread have been identified, and the highest bread volume was obtained when starch, proteins, and AXs were present together. In this case the AX/protein complexes had the highest molecular weight. It was



Table 4. Examples of usually applied baking protocols for investigation of baking quality of rye flours

Raw material	Dough type(s)	Mixing	Resting	Dividing/Shaping	Proofing	Baking	Reference
<i>Rye wholemeal (1,200 g)</i>	Imitated sourdough with lactic acid and acetic acid + dry yeast	1. Hand mixer (1 min) 2. Hobart mixer (9 min)	30 min, 30 °C Further mixing (1 min)	Dividing dough into 3 pieces (700 g each) Uniformly distributed in baking pans	37 min, 37 °C, 89% rh	Preheating: 250 °C Steaming: 20 s Baking: 35 min, 200 °C	(Boskov Hansen et al., 2002)
<i>Wholemeal rye flour (792 g)</i>	Yeast/sourdough with yeast/sourdough without yeast	n. d.	30 min, 30 °C, 100% rh	Dividing into 450 g pieces Moulding by hand and panning	15 min, 30 °C	60 min, 200 °C	(Kariluoto et al., 2004)
<i>Rye wholemeal</i>	Yeast fermentation (water addition equivalent to 200 FU)	Diosna mixer	90 min, 37 °C	Dividing into pieces containing 100 g flour Moulding and panning	60 min, 37 °C	30 min, 230 °C	(Buxsa et al., 2010)
<i>Rye flour type 1,150 (720 g)</i>	Yeast fermentation	25 °C 4 min at 100 r.p.m. 1 min at 200 r.p.m. Diosna mixer	-	Dividing into 300 g pieces Moulding by hand and panning	50 min, 30 °C, 80% rh	Initial steam injection of 0.5 L, 230 °C 55 min, 200 °C	(Döring et al., 2017)
<i>Wholemeal rye flour (1,000 g)</i>	Sourdough fermentation (water addition equivalent to 300 FU)	10 min spiral mixer (at low speed)	10 min	Dividing into 5 pieces (350 g each) Moulding by hand and panning	35 °C, 75% rh, until dough reaches top of the pan	10 s steaming 10 min, 260 °C 30 min, 220 °C	(Stępniewska et al., 2019)

(continued)



**Table 4. Continued**

Raw material	Dough type(s)	Mixing	Resting	Dividing/Shaping	Proofing	Baking	Reference
<i>Wholemeal rye flour (100 g)</i>	Yeast fermentation (batter system)	3 min	-	Poured into moulds	12 min	65 min 160 °C (upper heater) 220 °C (lower heater)	(Torbica et al., 2019)
<i>Wholemeal rye flour (800 g)</i>	Sourdough fermentation (German standard method)	10 min, 30 °C flat dough stirrer (Hobart N50)	45 min	Dividing into two pieces	45 min, 32 °C, 78% rh	Two steaming (for 1s and 3 s) 55 min, 210 °C	(Oest et al., 2020)

rh: relative humidity; FU: farinograph unit.

assumed that the possible mechanism of complex formation might be mainly enzymatic, suggesting that peroxidase and H_2O_2 produced by the yeast cells caused enzymatic cross-linking of AX via ferulic acid residues connected to AX and AX-ferulic acid–protein via ferulic acid-tyrosine (Bukša, 2016).

Among rye constituents, enzymes, especially amylases and endo-xylanases, play a significant role in bread quality. In general, rye flour with a low falling number (corresponding to high amylase activity) results in a dough-like bread with sticky crumb, while rye flour with a relatively high falling number results in a hard and dense bread (Katina et al., 2014). During fermentation, endo-xylanases hydrolyse internal 1→4 linkage between xylopyranosil residues in the AX backbone, causing a drastic reduction in molecular weight and consequently resulting in a partial solubilisation of water-unextractable AXs. The pH optimum of endo-xylanase is 4.5 and it is active between 3.8 and 5.3 pH at 40 °C, which corresponds well with the conditions of typical rye dough fermentation stages used in sourdough and direct rye breadmaking methods (Cyran, 2015).

Of course, rye bread properties and the functionality of flour constituents are influenced by other factors such as particle size distribution of the flour and the applied bread making method as well. Granulation significantly affects dough behaviour during fermentation. On the one hand, fermentation of dough with finer flour is more intense, which results from easier access of enzymes to starch. On the other hand, a flour with very fine granulation may have higher buffering properties, which is associated with a higher content of soluble ingredients; that poses a risk of excessive degradation of substrates responsible for creating the dough and bread structure (Stępniewska et al., 2019).

The most typical way of baking rye bread is to use sourdough method, which has several advantages against straight-dough method (Djukić et al., 2014). Sourdough originated acidity improves the baking quality of rye, which is mostly based on the swelling and degradation of cell walls, arabinoxylans, and proteins during fermentation. Acidity inhibits the activity of amylases and proteases in rye dough, preventing the excessive degradation of starch and proteins. The structure of rye starch is also changing during fermentation to enable the starch to absorb more water. Furthermore, acidic conditions increase the solubility and swelling capacity of arabinoxylans (Katina et al., 2014). Increased acidity protects also against mould growth and thus contributes to product shelf-life. Beside acids, alcohols and other volatiles forming during fermentation contribute to the aroma and taste of the bread (Deleu et al., 2020). Beside its technological benefits, sourdough fermentation has several health-promoting effects as well, such as increasing the level of bioactive compounds (Koistinen et al., 2018).

4. NOVEL RYE PRODUCTS AND FUTURE TRENDS

Nowadays, beside conventional breads and bakery products, several different types of food products from rye can already be found on the market (e.g. crispbreads, snacks, porridges, breakfast cereals, etc.), especially in the Nordic countries, and their number is growing continuously (Nordic Rye Forum).

Development of new rye-based products is carried out according to different aspects and objectives. As consumers became more health-conscious, the demand for healthier products of higher dietary fibre and bioactive compound contents increased as well. Therefore, more studies



aim the development of novel fibre-rich rye milling products (Silventoinen et al., 2021) and bakery products of higher fibre (Kołodziejczyk et al., 2020) and bioactive compound (Przygodzka and Zieliński, 2016) contents. However, increased dietary fibre content usually impairs end-product quality, therefore, the improvement of technological and sensory properties of rye products are also the objectives of several R&D works. Heat treatment might be able to contribute to improve baking quality of rye flours by the modification of pasting properties (Torbica et al., 2019). Another approach is using enzymes to modify and improve bread dough rheological properties and baking quality. The proper combination of xylanase and transglutaminase seemed to be enhancing protein networking in rye dough and improving the quality of simple yeast-leavened rye bread (Döring et al., 2017). Sensory properties of high fibre rye crispbreads can be improved by particle size reduction (Alam et al., 2014) or by lactic acid fermentation (Nikinmaa et al., 2020) of the bran fraction.

Extrusion-based 3D printing technique can be applied to develop high protein and fibre snacks consisting of milk powder and wholemeal rye flour (Lille et al., 2020), which is an interesting but currently a challenging solution for developing novel rye-based products.

More and more people are affected by a kind of food intolerance nowadays, and it might be challenging for them to maintain a balanced and varied diet. In the last few years, great efforts have been made to develop gluten-free products of higher nutritional value. The possibility of developing gluten-free rye bread by degrading proteins has been investigated by Walter et al. (2015). It was found that the application of prolyl endopeptidase in sourdough system results in the degradation of gluten to concentrations below 20 mg kg^{-1} , however, the loss of rye protein functionality should be replaced by gluten-free proteins or hydrocolloids. As mentioned in Section 2.3, rye products due to potentially high FODMAP content might not be suitable for patients suffering from IBS. Low-FODMAP diet, which usually coupled also with low fibre intake, however, can influence intestinal microbiota negatively (Laatikainen et al., 2019). Randomised clinical trials confirmed the suitability of low-FODMAP rye breads in the diet of IBS patients (Laatikainen et al., 2016; Pirkola et al., 2018). Therefore, the development of rye products with low FODMAP content is of great interest to researchers, to enable IBS patients to consume rye products rich in nutrients (Pejcz et al., 2020; Pitsch et al., 2021).

As it can be seen, rye, like wheat, is a versatile raw material and can be utilised in many ways. However, rye still holds many untapped opportunities.

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