Capitalizing on a double crop: How processing can help with proso millet's transition to a food crop

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Abstract

Across the globe, strategies to adapt food production to a changing climate as well as to unforeseen events (such as a pandemic), e.g. if farmers miss planting times due to abnormal weather patterns or harvests are lost, are needed. Such food security considerations represent reasons for why proso millet deserves a more prominent place at the table. It has one of the shortest growing seasons and water requirements among cereals and is already grown in rotation with other crops e.g. in the American Midwest. Yet, most consumers in the Western world are unfamiliar with it, which limits its market potential as ingredient. Introducing proso millet to consumers requires development of products with acceptable textural and sensory attributes as well as convincing selling points. These can be found in its nutritional profile, as it is a gluten-free 'ancient' grain and millet-based products frequently have low glycemic indices. This review presents a synthesis of recent studies that utilized processing strategies to advance proso millet functionality. Results are put into the context of the most frequently addressed compositional and functional attributes, organized in clusters. Diversity across varieties in amylose to amylopectin ratios presents an opportunity to utilize proso millet for foods with specific pasting requirements, as in bread vs pasta. Hydrothermal or pressure treatments may further adapt its functionality for baked goods. Bitterness remains an unsolved issue, even when decorticated material is used. In addition, heating dramatically lowers *in vitro* protein digestibility, while starch digestibility appears to be matrix-dependent (more than raw material-dependent).

1 | INTRODUCTION

Millet is a generic name for several small-seeded cereals with pearl (*Pennisetum glaucum*), foxtail (*Setaria italica*), proso (*Panicum miliaceum*) and finger (*Eleusine coracana*) millet among the major species. Pearl millet has been the most widely studied as evidenced by the fact that 60% of the published papers with “millet” as topic focus on pearl millet, followed by finger (16%), foxtail (15%), and proso (8%) millet (source: Web of Science; till June 2020). The lower number of publications found for proso millet compared to the other species might be because till very recently it was almost exclusively used in animal nutrition. However, proso millet’s agronomic characteristics provide convincing incentives for expanding its use as human food in the western hemisphere (Das, Khound, Santra, & Santra, 2019). The facts that it qualifies as ’ancient grain’, is gluten-free and can be used for foods of low glycemic index support such goals. Numerous recent studies have provided more insight on properties of proso millet relevant for food use, how to modify these properties and how they are affected by genotype differences and processing conditions.

The environmental and health benefits of proso millet – summarized in recent review articles (Das et al., 2019; Habiyaremye et al., 2017) - are the driving force for the growing interest in this species around the world. A summary of the opportunities and challenges of using proso millet in food products will complete the picture of this crop that has been part of human nutrition for millennia and has the potential to play a vital role in ensuring global food security. This review’s intention is to highlight recent insights into proso millet attributes, and the efforts made to expand the use of proso in foods. Specifically, this review presents the reader with proso millet's trajectory from its traditional use in regions where it has a long domestication history to ingredient in products adapted to the global market of the 2020ies.

1.1 Research on proso millet – past & present

Using the "Proso millet or Panicum miliaceum L." as topic in the Web of Science (till June 25th 2020) database we found 762 records (research articles and reviews). The interest in proso millet is growing as shown by the increase in publications over the previous 25 years (Figure 1). The numbers of publications on proso millet in the research area of Food Science and Technology represents almost 20% of the total records. Figure 1 highlights the most relevant recent reviews, which mostly cover health benefits and aspects related to food security and climate changes.

Most of the studies on proso millet cover research in agriculture (46%) and plant sciences (34%), due to its interesting agronomic and nutritional traits, summarized in Table 1. With global warming predicted to lead to more abnormal weather patterns, the demand on agronomic traits of crops has expanded. For instance, if global warming is leading to more floods, farms may be unable to meet deadlines for planting certain crops. On the other hand, rainfall may also become scarcer in certain areas. Millets, having been cultivated for millennia in semi-arid areas around the globe, may therefore become more popular (Saxena, Vanga, Wang, Orsat, & Raghavan, 2018). Proso millet is renowned for its ability to grow under relatively dry conditions (Habiyaremye et al., 2017) and has an exceptionally short growing season of just 10-11 weeks, oft cited as the lowest among the cultivated cereal crops (Baltensperger, 2002). This makes it uniquely suited as a double crop in rotation with other crops (often other cereals) or even as catch crop, i.e. a substitute crop if the first harvest is lost

(Habiyaremye et al., 2017). In addition, as the global COVID-19 pandemic has reminded us, it may be important to have crops at hand that can be planted and harvested within a short time frame if supply chains are disrupted. Interestingly, the agronomic and nutritional traits of proso millet could be valuable tools to counteract some of the main challenges that the world of the 21st century are facing, from the scarcity of resources to the prevalence of cardiovascular diseases (Table 1).

Going a little deeper into the literature, Figure 2 shows the bibliometric map created - using VOSviewer software version 1.6.5.0 – on the 143 publications in the area of food science and technology. The map obtained is a two-dimensional representation in which each term is represented by a circle. The diameter and the dimensions of its label indicate the number of publications that have the corresponding term in their title, abstract, or keyword. Terms in a bubble of the same colors form a research area, as recently highlighted for another cereal, durum wheat (Cecchini, Menesatti, Antonucci, & Costa, 2020). Strongly correlated terms are close to each other and assigned to the same cluster by the software. Overall, the terms displayed in Figure 2A are grouped into five clusters.

The green cluster mainly includes terms related to product development and product quality, key to successfully introducing proso millet into the mainstream food market. This cluster is connected to the red one where we find other grains, with which proso millet is often compared and/or blended to make millet-enriched products. Germination is also part of the red cluster since proso millet has previously been described as material suitable for brewing purposes (Zarnkow et al., 2009). Ferulic acid, part of the red cluster too, is connected to the blue cluster that includes studies on the characterization of millet varieties (including proso millet) for their phenolic content and antioxidant activity, as summarized by some reviews (Saleh, Zhang, Chen, & Shen, 2013; Shahidi & Chandrasekara, 2013).

A member of the yellow cluster is protein, connected to the majority of other terms in all clusters. Its functionality is a major determinant for cereal product development considerations, as previously highlighted (Taylor, Belton, Beta, & Duodu, 2014). Digestibility, also within the yellow cluster, has strong links to protein and starch (purple cluster) as numerous studies have evaluated the digestibility of both nutrients affected by of processing, as covered by Annor, Tyl, Marcone, Ragaee, and Marti (2017). Variety (blue cluster) is strongly linked to starch-related key terms represented by the purple cluster, as well as the yellow cluster that includes processing, which in turn all have strong links to quality.

Figure 2B displays the same network in a color scheme related to average publication year and illustrates that the most recent studies frequently have a strong focus on processing. These considerations illustrate the need for a review on proso millet processing. The following sections will be guided by the main topics highlighted by the map but not strictly follow them especially when terms have been the objectives of recent reviews.

2 | THE PURPLE CLUSTER: STARCH AND ITS PROPERTIES

Starch is typically the major constituent of domesticated cereal grains. As main energy source and able to influence texture, starch contents, structure, and properties are of interest for product development. Starch characteristics such as amylose content and properties influenced by it, e.g., gelatinization and retrogradation properties, are crucial for the quality of gluten-free products, a possible market niche for proso millet-based products, as discussed in sections 6.2.2, 6.3, and 6.4.

A wide range of starch contents as well as amylose to amylopectin ratios has been reported for proso millet (ca. 62-70% for whole and 71-80% for decorticated proso) (Kurek, Karp, Wyrwisz, & Niu, 2018; Mustac et al., 2020; Shen et al., 2018; Tyl, Marti, Hayek, Anderson, & Ismail, 2018; Yang et al., 2018). While many regular proso varieties contain more amylose (>30%) than most other commonly used cereal grains (Annor, Marcone, Bertoft, & Seetharaman, 2014a; Tyl et al., 2018; Yanez, Walker, & Nelson, 1991; Yang et al., 2018; Yang, Zhang, Li, Gong, & Feng, 2019), some also appear to have amylose contents in the range of regular wheat or corn starch (Chao et al., 2014; Singh & Adedeji, 2017; Tyl et al., 2018; Yang et al., 2018), as well as similar pasting properties (Chao et al., 2014).

Waxy proso millets varieties also exist, and amylose contents corresponding to a partially waxy type are also described (K. H. Li et al., 2020; Tyl et al., 2018; Zheng, Xiao, Yang, Liu, Liu, et al., 2020). Such differences in amylose contents expand its application potential, further described in section 6.4.

Regarding starch structure, a thorough characterization of proso amylopectin was reported by Annor, Marcone, Bertoft, and Seetharaman (2014b). The average amylopectin chain length ranged from 18.12 to 20.1 for non-waxy proso varieties (Annor et al., 2014b; Yang, Zhang, et al., 2019). However, though not specified, it is likely that these studies used different proso varieties which could have contributed to the observed differences.

Overall, average and external chain length of proso millet starch found by Annor et al. (2014b) was comparable to other cereals and shorter than for starches commonly found in tubers (Bertoft, Piyachomkwan, Chatakanonda, & Sriroth, 2008). On the contrary, proso millet amylopectin had shorter internal chains, which are the segments between branches, than other plant sources (Annor et al. 2014b). This indicates a high degree of branching.

Amylopectin molecules from waxy proso varieties were characterized by higher weight-average molar mass (17 vs 2.4 x 10^7 g/mol) and degree of branching (4.2 vs 2.8% for waxy vs regular, respectively), but lower average chain length, than amylopectin in starch of regular proso millet (Yang, Liu, et al., 2019). Waxy proso millet starches had significantly higher phosphorus contents than regular proso millet or corn starch (Chao et al., 2014), which would enhance starch functionality (i.e., swelling, gelatinization and pasting properties) due to electrostatic repulsion between the negatively charged groups (Ramadan & Sitohy, 2020).

The properties of starch pastes tend to also differ based on amylose contents. For instance, proso flours peak at lower temperature when their starch contains less amylose (i.e., ≤ 10%) (Tyl et al., 2018). Waxy proso millet starch experienced more breakdown during pasting than non-waxy proso millet starch (Yang, Liu, et al., 2019). On the other hand, setback values of waxy proso millet starches were lower, which can explain why the waxy starches retrograded slower (Yang, Liu, et al., 2019). Less syneresis was shown for waxy proso millet starch over the retrogradation period, thus pastes were more stable upon storage (Chao et al., 2014). On the other hand, starch pastes of regular proso millet were reported to be harder and chewier when assessed via a texture analyzer than pastes from waxy proso millet (Yang et al., 2018).

Understanding functional properties of starch is important since its gelatinization and retrogradation behavior represent a selection criterion when screening proso millet varieties for food applications. Based on the pasting profiles and amylose contents of proso millet varieties, Tyl et al (2018) suggested using Earlybird cv (low in amylose) for bread-making, where retrogradation needs to be prevented, while using other proso millet varieties (i.e., Snobird, Sunrise, Sunup) for products that require higher cold paste viscosity or starch gel-forming abilities (i.e., gluten free pasta).

3 | THE YELLOW CLUSTER: PROTEIN, DIETARY FIBER, DIGESTIBILITY AND PROCESSING

3.1 | Dietary fiber

Depending on whether flour has been refined or is in its whole-grain form, the ratio of its constituents will differ. Millet grains are typically decorticated to be palatable, which increases starch but lowers dietary fiber contents (Mustac et al., 2020; Nemeth et al., 2019).

Arabinoxylans are a major polysaccharide type in many cereals, and were described in proso millet as well (Nemeth et al., 2019; Sharma & Gujral, 2019a). Due to their impact on bread making and gastrointestinal health, arabinoxylans from other sources, especially wheat and rye, have been extensively characterized (Knudsen & Laerke, 2010; Saulnier, Sado, Branlard, Charmet, & Guillon, 2007). Since the length and frequency of the arabinose side chains can affect properties such as water solubility, the ratio of arabinose to xylose is frequently assessed. Arabinoxylans from proso millet had a higher ratio of xylanose to arabinose than foxtail, but lower than kodo millet (Bijalwan, Ali, Kesarwani, Yadav, & Mazumder, 2016). This indicates that they were less branched than kodo, but more branched than foxtail millet. Refined flours contain more branched arabinoxylans than wholegrain (Nemeth et al., 2019).

As for soluble β-glucans, their content (0.5 – 1%) was comparable to wheat, rice, and spelt; and lower than oats and barley (Demirbas, 2005).

Comparatively less work than for starch has been performed on the non-starch carbohydrate composition of proso millet. A complete sugar profile of proso millet dietary fiber has, to the best of our knowledge, not been reported. For instance, low molecular weight soluble fibers such as fructans are not quantified in some types of dietary fiber assays because they are soluble in 80% ethanol which is the solvent used to precipitate high molecular weight soluble fibers. Fructans are abundant in many cereals such as wheat or rye (Verspreet, Dornez, Van den Ende, Delcour, & Courtin, 2015), but studies that compare millet types for their contents are currently lacking.

3.2 | Protein

Proteins are of central interest to food scientists and processors due to their importance on end-use quality, while consumers seek their nutritional value. Protein contents from 9.3 – 15% have been reported for field-grown proso millet. In some studies, the protein content of proso millet was higher than other millets such as finger millet (Kumari, Madhujith, & Chandrasekara, 2017; Sharma & Gujral, 2019a), foxtail or pearl (Gulati, Jia, et al., 2018).

Higher contents of certain (but not all) essential amino acids (especially leucine) than commonly found in wheat were reported for proso millet (Kalinova & Moudry, 2006; Wiedemair, Scholl-Burgi, Karall, & Huck, 2020). Similar to other cereal grains, lysine and the sulfur-containing methionine and cysteine represent limiting essential amino acids (Jones, Beckwith, Khoo, & Inglett, 1970; Kalinova & Moudry, 2006; Shen et al., 2018; Wiedemair et al., 2020). It was recently shown that methionine contents vary considerably across proso millet cultivars, which may be an important selection criterion when choosing a variety for food production (Wiedemair, Ramoner, & Huck, 2019). Interestingly, two varieties with a red seed coat (Lipetskoe and Toldanskoe) were described as having a lower amino acid score, for instance containing less valine and isoleucine than most other millet samples with a different seed coat color (Kalinova & Moudry, 2006). The amino acid composition was shown not to be significantly changed by decortication (Wiedemair et al., 2020). However, while the overall range in protein contents was similar for whole and decorticated proso, in some studies, decortication reduced the amount of protein (Mustac et al., 2020; Nemeth et al., 2019)

Proso millet, like other millets, does not contain the amino acid domains found in wheat gliadin, rye secalin and barley hordein which are toxic for people affected by celiac disease, and thus can be utilized for gluten-free products, such as those discussed in sections 6.2.2, 6.3 and 6.4.

3.3 | Digestibility

3.3.1 | Protein digestibility

The digestibility of proso millet protein presents an issue, in particular its decline over heating, regardless of whether digestion is performed with pepsin alone (Gulati et al., 2017) or by pepsin and trypsin (Tyl et al., 2018). Values for raw proso millet flour are often 70-80%, e.g. 75.4% (for whole proso) (Sharma & Gujral, 2019b). Protein digestibility for heated samples from seeds obtained from various countries ranged from 26 – 57 %, with an average of 32% (Gulati, Jia, et al., 2018). Protein profiling via SDS-PAGE did not show appreciable differences among samples of high or low protein digestibility. On the contrary, several peptides of low molecular weight had significant positive correlations to pepsin-digestibility; in contrast, some peptides of higher molecular weight with clusters of hydrophobic amino acids in their sequence exhibited negative correlations with digestibility.

The protein digestibility decline is not necessarily observed for other millet species (i.e., finger, foxtail or pearl millet) (Gulati, Jia, et al., 2018), and could, for instance, not be counteracted by treatments like autoclaving or extrusion (Gulati et al., 2017). Protein interactions known to lower its digestibility include polymerization via disulfide formation, as in sorghum (Hamaker, Kirleis, Butler, Axtell, & Mertz, 1987; Taylor & Duodu, 2015). However, Gulati et al. (2017) showed the formation of hydrophobic aggregates to prevail in proso millet. Reducing agents such as β-mercaptoethanol, capable of cleaving disulfide bonds, were not successful in counteracting the decrease in protein digestibility, but the chaotropes urea and guanidine hydrochloride were. Proso millet heated in their presence did not significantly differ from the raw flour in its digestibility. In combination with increased surface hydrophobicity, these results showed that the hydrophobic interactions promoted by heating led to structures that escape digestion.

Interestingly, the use of transglutaminase, an acyl transferase creating iso-peptide bonds between glutamine and lysine residues (Motoki & Seguro, 1998), partially prevented cooking-induced declines in digestibility (Gulati, Sabillon, & Rose, 2018). While the underlying mechanism was not entirely clear, some studies on other raw materials (pearl millet or kidney beans) observed transglutaminase to reduce heat-induced aggregation and corresponding solubility loss (Hassan, Osman, & Babiker, 2007) or improve protein digestibility (Tang, Sun, Yin, & Ma, 2008). However, the addition of certain salts and sugars to water used for cooking proved effective in overcoming cooking-induced declines in digestibility (Gulati, Sabillon, et al., 2018). Specifically, maple syrup and honey had similar effects as sucrose, in line with the known effect of low-molecular weight sugars to stabilize proteins against thermal stress (Ohtake, Kita, & Arakawa, 2011), while calcium may have undergone electrostatic interactions with functional groups on the proteins, thereby hindering hydrophobic association.

3.3.2 | Starch digestibility

Based on its digestibility rate (in presence of a mixture of pancreatin, invertase and amyloglucosidase), starch is classified into rapidly digestible starch (RDS) and slowly digestible starch (SDS), using *the in vitro* method proposed by Englyst, Kingman, and Cummings (1992). The fraction that remains undigestible after 120 min is often called resistant starch (RS). The same term is used to refer to the starch amount that remains undigested after 16 hours of hydrolysis with alpha-amylase and amyloglucosidase (AACC Method 32-40.01). In our opinion, using the same term for results from two different methods impairs comparison among studies. In the present review, the term residual starch (ReS) will be used to indicate the amount of undigestible starch after 120 min hydrolysis. In addition, in this review, only results obtained from food products (not raw flours) will be discussed for effects on starch digestibility fractions. Millets have been extensively studied for aspects related to the digestibility of their starch fraction, as recently reviewed by Annor et al. (2017). The wide range of amylose contents in proso millet starch has a profound impact on its digestibility. Besides amylose content, amylopectin fine structure and the interplay between starch, proteins and lipids can affect starch digestibility but is still poorly understood.

Proso millet starch has been shown to undergo complex formation with lipids more than pearl millet, but similar to finger millet (Annor, Marcone, Corredig, Bertoft, & Seetharaman, 2015). The extent of complexation with linoleic acid was higher than for the other tested fatty acids, which coincidentally is also the main fatty acid in proso millet lipids (Bora, Ragaee, & Marcone, 2019a; Shen et al., 2018; Vrancheva, Krystev, Popova, & Mihaylova, 2019), similar to other cereal grains including some other millet types such as foxtail (Bora et al., 2019a). Moreover, addition of linoleic acid to cooked starch pastes also significantly decreased RDS and SDS, and increased the ReS underlining the effect of complex formation on starch hydrolysis kinetics (Annor et al., 2015).

In regard to amylopectin structure, it is possible that the extended branching of proso millet starch (Annor et al., 2014b; Yang, Liu, et al., 2019) poses some steric hindrance to starch-degrading enzymes, as proposed for other starches (G. T. Li & Zhu, 2017).

Factors with the capability to lower starch digestion rates either prevent accessibility of the substrate or relate to structural characteristics of the starch that impair hydrolysis (Dhital, Warren, Butterworth, Ellis, & Gidley, 2017). This for instance involves intact plant cell walls, dense protein matrices, or viscous soluble dietary fibers. Consequently, in composites made of proso millet starch and various proteins and subjected to heat-moisture treatment, RDS decreased while SDS and ReS significantly increased (Zheng, Xiao, Yang, Liu, Feng, et al., 2020). The effects were most pronounced for composites with soy or whey protein, employed at 15 or 10%, respectively. At such concentrations, both proteins form gels when denatured via heat, and the authors hypothesized that a dense protein matrix prevented enzymatic access and thus hindered starch digestibility (Zheng, Xiao, Yang, Liu, Feng, et al., 2020).

4 | THE BLUE CLUSTER: ANTIOXIDANT ACTIVITY AND DIFFERENCES TO OTHER MILLET TYPES

For a more extensive overview of phenolic phytochemicals in millets, their extraction and results in *in vitro* antioxidant assays, the reader is referred to a recent review (Kaur, Purewal, Sandhu, Kaur, & Salar, 2019). One general conclusion among multiple studies is that when comparing a range of millets for their contents in phenolic acids, proso millet tends to be on the low end of the spectrum (Chandrasekara & Shahidi, 2011; Kumari et al., 2017; Sharma & Gujral, 2019b).

Among the millets, proso millet is comparatively low in flavonoids and tannins (Chandrasekara & Shahidi, 2010; Taylor & Duodu, 2015). However, values were higher than for whole wheat (Sharma & Gujral, 2019b). Phytic acid contents however were significantly higher than for other millets. Aside from featuring lower contents than other millets for some phytochemicals, tocopherols and tocotrienols were also found to be lower in proso millet than in a range of other cereals and pseudocereals (e.g., amaranth or quinoa) suitable for production of gluten-free products (Niro et al., 2019). The main tocol in proso millet was γ-tocopherol, and the total tocol content was similar to sorghum, but lower than for several other samples such as. Despite of these results in comparison to some other sources, proso millet may contain higher contents of some phenolic acids and other phytochemicals than other cereal grains such as wheat (Ceccaroni et al., 2020).

Just like other cereal grains it contains numerous phenolic acids, typically derivatives of hydroxybenzoic (*p*-hydroxybenzoic acid, gentisic, vanillic acid (Chandrasekara & Shahidi, 2011), syringic (Bora et al., 2019a) and salicylic acid (Ceccaroni et al., 2020)) or hydroxycinnamic acids (*p*-coumaric and ferulic acid as the two main hydroxycinnamic acids (Azad et al., 2019; Bijalwan et al., 2016; Chandrasekara & Shahidi, 2011; Tyl et al., 2018), as well as caffeic (Chandrasekara 2011a)) and chlorogenic acid (Zhang, Liu, & Niu, 2014

Hydroxycinnamic acids, in particular ferulic and *p*-courmaric acid, also occur as esters with phytosterols in cereal grains. However, only traces of such acylated phytosterols were found in proso millet (Tsuzuki et al., 2018), in contrast to foxtail millet that outperformed proso millet by about two orders of magnitude.

Cell wall-linked ferulic acid molecules can undergo coupling reactions to form a covalent bridge of two ferulic acids between polysaccharide chains (Bunzel, 2010), with the possibility of other compounds (hydroxycinnamic acids, proteins or lignin) participating. The resulting cross-linked structures have been found in a wide array of plants including proso millet, especially in its insoluble rather than the soluble dietary fiber portion (Bunzel, Ralph, Marita, Hatfield, & Steinhart, 2001), indicating that proso millet arabinoxylans are heavily cross-linked. Cross-links in plant cell walls have been investigated for their contribution to bread making (Hartmann, Piber, & Koehler, 2005). The fact that these derivatives for ferulic acid were often analyzed in proso millet along with other cereal grains aside from millets is part of the reason why ferulic acid is part of the red cluster but has such strong links to terms in the blue cluster (Figure 2a).

Cereals typically contain lutein (sometimes also referred to as xanthophyll; which however is also the general name for the group of carotenoids that contain oxygen in their structure) and zeaxanthin as the main carotenoids (Abdel-Aal, Young, Rabalski, Hucl, & Fregeau-Reid, 2007), and this has been found for proso millet as well (Niro, D'Agostino, Fratianni, Cinquanta, & Panfili, 2019; Tyl et al., 2018; Zhang et al., 2014). In some studies, zeaxanthin contents (16-16.8 µg/ g d.b.) were higher than lutein contents (4.9 – 15.1 µg/ g d.b) (Zhang et al., 2014) in others (Niro et al., 2019; Tyl et al., 2018) lutein was more prevalent. While fewer studies seem to have quantified individual carotenoids than phenolic acids in proso millet, the emerging picture is that its values are above those of several other cereals such as einkorn and emmer, but lower than for corn (Abdel-Aal et al., 2007). In particular, proso millet seems richer in carotenoids than other gluten-free raw materials such as sorghum, teff, amaranth or quinoa (Niro et al., 2019). Selecting proso millet varieties rich in carotenoids for food formulations will allow for improving the nutritional value of products, especially gluten-free ones that are often inferior to e.g. whole grains. However, up to now, most studies on millet carotenoids have evaluated flour samples, neglecting how processing operations and conditions affect carotenoids in proso millet-based food products.

4.1 | *in vitro* antioxidants

In addition to analysis of individual phenolic constituents, the reactivity of phenolics towards the so-called Folin-Ciocalteu reagent is often exploited, and results reported as 'total phenolic' contents and expressed in equivalents of gallic (Ceccaroni et al., 2020) or ferulic acid (Chandrasekara & Shahidi, 2011; Kumari et al., 2017). However, the reagent is not specific towards phenolics, and a wide range of other compounds have been reported to react with it (Everette et al., 2010). The main reason for the interest in assessing phenolic phytochemicals relates to the capability of phenolics to intercept the lipid oxidation reaction cascade (Huang, Ou, & Prior, 2005). They may therefore retard lipid oxidation processes, which play a role in both the stability of foods as well as the etiology of several chronic diseases. Numerous *in vitro* assays have been developed to compare phytochemicals or extracts for their ability to prevent oxidation reactions, e.g. by reacting with radicals or chelating metals. For instance, numerous studies on millet phenolics have evaluated them via the 2,2-diphenyl-1-picrylhydrazyl (DPPH) and ferric reducing ability of plasma (FRAP) assay. Regardless of the method used, results are influenced by conditions chosen for their extraction and analysis (Bonoli, Verardo, Marconi, &

Caboni, 2004; Zhou & Yu, 2004) which often differ among studies and impair comparisons. A large proportion of cereal phenolics, including the ones in millet, is present in the form of esters, which frequently are insoluble in water or aqueous mixtures. In this case, the phenolics are frequently referred to as 'bound' and can only be obtained if the ester bond is first cleaved. As a likely consequence to the lower phenolic contents in proso compared to other millets, its extracts gave lower values in several *in vitro* antioxidant assays except for singlet oxygen scavenging (Chandrasekara & Shahidi, 2011). The lower results in relation to other tested millets were also reflected by proso millet extracts being among the least effective in lowering formation of lipid oxidation products in model food systems, i.e. bulk oil, linoleic acid emulsion, and ground pork (Chandrasekara & Shahidi, 2012). However, the extracts did exert a protective effect compared to the control.

Antioxidant assays did not give significantly different results for samples with regular vs waxy starches (Shen et al., 2018). However, samples of proso millet with testa of different colors were shown to differ in their phytochemical profile and results in *in vitro* antioxidant assays, as for instance seen in a comparison between proso millets with white, red and brown testa. The brown variety Gumi 20 was the only one to contain free caffeic and *p*-coumaric acid, had more syringic but less ferulic acid than the other two varieties (Zhang et al., 2014) and outperformed the other two in peroxyl radical scavenging ability. The free phenolics of the brown variety also had the lowest EC_{50} against proliferation of HepG2 human liver cancer cells, while its extract of esterified phytochemicals had higher EC_{50} values than from the other two varieties. Compared to results from other plant sources, the EC_{50} values were relatively high, indicating that inhibitory activities against HepG2 cell proliferation exerted by millet extracts are less potent than for extracts from other sources e.g. from strawberry (Meyers, Watkins, Pritts, & Liu, 2003). Extracts from oat, rye, barley and wheat in their whole grain from also inhibited HepG2 cell proliferation at lower concentrations than the millet extracts (Kim et al., 2013).

5 | PROCESSING: PART OF THE YELLOW CLUSTER, BUT LINKED TO ALL OTHERS

The review by Saleh et al. (2013) provided an overview on challenges, limitations, and future perspectives of the processing technologies used for improving the nutritional characteristics of millet, including thermal and mechanical processing, fermentation, and germination. In the following section the most recent studies on the effects of processing on proso millet components are presented. Together with lessons learned from incorporating proso millet into food products (section 6), an overview of results is also given in Table 2.

5.1 | Thermal treatments

Two categories of hydrothermal treatments are annealing and heat-moisture treatments (HMTs), reviewed by BeMiller & Huber (2015). Both treatments expose starch to a temperature above its glass transition (at moisture contents $< 35\%$ for HMTs and $\geq 40\%$ for annealing) (BeMiller & Huber, 2015). Starches experiences a profound rearrangement during HMT which typically delays the gelatinization process of starch modified this way. This is reflected in shifting the gelatinization to higher temperatures, and decreasing viscosity (BeMiller & Huber, 2015). Annealing makes amorphous granule regions more rigid and leads to structural rearrangement and perfection of crystals. After annealing, gelatinization onset is increased while the gelatinization range is narrower. Swelling and amylose leaching is less; pasting parameters are affected in a similar fashion as by HMT with the side effect of increased hot paste stability.

Hydrothermally and acid-modified starch obtained from commercial proso millet was recently produced and analyzed for various properties (Singh & Adedeji, 2017). Acids predominantly cleave glycosidic linkages, of amylose molecules in amorphous granules regions (Hoover, 2010). Hydrothermal treatment significantly increased water binding capacity and in line with other research on starch (BeMiller & Huber, 2015), led to higher temperatures necessary for gelatinization as evidenced by a higher onset, peak and conclusion temperature in differential scanning calorimetry (Singh & Adedeji, 2017). This larger temperature range was still observed after 10 days, which the authors explained as being due to more double helices being formed and their association during retrogradation.

5.2 | Ultra-high pressure (UHP) treatment

UHP processing conveys unique properties to starch: only inner regions in the granules gelatinize while outer regions remain relatively unaffected (Blaszczak et al., 2007). In a comparison among treatments, the highest applied pressure, 600 MPa, resulted in starch with significantly increased swelling power and solubility at 50 and 60° C than native starch (Li et al., 2018). These changes corresponded loss of molecular order and to profound changes in gelatinization and pasting profiles, i.e. the endotherm essentially disappeared, and the viscosity significantly decreased over the entire pasting program. However, at intermediate pressure ranges, from 150 – 450 MPa, an annealing effect could be observed (Li et al., 2018). Overall, up to 450 MPa, a structural reorganization with a weakening effect occurred in the granules, while at 600 MPa, the gelatinization process was essentially complete. This indicates that UHP treatments can be utilized to induce targeted alterations in starch intended for different purposes. As an example, UHP treatment has been used to improve the viscoelastic properties of gluten-free flours (i.e., buckwheat, rice and teff), by inducing both starch gelatinization and protein cross-linking, (Vallons, Ryan, & Arendt, 2011). However, since the type of flour might affect the impact of UHP treatments on both protein and starch, specific studies on proso millet are required.

5.3 | Decortication and cooking

Chandrasekara et al. (2012) evaluated differences in phenolic phytochemicals between whole, decorticated and cooked millet samples. Parallels were observed between results of the Folin-Ciocalteu and DPPH scavenging assay, where whole millet extracts outperformed the other samples. Cooked and decorticated proso millet samples were not significantly different from each other in these assays and had significantly lower Folin FAE and DPPH radical scavenging ability than all other tested millets (Chandrasekara et al., 2012). Free phenolics extracts from decorticated proso millet subjected to roasting, steaming, puffing and extrusion showed higher FAE in the Folin-Ciocalteu reagent than the unheated, decorticated control (Azad et al., 2019). The flavonoid content increased in a similar manner, suggesting that extractability of the compounds increased. All evaluated processing methods increased extractability of all evaluated phenolic acids. Consequently, results in all *in vitro* antioxidant assays were also higher.

5.4 | Germination (or sprouting)

In recent years, use of sprouted cereals in the form of flours or as stand-alone products has increased due to favorable nutritional attributes as recently reviewed by Lemmens et al. (2019). It activates enzymes that degrade proteins and carbohydrates to provide energy for the developing plant. Germination was part of the red cluster, but due to its effect on cereal constituents, it was linked to terms such as protein (Figure 2a).

Sprouting over a period of 3 days was shown to induce changes in the chemical profile of proso millet, and these changes were affected by the temperatures to which the grains were exposed to (Ceccaroni et al., 2020). Several free phenolic acids that had not been detectable before the sprouting treatment were already present after one day. Some free and esterified phenolic acids were only detected in samples sprouted at one of the two evaluated temperatures (15 vs 20 °C). Overall, increases in phenolic acids were more pronounced when sprouting was performed at 20 as opposed to 15 °C. Samples sprouted at 20 °C had significantly higher values for free + esterified phenolics in the Folin-Ciocalteu assay after 2 or 3 days than at the start. Although present at 2-3 orders of magnitude below the levels of the esterified phenolics, the changes seemed driven by the free phenolic acids as their percentual increase was much higher. Sprouting temperature also influenced the rate of starch hydrolysis, and glucose, fructose and sucrose levels increased much faster when grains were sprouted at 20 °C. Sprouting of proso millet for up to 48h decreased the content of phytic acid, an antinutritional factor, while a significant increase in α-amylase activity led to decreases in starch content (from 63.7 to 56.3%) (Sharma & Gujral, 2020). Activity of proteases slightly increased, also reflected in significantly increased protein solubility, from 36.4% for un-germinated proso to 37% after soaking and up to 47.6% after 48h of sprouting. Protein degradation, and resulting solubility increase improved *in vitro* protein digestibility to values up to ca. 83% after 48h (Sharma & Gujral, 2020). Changes in protein digestibility after heating of these sprouted flours were not a focus of the study by Sharma & Gujral (2020) but could yield valuable information as provided by Gulati et al. (2018) who assessed the effect of sprouting on *in vitro* protein digestibility. While few changes were apparent in raw flours upon germination, cooked sprouted flours had significantly higher digestibility than the cooked control, regardless of germination time. However, the digestibility values were still lower (< 60%) than for raw flours and not improved to the same extent as by e.g., high sucrose or calcium chloride concentrations in the cooking water (Gulati, Sabillon, et al., 2018).

6 | THE GREEN CLUSTER: QUALITY OF PRODUCTS WITH PROSO MILLET

As shown in Figure 2B, in the last 5 years, topics related to processing and product development attracted the attention of researchers. In following sections, an insight of the quality of the main food products will be provided as also summarized in Table 2.

6.1 | Products in the style of traditional foods

Proso millet is traditionally consumed as porridge and cous-cous. In order to improve the technological and nutritional properties of millet and resultant products, recently, parboiling prior to decortication was applied (Bora, Ragaee, & Marcone, 2019b). The effects of parboiling ranged from increasing the decortication yields to altering compositional aspects. Specifically, by (partially) gelatinizing starch which retrogrades upon cooling, parboiling caused an increase in kernel hardness and resistant starch. Consequently, porridge and couscous had lower RDS when prepared with parboiled millet, while SDS contents were not affected, and the expected GI of both products decreased. However, the magnitude of changes was very small.

In line with the discussion on the effect of heat on protein digestibility of proso millet in section 3.3.1, the *in vitro* protein digestibility values of the products made from parboiled millet were significantly reduced and below 50% (Bora et al., 2019b).

Meanwhile, the FAE in the Folin-Ciocalteu assay of free and bound phytochemicals increased in products made of parboiled millet. During parboiling, some compounds may migrate into the inner grain layers and the authors hypothesized that this led to reduced phytochemical losses during milling. Correspondingly, the scavenging ability for DPPH was also greater in extracts from products prepared with parboiled millet.

In addition to nutritional traits, sensory properties of proso millet-based products are crucial for consumer acceptability and establishing a market for them. Sanderson et al. (2017) developed a couscous-style product based on decorticated white proso millet, prepared on a stove top method or in a rice cooker. Compared to wheat-based couscous, proso millet couscous contained significantly more protein and total dietary fiber, mostly at the expense of starch (Sanderson, Duizer, & McSweeney, 2017). A notable finding was the higher bitterness for both millet couscous types. Other sensory scores where millet couscous differed from the wheat control were its significantly higher cohesiveness, dryness, nuttiness, and tooth-packing. Considering the cooking method, the millet couscous was rated as better when prepared on the stove top than in the rice cooker (e.g. as less dry). The millet couscous sample prepared in the rice cooker received significantly lower scores for liking of texture and appearance than the wheat couscous. However, scores for overall liking and liking of flavor were not different among the three samples (Sanderson et al., 2017). Thus, millet is a promising raw material for such an application, provided that preparation methods are adjusted to obtain a product with acceptable attributes.

Another traditional use for millet is in the form of sour porridge consumed in certain parts of China. Wang et al. (2018) compared fermentation of proso millet via lactic acid bacteria, acetic acid bacteria, and yeast. Response surface methodology was used to optimize the fermentation conditions based on sensory scores for color, flavor, taste, and texture. Highest rated sour millet porridge was produced using a 1:1:1 combination of the two bacteria strains (*Acetobacter aceti, Lactobacillys brevis*) and baker's yeast, and described by the trained panel as milky white, soft and of sour smell and millet taste (as opposed to bitter) (Wang, Liu, Jing, Fan, & Cai, 2019). Such studies could encourage proso millet consumption in dry regions that would especially benefit from its cultivation. A product like sour porridge is well suited for regions with a long history of millet consumption. However, proso millet has the potential to also be included into foods more familiar to consumers in the Western hemisphere, which may facilitate its promotion in such places.

6.2 | Bread

6.2.1 | Millet bread including wheat-derived ingredients

Earlier studies on using proso millet for bread making focused on its inclusion into wheat bread recipes (Schoenlechner, Szatmari, Bagdi, & Toemoeskoezi, 2013). Replacing up to 50% of the wheat flour could be achieved, however specific volume and number of pores were significantly reduced while firmness increased. Incorporation of certain emulsifiers partially ameliorated these effects. Further addition of enzymes (xylanase and transglutaminase, either individually or in combination) improved bread properties even more. All three conditions led to higher specific volume and dough elasticity. Firmness was significantly increased when transglutaminase was added, either alone or with xylanase, and in both cases the number of pores was reduced. Xylanase by itself did not significantly change firmness, number or mean area of pores, but did not increase the specific volume to the same extent as when transglutaminase was present (Schoenlechner et al., 2013). The rationale for using xylanase in combination with transglutaminase is that use of cross-linking enzymes by themselves may strengthen the dough too much, i.e. reduce the elasticity and produce dense, unacceptable crumb (Caballero, Gomez, & Rosell, 2007).

Besides xylanase and transglutaminase, using pyranose-2-oxidase was effective in improving the properties of millet dough enriched in rye bran arabinoxylans. Specifically, the mixing stability of arabinoxylan-enriched dough increased when pyranose-2-oxidase was added to the formulation, likely due to cross-linking between arabinoxylans and/or to their interactions with other flour components (i.e., proteins) (Nemeth et al., 2019). While the direct effects of pyranose-2-oxidase on bread quality need to be assessed, these findings are encouraging for improving the quality of proso millet products.

Among chappati-style flat breads where different millet species were combined with vital wheat gluten, proso millet breads experienced less baking loss than breads made with other millet types (Sharma & Gujral, 2019a). However, all millet breads had significantly and substantially higher shrinkage (6.8%) than wheat breads (1.4%). Proso millet had significantly lower dough development time and stability than the other millet flatbreads during mixing. The authors related this to proso millet ranking low in dietary fiber content among the samples, which may have also contributed to its high extent of retrogradation. Proso millet breads also had one of the highest proportions of SDS, either in fresh form (40.5g/ 100g d.b.; 62% on a starch basis) or when stored up to 2 days (44.8 g/100 g d.b.; 69% on a starch basis). Consequently, these breads had the second lowest predicted glycemic index after kodo millet. From a commercial perspective, product formulation may be more feasible and preferred if blends of millet and wheat flour can be used.

In flat breads where 25% of wheat flour was replaced with the same millet types as described above (Sharma & Gujral, 2019a), chapattis made from proso millet/wheat blends exhibited significantly lower shrinkage and puffed better than blends of wheat and other millet flours (Sharma & Gujral, 2019c). However, SDS values of the wheat/proso blends were lower than for other wheat/millet combinations but still higher compared to wheat-based product. Scores for overall acceptability were among the highest among the tested samples, thus suggesting that proso millet is a good candidate for incorporation into wheat-based flat breads.

6.2.2 | Gluten-free breads

Recent work on proso millet in bread capitalized on its gluten-free aspect (Tomic, Torbica, & Belovic, 2020). Adding proteins (i.e., pea, rice, or whey) and transglutaminase to proso millet enhanced the quality of the resulting bread, in terms of increasing volume and decreasing hardness and bitterness. Overall, the type of protein by far outweighed the effect of transglutaminase and especially the inclusion of whey protein altered the investigated properties of gluten-free proso millet bread. Bread with incorporated whey protein was perceived as less moist in sensory analysis and exhibited a finer crumb structure less prone to collapse.

A different strategy to produce gluten-free proso millet bread was used in a study that evaluated proso millet as sole flour in contrast to 1:1 blends of proso millet with starches from gluten-free materials, corn or potato (Woomer, Singh, Vijayakumar, & Adedeji, 2019). Recipes also incorporated carboxymethylcellulose and xanthan gum blend and milk powder. The partial substitution of proso millet with corn starch resulted in breads with higher specific volume and lightness. Both starch types led to significantly lower crumb firmness. However, corn starch inclusion led to a very light crust color that received a significantly lower score on a 9-point hedonic liking scale. However, there was no significant difference among overall acceptability among the three products, which received a score close to “like slightly”.

Besides millet flour, also bran from proso millet was recently utilized for bread-making (Mustac et al., 2020). Incorporation of (pre-soaked) bran into a gluten-free rice bread for up to 10% significantly increased the specific volume and lowered hardness as well as chewiness, but also reduced cohesiveness and lightness. Breads with proso millet bran also contained higher amounts of insoluble dietary fiber, soluble dietary fibers, and compounds reactive towards the Folin-Ciocalteu reagent (Mustac et al., 2020).

6.3 | Other baked products and snacks

As use of a gluten-free ingredient can be easier in unleavened products, the production of cookies from proso millet flour was assessed (Devisetti, Ravi, & Bhattacharya, 2015). Recipes contained 1 %w/w of hydrocolloids (on a flour basis) to prevent dough from being too crumbly and allow for it to be handled and shaped. Comparing the performance of acacia, guar and xanthan gum, the authors discourage the use of guar or xanthan gum, since they led to high adhesiveness and stickiness. On the other hand, addition of acacia gum to recipes resulted in the lowest stickiness and adhesiveness. This hydrocolloid was thus judged as best among the tested and came closest in overall quality to a wheat cookie evaluated as control.

Biscuits and extruded snacks made with refined corn/refined proso millet blends with either 100%, 75%, 25% or 0% millet were less liked overall, for texture and flavor, the more millet was incorporated (McSweeney, Duizer, Seetharaman, & Ramdath, 2016). While there were some differences between how female and male panelists evaluated the products, the main issue for the products revolved around bitterness. Biscuits with the highest levels of millet inclusion (75 and 100%) were also associated with descriptors such as oily, rancid, gritty and crumbly. The extruded snacks with more millet were evaluated as denser and crunchier, in addition to bitter aftertaste. Sensory profiles of millet products might be enhanced by applying suitable pre-treatments (i.e., fermentation or sprouting) similar to what has been proposed for other bitter grains such as quinoa (Suarez-Estrella, Torri, Pagani, & Marti, 2018). Considering textural properties of snacks, adjusting the moisture content during extrusion was shown to be of crucial importance (Gulati, Weier, Santra, Subbiah, & Rose, 2016) as lower feed moisture contents yielded product that was less hard and more expanded, hence of lower bulk density. In addition, these products had a higher water solubility index, and higher *in vitro* antioxidant capacity as assessed by the Trolox equivalents antioxidant capacity, (TEAC) assay. Higher Trolox equivalents corresponded to flours of lower CIE*L but higher CIE*a values, indicating that they were influenced by non-enzymatic browning reactions, in agreement with Maillard reaction products having been shown to possess activity in the TEAC (Mondaca-Navarro et al., 2017). Processing methods may improve product properties of baked goods, such as described for heat-moisture treated proso millet flour as ingredient in gluten-free cakes (Fathi, Aalami, Kashaninejad, & Mahoonak, 2016). Four heat-moisture treatment conditions were compared, and except for the condition using the highest moisture (30%) and temperature (120°C) among the tested parameters, the cake volume increased, and crumbs became airier and softer. However, the heat-moisture treatments affected the color by inducing browning. Using a combination of un-treated and heat-moisture treated proso millet flour resulted in better sensory ratings for parameters such as taste and texture, as well as overall acceptability than when only using heat-treated proso millet flour. Thus, heat-moisture treatments present a suitable processing operation to improve some product parameters, as long as the temperature and moisture are not too high (Fathi et al., 2016).

Using blends of refined corn with refined white proso millet, McSweeney et al. (2017) showed starch digestibility was significantly altered with increased incorporation of proso millet. In four product types, i.e. couscous, extruded snacks, muffins and porridge, the more corn was replaced with proso millet, the lower the RDS and the higher the ReS (McSweeney, Seetharaman, Ramdath, & Duizer, 2017). However, the actual extent of digestion, as well as expected glycemic indices, considerably varied by food type. Extruded snacks with 100% millet had higher RDS (35.2%) than porridge (30.8%) and couscous (27.6%), and lower RS (27.1 vs 45.4 and 46.8%, respectively). In follow-up work, the physiological response (areas under the curve, AUC) to those products was evaluated. When the products were given to healthy male volunteers at equivalent starch contents, the glycemic response differed more than the *in vitro* results indicated (McSweeney, Ferenc, et al., 2017). Products made entirely with refined proso millet were not found to significantly differ from those made of refined corn. Interestingly, the AUC for whole millet couscous was not significantly lower than for the refined millet couscous.

Strikingly, the extruded snacks had AUC > 189, much higher than couscous and porridge. The authors hypothesized that the couscous type products elicited lower responses due to grains remaining intact. Overall, the study illustrated the crucial effect of the food matrix on glycemic response.

6.4 | Pasta

Several studies suggest that proso millet may be a suitable material to expand the ingredient range used for gluten-free pasta production. Specifically, varieties with high amylose and carotenoid contents may lend themselves well for such applications as amylose contents determine the structure of gluten-free pasta (Marti & Pagani, 2013), and color is an important quality parameter (Marti, D'Egidio, & Pagani, 2016). Production of gluten-free spaghetti was possible when 1-2% hydrocolloids were incorporated into recipes (Romero, Santra, Rose, & Zhang, 2017). Xanthan gum and guar gum both allowed for the formation of a coherently structured dough, whereas spaghetti produced with sodium alginate were unable to hold their shape upon cooking and disintegrated. The gluten-free dough samples were characterized by being lighter and more yellow than wheat dough. After cooking, only gluten-free pasta with xanthan gum was lighter than wheat pasta, whereas all gluten-free pasta remained more yellow. Texture profile analysis showed that the gluten-free pasta had lower hardness, cohesiveness and chewiness than the wheat pasta. Textural differences to commercial wheat pasta were also found for gluten-free fresh-pasta based on proso millet, in both instrumental and sensory analysis (Cordelino et al., 2019). Four millet varieties were compared for their performance as ingredient in this pasta, and had been selected based on differences in prolamin profile (high molecular weight prolamins present or not) as well as in amylose contents (Tyl et al., 2018). Similarly to the gluten-free spaghetti (Romero et al., 2017), fresh gluten-free millet -pasta was more yellow than wheat pasta before cooking, and the commercial gluten-free rice/corn products had the lowest yellowness. These differences were a consequence of higher lutein and zeaxanthin contents in the millet pasta, and partly due to the incorporation of eggs into the formula. However, similar to the color of proso millet spaghetti referenced above, the yellowness of cooked millet fettuccine was not higher than for cooked wheat pasta (Cordelino et al., 2019) except for one sample made from a millet variety that contained significantly more lutein than other millets (Tyl et al., 2018). Sensory panelists also noticed gray color in the cooked millet pasta. The protein profile and amylose content exerted some influence on sensory scores. Notably, millet pasta based on varieties with prolamins of high molecular weight present were rated as less sticky, and this was one of the properties where millet pasta in general received less favorable ratings than the two commercial samples. Millet pasta from flour with high amylose content was perceived as less sticky, but chewier, in agreement with other studies (Jeong, Kim, Yoon, & Lee, 2017). Regardless of variety used, millet pasta had lower contents of RDS than the commercial gluten-free pasta, which however was also a consequence of the lower overall starch contents (Cordelino et al., 2019). Nevertheless, other authors have pointed out that gluten-free products are frequently faster digestible than their gluten-containing counterparts and contain less resistant starch (Giuberti & Gallo, 2018). Depending on the formulation (raw material) and processing, the starch in commercial gluten-free pastas may be predominantly RDS (Marti et al., 2017). Thus, formulating with proso millet could lead to gluten-free products of lower glycemic index. Overall, compositional differences among proso millet varieties may favor different product applications. An additional characteristic of the millet pasta evaluated by Cordelino et al. (2019) was lower cooking loss than wheat or commercial gluten-free pasta, regardless of variety. In subsequent experiments, it could be shown that this difference corresponded to a difference in protein alignment (Tyl, Marti, & Ismail, 2020). Proteins in cooked millet pasta were almost entirely folded into β-sheets, whereas both commercial pasta types retained some random segments and, to a lesser degree, α-helices. Moreover, the study highlighted how protein secondary structure distributions affect the cooking quality of fresh pasta and its protein digestibility in opposite ways, with β-sheet structures being of particular importance and negatively affecting protein digestibility. However, further studies are required for a deeper understanding of the relation between secondary structure distribution and digestibility in order to find strategies for its improvement.

6.5 | Beverages

In countries with a long cultivation history of millets, these cereals are frequently used to make alcoholic beverages such as yellow wine in certain Chinese provinces. A study where wine was prepared from proso millet and instrumental methods used to evaluate its aroma profile found 64 volatile compounds (Liu et al., 2018). Among the 14 compounds that reached their odor threshold were primarily esters, alcohols, aldehydes and benzene derivatives that mostly contributed sweet and floral notes except for the benzene derivatives which imparted phenolic and medicinal aroma. Future studies could explore how the aroma is perceived by a sensory panel or how it differs from wine made from other millet types or rice, which is produced via similar technology (Liu et al., 2018).

Staying within the realm of beverages, one of the traditional uses of millets in African countries, where several millet varieties are widely cultivated (Saxena et al., 2018) is for brewing purposes (Kubo, 2016). One key parameter to assess when evaluating a cereal as source for malt is the activity of digestive enzymes, especially α- and β-amylases to produce fermentable sugars from starch. Both enzymes exhibit lower activity in proso than for barley (Zarnkow, Faltermaier, Back, Gastl, & Arendt, 2010). In related work, starch hydrolysis during mashing was investigated (Zarnkow, Kessler, Back, Arendt, & Gastl, 2010). The pH and temperature optima of α- and β-amylase, as well as limit dextrinase were determined to optimize mashing of proso millet malt. Full saccharification was achieved, and the characteristics of the so generated malt were mostly within the common range reported for barley malt (Zarnkow, Kessler, et al., 2010). One notable exception was the thiobarbituric acid index, where proso malt displayed higher values than typical for barley malt. Higher thiobarbituric acid indices are regarded as indicators for thermal stress and thus linked to oxidation and off-flavors produced by it (McGivney et al., 2008). Thus, proso millet malt could be a useful tool for production of gluten-free beer, yet attention should be paid to minimize oxidation.

This is especially important as linoleic acid is the dominant fatty acid in proso millet and its two double bonds make it prone to undergo lipid oxidation (Belitz, Grosch, & Schieberle, 2009). Thus, storage studies and experiments evaluating strategies against lipid oxidation of proso millet-based products are warranted. For other millets, varietal differences in the susceptibility to undergo oxidation have been reported (Alavi, Mazundar, & Taylor, 2018) and such evaluations could aid in breeding programs for proso millet. Varieties less prone to rancidity development may be more suited for processing methods involving heat treatments, which may gain popularity due to their effect on functionality (see sections 5.1 and 6.3).

7 | CONCLUSION AND PERSPECTIVES

Much progress has been made in expanding the range of products that incorporated proso millet and describing such products, yet some challenges remain (Table 3). Several studies have focused on characterization of proso millet starch in its composition, thermal and other properties as well as digestibility along with evaluating modifications. The low protein digestibility of cooked proso millets has been noticed, and the underlying chemical mechanisms and strategies for digestibility improvement have been assessed. Phenolic acids are relatively well-assessed, but less work has been devoted to other phytochemicals, especially their fate over processing. Comparatively little information is also available on the dietary fiber make-up and lipid stability.

It remains to be shown if improvements in cooking quality can be made without compromising on nutritional quality, e.g. heat treatments leading to better structural properties in baked goods but resulting in increased oxidation, loss of protein digestibility and phytochemicals. Strategies (e.g., application of sprouting or fermentation) to reduce bitterness are needed, as it may lead to consumer rejection. The selection of varieties imparting lower bitterness and longer shelf life or with more favorable properties for a certain application has not been fully exploited yet. Further studies on more varieties will also help elucidate relationships between e.g., variety, amylopectin structure and starch functionality as well as between variety, prolamin composition/structure and protein functionality. Such efforts would benefit from collaborations between plant breeders and food scientists, to fully capitalize on the agronomic, nutritional and technological traits of proso millet.

Author Contributions

C. Tyl conceived the review. A. Marti and C. Tyl conducted literature search, created tables and figures, wrote and edited the manuscript.

Conflicts of Interest

The authors have none to declare.

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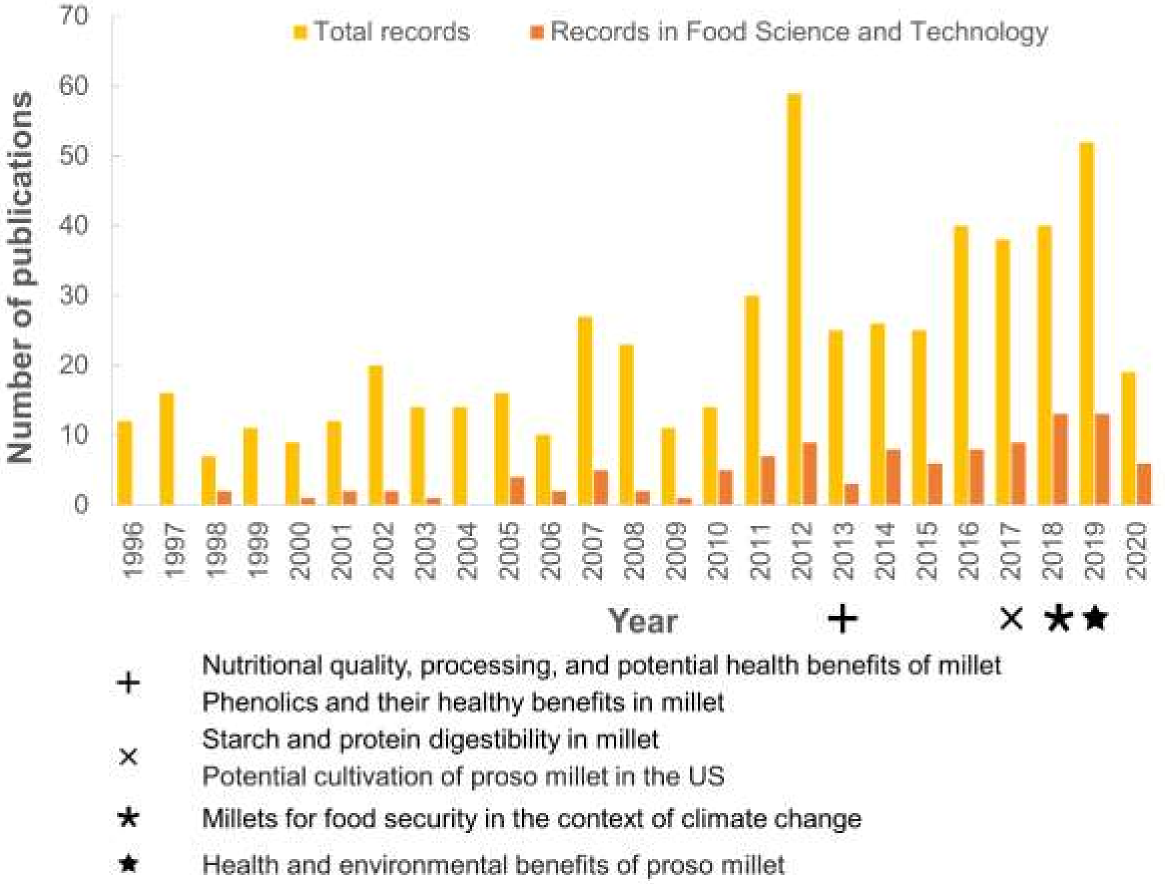
Figure 1. Progression of research (retrieved in June 2020 from Web of Science) interest in proso millet, contrasting all scientific disciplines to studies in food science. Topics of relevant reviews on proso millet are indicated on the time scale.



Figures 2A and B. Network visualization of terms occurring at least 5 times in titles or abstracts of Food Science research articles on proso millet. Among the 140 terms that fulfilled this criterion, 30 were manually selected as most relevant. The visualization scale is weighted by occurrence. Figure 2A shows the network according to clusters, Figure 2B color-coded by average publication year. Whenever multiple terms showed up in the word list, the one used the most was selected (e.g. “protein” vs “protein content”; “amylose” instead of “amylose content”; “phenolic” instead of “tpc”). General terms such as “flour” or “*Panicum miliaceum*”, “temperature”, “difference”, etc. were not selected as relevant.

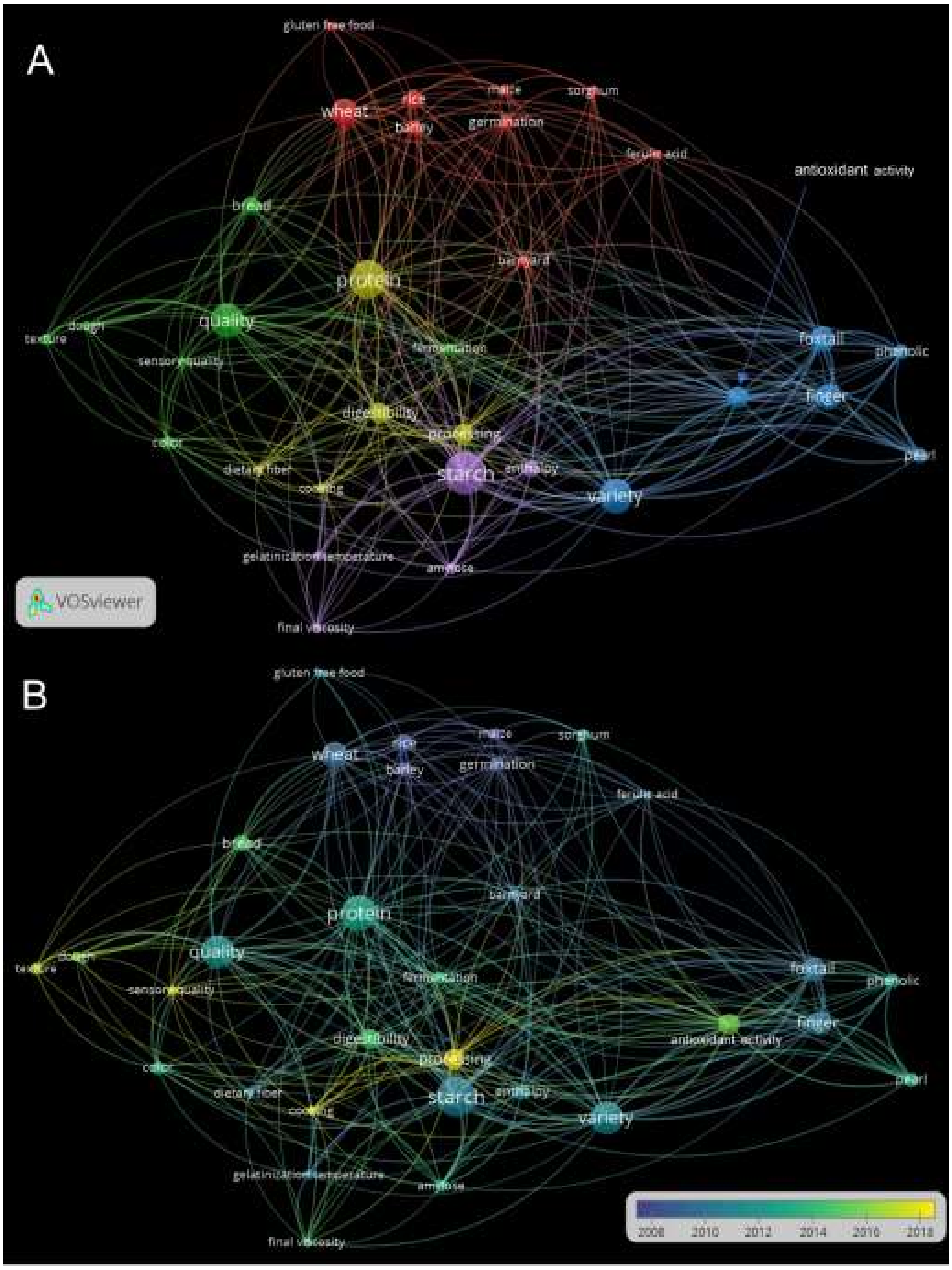


Table 1. Main environmental, agronomic and nutritional features of proso millet adapted to 21st century challenges

Event/Challenge	Need	Proso millet features	References
The world's population is expected to increase by 2 billion persons in the next 30 years, from 7.7 billion currently to 9.7 billion in 2050	Increased demand for food/source of energy other than common grains (wheat, corn, rice)	High content in starch and proteins (compared to other grains)	Saleh, A. S., Zhang, Q., Chen, J., & Shen, Q. (2013). Millet grains: nutritional quality, processing, and potential health benefits. Comprehensive Reviews in Food Science and Food Safety, 12(3), 281-295
Climate change and increasing global average temperatures are reported to have a direct impact on crop yields, crop productivity and overall sustainability of our food systems	Development of climate resilient and high yielding varieties	Wide adaptability to different climatic zones; shallow root system; short growing season; rotational crops; high water use efficiency	Das, S., Khound, R., Santra, M., & Santra, D. K. (2019). Beyond Bird Feed: Proso Millet for Human Health and Environment. Agriculture, 9(3), 64. Saxena, R., Vanga, S. K., Wang, J., Orsat, V., & Raghavan, V. (2018). Millets for food security in the context of climate change: A review. Sustainability, 10(7), 2228.
Sedentary lifestyle and modern dietary patterns increase risk for diabetes, obesity and cardiovascular diseases; Increased number of people affected by celiac disease	Provide consumers with food choices to support healthy lifestyles, especially for diabetics and celiacs.	Suitable raw material for foods of low glycemic index; good source of fiber and phenolic compounds when consumed undecorticated; gluten free; some varieties high in carotenoids	Saleh, A. S., Zhang, Q., Chen, J., & Shen, Q. (2013). Millet grains: nutritional quality, processing, and potential health benefits. Comprehensive reviews in Food Science and Food Safety, 12(3), 281-295. Shahidi, F., & Chandrasekara, A. (2013). Millet grain phenolics and their role in disease risk reduction and health promotion: A review. Journal of Functional Foods, 5(2), 570-581.

Table 2. Current achievements in the use of processing strategies to improve properties of products formulated with proso millet.

Achievement	Description	References
Partial incorporation into products is feasible	Combination with wheat or corn flour, as well as potato or corn starches has been shown to be possible for flat breads, regular breads, biscuits, extruded snacks or gluten-free breads	McSweeney, Duizer, Seetharaman, & Ramdath, 2016; Schoenlechner, Szatmari, Bagdi, & Toemoeskoezi, 2013; Sharma & Gujral, 2019c; Woomer, Singh, Vijayakumar, & Adedeji, 2019
Suitable material for gluten-free pasta	Some quality parameters superior to other gluten-free pasta (e.g. color, potentially less rapidly digestible starch)	Romero, Santra, Rose, & Zhang 2017; Cordelino, Tyl, Inamdar, Vickers, Marti, & Ismail, 2019
Addition of certain plant and animal proteins improves nutritional and functional properties	- Breads with whey protein had better crumb structure - Blends with whey protein decreased RDS, increased SDS and ReS - Addition of liquid eggs allowed for a coherent structure in gluten-free pasta	Tomic, Torbica, & Belovic, 2020 Zheng et al., 2020 Cordelino, Tyl, Inamdar, Vickers, Marti, & Ismail, 2019
Enzymes can be used as processing aids	- Transglutaminase addition led to better breads - Pyranose-2-oxidase increased dough mixing stability in rye arabinoxylan/proso blends	Schoenlechner, Szatmari, Bagdi, & Toemoeskoezi, 2013 Nemeth et al., 2019
Hydrocolloids may assist with structuring processes	- Acacia gum prevented stickiness in cookies and allowed for shaping and handling - Coherently structured dough for gluten-free spaghetti achieved with guar and xanthan gum	Devisetti, Ravi, & Bhattacharya, 2015

		Romero, Santra, Rose, & Zhang 2017
HMT and UHP can induce targeted starch modifications	Successfully used for cake making; however, browning may occur	Fathi, Aalami, Kashaninejad, & Mahoonak, 2016
Loss of *in vitro* protein digestibility after heating can be lowered or prevented	Transglutaminase and sprouting lower the loss of protein digestibility; at sufficient concentrations, sugars and salts prevent it; some varieties experience less loss than others	Gulati, Sabillon, & Rose, 2018

HMT: heat-moisture treatment; UHP: ultrahigh processing

Table 3. As-of-yet unresolved challenges and research gaps for maximizing the utilization potential of proso millet in foods

Research gap	**Food for thought**
Bitterness remains an issue, even for decorticated proso	- Additional processing strategies need to be exploited, e.g. sprouting or fermentation - Currently it is unclear which constituents contribute the most to bitterness as it is even perceived in products likely to be low in tannins - More products need to be assessed
Compromise between cooking quality and nutritional attributes	Protein aggregation may prevent cooking loss in pasta, but impair protein digestibility
Impact of heat treatments (parboiling, HMT) on product properties warrants assessment	Effects on phytochemical profile (e.g., carotenoids), lipid oxidation, protein digestibility not thoroughly evaluated yet

Variety selection	Effect of varietal differences in e.g., bitterness, cooking quality, phytochemical profile, not well understood
Not all constituents well-assessed	Limited information available on dietary fiber; phytochemical profile over processing, relation of compositional traits to shelf life

HMT: heat-moisture treatment

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