Review

Current trends in Extrusion: Development of Functional Foods and Novel Ingredients

Sharmila S. Patil* and Charanjit Kaur

1ICAR-Central Institute for Research on Cotton Technology, Adenwala Road, Matunga, Mumbai- 400 019, India
2Division of Food Science and Postharvest Technology, ICAR-Indian Agricultural Research Institute, New Delhi-110 012, India

Received July 1, 2017; Accepted October 10, 2017

Extrusion is a versatile and state-of-art technology and provides enormous opportunity for modifying the functionality of food materials for improved digestibility and high sensory quality. With considerable previous research on cereal based products, the current focus has now shifted towards millets and pulses for enhancing nutritional and functional quality for high-end consumer. The present review highlights the current advances made in development of cereal, millet and pulse based extruded products. In addition, the current trends in use of extruded flours as novel green ingredients as hydrocolloids, fat replacers and for developing gluten-free, phenolic-rich, low-glycemic and functional foods has also been reviewed.

Keywords: extrusion, functional foods, phenolics, pasting properties, hydrocolloids, fat replacer

Introduction

The current demand for novel and healthy foods together with the increasing lifestyle diseases has dramatically driven a new market for whole grains, millets, pseudocereals and legumes. In this context, unique nutritional profile of these grains comprising of high dietary fibre, micronutrients, non-gluten proteins and phytochemicals deserves special attention in new product development. However, use of unprocessed or native flours suffers from certain defects. Native flours have poor functional properties, making them unsuitable for their use in certain products and often require some modification or other ingredients or additives to achieve desired results (Martinez et al., 2015a). Native flours are characterized by low water absorption, low solubility and high pasting profile over their processed counterparts (Angioloni and Collar, 2012). Incorporation of native non-gluten flours in bakery products has detrimental effect on technological and textural properties, especially poor crumb texture and faster staling. These defects can be managed by using technological additives such as gluten, hydrocolloids, modified starches and enzymes (Ho and Noor-Aziah, 2013; Schoenlechner et al., 2013).

The functional properties of native flours can also be improved by hydrothermal treatments such as extrusion; without using any chemicals. Extrusion is a high-temperature, short-time processing technology in which food materials are plasticized and cooked by the combination of temperature and mechanical shear under pressure. This results in molecular transformation and chemical reactions that modify functional properties, nutrient and phytochemical composition of the food (Morales et al., 2015). The extruded product is stable, possesses defined texture and extended shelf life which increases their acceptability. The interest in the use of extrusion in the food industry stems from the fact that they are capable of blending diverse ingredients into novel foods and hence may be useful in the development of functional foods (Areas et al., 2016). Recent publications critically highlight the potential of extruded flours as functional snacks, breakfast cereals, as additives in breads and mayonnaises (Martinez et al., 2013b; Martinez, et
Effect of Extrusion on Functionality of Flours

During extrusion, flour is subjected to high temperature and high shear at relatively low levels of moisture content, which can effectively modify the functionality of composite cereal matrices by the way of gelatinization and degradation of starch, solubilization of dietary fibre, protein aggregation and inactivation of anti-nutritional factors (Hagenimana et al., 2006; Martinez et al., 2014c). Extrusion process offers significant opportunity to modulate feed rate, feed moisture, screw speed and barrel temperature, suited to product composition; accentuating the changes in their hydration properties, texture, bioactive compounds and pasting profile or viscometric properties (Martinez et al., 2015b). However, selection of appropriate processing conditions is must, as the extent of modifications is governed by severity of the process variables involved.

Effect of extrusion on hydration properties Extruded products are characterized by several physicochemical properties such as water absorption index (WAI), water solubility index (WSI), water-oil absorption index, protein solubility index, nitrogen solubility index, gelatinization capacity, emulsion solubility index etc. In particular, the hydration properties such as the WAI and WSI are important and predict how the materials behave if further processed into extruded products (Oikonomou and Krokida, 2011). The changes in hydration properties during extrusion can be attributed to structural changes in polymeric (starch and protein) and/or non-polymeric (lipid) macromolecular components. These properties are influenced mainly by size and structure of starch granules (Nura et al., 2011). WAI indicates the amount of water immobilized by the starch and considered as indicator of degree of starch gelatinization. High WAI values are good indicator of damaged starch fragments in the final product (Rwiyemamu et al., 2015). Whereas, WSI determines the amount of leached molecular components out of the starch granule, thus reflects the degree of degradation and conversion of molecular components (starch, proteins and fiber) on extrusion (Siddiq et al., 2013).

In general, the extruded products present improvement in water absorption and solubility over their native counterparts due to starch gelatinization (Hagenimana et al., 2006). Gelatinized starch has higher ability to absorb water than the native starch granules at room temperature. Increase in the value of WAI is probably due to uncovering of hydrophilic groups in extruded starch–protein material, unfolding and loosening of biopolymer chains, resulting in greater availability and easier penetration of structures by water molecules (Marzec and Lewicki, 2006). Besides starch gelatinization, which results in release of amylose and amylopectin, extrusion can also induce dextrinization and other reactions that lead to the formation of low molecular weight compounds, increasing the WSI (Mesquita et al., 2013). However, molecular interactions between degraded starch, proteins and lipids may reduce the extent of increase. Improved hydration properties of extruded products have been confirmed by multiple researchers (Awolu et al., 2015; Bhise et al., 2013; Camacho-Hernandez et al., 2014).

The WAI and WSI values of extruded products depend on several factors such as properties of the raw materials (particle size, composition), pre-processing treatments and processing parameters (Oikonomou and Krokida, 2011). Extrusion variables such as feed moisture, temperature and screw speed significantly influence the hydration properties. Intensity of extrusion, high barrel temperature coupled with low feed rate and high feed moisture increases hydration properties (Martinez et al., 2014a). It is generally agreed that feed moisture exerts the greatest effect on the extrude by promoting gelatinization (Arun Kumar et al., 2015). At high moisture, the viscosity of the starch would be low, which allows extensive internal mixing and uniform heating that would account for enhanced starch gelatinization (Rodriguez-Miranda et al., 2011). Furthermore, lubricant effect of high moisture reduces the friction between dough and screw elements as well as between dough and barrel, resulting in decreased dough temperature which prevents the starch granules from severe mechanical breakdown (Camacho-Hernandez et al., 2014). On the other hand, low moisture conditions results in greater shear degradation of starch during extrusion. Therefore, WAI increases and WSI decreases with increase in feed moisture. Similar effects also have been reported by other researchers (Chakraborty et al., 2011; Filli et al., 2013; Ito et al., 2015; Singh et al., 2007).

High temperature coupled with high screw speed contributes to the breaking and collapsing of the starch granules, promoting high dextrinization/starch melting and protein coagulation that prevails over gelatinization, thus increasing water solubility (Bhise et al., 2013; Spinello et al. 2014). On other hand, low temperature and screw speed decrease the shear effect on starch granules; thus favour the process of gelatinization and increases WAI over WSI (Ding et al., 2006). Taverna et al. (2012) however observed high WSI in extruded cassava starch and quinoa flour blends snacks at low screw speed and high temperature. This was attributed to high residence time (at low screw speed) exposing material to high thermal energy enhancing starch degradation and WSI. Similar effects of screw speed on molecular degradation and gelatinization of starch was observed by Keawpeng et al. (2014) and Arun Kumar et al., 2014b; Roman et al. 2015b). Parallel to the increased applications, concern has grown in the physico-chemical, functional and nutritionally relevant effects of extrusion processing.

The present review outlines the effect of extrusion on physicochemical (hydration), functional (antioxidants, phenolics) and viscometric/pasting properties of cereal grains and pulses. An attempt has also been made to summarize current trends and perspectives in extending application of extruded flours as novel green ingredients and additives for developing quality gluten free and low fat products.
Thus it is understood that hydration properties of extruded products are mainly interplay of different extrusion variables and feed composition, accounting for a reflective change. Improved WAI and WSI of extruded flours can find food applications in instant products such baby foods, desserts, milk-based products, sausage, mayonnaise, processed cheese, soups etc.

Effect of extrusion on phenolic compounds  Whole grain cereals, millets and pulses are one of the perfect sources of biologically active compounds, including phenolics, flavonoid compounds which have proven health-promoting effects on human body (Sriti et al., 2014). Several cereals, millets and pulses have been evaluated for phenolic compounds in search for safe sources of natural bioactives. However, focus of the research still remains on quantifying phenolics and antioxidant activity of raw/unprocessed grains, which doesn’t appear to be justified as cereals and other grains are eaten after cooking or processing. Lately, focus of research has shifted and effect of extrusion on bioactives is being thoroughly investigated.

Retention or degradation phenolics, flavonoids or other bioactives during extrusion processing is a function of temperature and other variables as they are heat sensitive and get altered when exposed to temperature above 80°C (Moussa-Ayoub et al., 2015). High temperature during extrusion decomposes or alters the molecular structure of phenolic compounds; which may further lead to reduction in their chemical reactivity or extractability (Sriti et al., 2014). El-Hady and Habiba (2003) reported significant decrease in total phenolics in extruded whole meal of peas, chickpeas, faba and kidney beans. Some studies showed up to 80% decrease in the level of total phenolics after extrusion of Kiwicha (Amaranthus caudatus) (Repo-Carrasco-Valencia et al., 2009). Sarawong et al. (2014) evaluated the total phenolic content of extruded green banana flour; showing significant decrease (32–55%) over raw flour. Extrusion at high moisture content retained higher amount of phenolics at low temperature than that of high temperature. Results reported by Patil et al. (2016b) were also in similar line; showing significant loss in bioactives and antioxidants activity of extruded finger millet and sorghum. However, extrusion at high feed moisture, low temperature and high screw speed retained considerable percentage of bioactives. Maximum retention of total phenolics and total flavonoids was observed as 54% and 78% in finger millet; whereas 87% and 89% in sorghum respectively. Similar findings have also been seen in rice-horse gram extrudates (Gat and Ananthanarayan, 2015) and extruded barley flour (Sharma et al., 2012). Authors observed that the decrease in bioactive compounds was dependent on process condition. High feed moisture during extrusion protects phenolics from degradation due to mild or gentle processing in the extruder barrel.

Interestingly, some studies presented marked increase in free/bound phenolics after extrusion. Phenolic content of extruded dark-red beans was found to increase by 14%; on account of increase in quercetin and ferulic acid along with a significant decrease in chlorogenic and caffeic acids (Korus et al., 2007). Similar results have been outlined by Anton et al. (2009); illustrating an increase in total phenolic compounds of extruded starch-bean. White et al. (2010) investigated the changes in cranberry pomace-corn starch blends during extrusion and observed significant increase (30–34%) in total flavonoids. Increase in total flavonoid content (4.1–8.2%) of extruded chickpea has also been reported by Tiznado et al. (2013). Most of the phenolic compounds (>80%) in cereals and millets are bound or attached primarily to hemicelluloses in cell walls of the pericarp, aleurone layer and germ. High shearing effect induced by extrusion causes severe degradation condensed tannins and bound phenols to low molecular weight oligomers that are more extractable. The released bound phenolics from cell walls may contribute to high phenolic content of extended flours (Nayak et al., 2011).

Effect of extrusion on antioxidant activity In general, the total antioxidant activity of food is mainly contributed by phenolics compounds present. Following this fact, antioxidant activity must have to be highly correlated with phenolic compounds; decreasing simultaneously with phenolic compounds after extrusion. Dlamini et al. (2007) found that the total phenolic content and thus antioxidant activity of sorghum reduced significantly following extrusion. Altan et al. (2009) outlined significant losses in antioxidant activity (60 to 68%) of barley extrudates compared to unprocessed barley flour. The study on extruded brown rice also revealed that extrusion and rise in extrusion temperature lowered total phenolic content and antioxidant activity (Gujral et al., 2012).

Some studies detected concomitant increase in antioxidant activity with extrusion, which may be due to production of dark colour pigments (particularly melanoids) at high temperature; extensively known to have antioxidant activity (Xu and Chang, 2008). The thermal processing is known to alter the antioxidant profile and generate more antioxidants that contribute in antioxidant activity. White et al. (2010) observed an increase in antioxidants (16–30%) with an increase in barrel temperature. High antioxidant profile due to extrusion processing has been widely reported in potato-pea extrudates (Nayak et al., 2011) and com-pumpkin extrudates (Rocha-Guzman et al., 2012).

The literature reviewed suggests that overall variability in thermal stability of phenolics, flavonoids and antioxidants is primarily attributed to nature of matrix subjected to extrusion. High retention of bioactives in extruded flours as observed in some studies demonstrated their enormous potential as healthy ingredient for development of phenolic and antioxidant rich ready-to-eat products. However, influence of extrusion processing on bioactive compounds of millets and pulses has been occasionally investigated.

Effect of extrusion on pasting properties  Pasting profile or viscosity curves are the most useful tool available for rapidly and
reproducibly assessing cooking quality of flour (Jan et al., 2016). Pasting properties are mainly dependent on the rigidity of starch granules, which in turn affect the granule swelling potential and the amount of amylase leaching out in the solution (Kaushal et al., 2012). It gives an idea about the degree of modification of the starches when subjected to heat treatment under moist conditions. These changes are dramatic in the case of extrusion, since the shear forces generated are high (Desouza et al., 2011). Pasting properties of extruded flours determine their suitability into various food products viz. high viscous foods, as a good gelling agent, in dessert and other food formulations and could replace chemically modified starches that are currently being used in a number of products (Adebowale et al., 2008). In this regard, pasting properties of flours as affected by extrusion need to be studied for their applicability to food systems.

Overall protein, starch and amylase/amylopectin ratio justify differences in pasting characteristics of flours (Sun et al., 2015). Pasting properties are also influenced by the amylose content of the starch, as it provides an indication of the gelling ability of starch (Adedokun and Itiola, 2010). Native starches are more susceptible to changes in viscosity during the heating and cooling cycle than pre-gelatinized flours, thus shows high pasting profile (Oliveira et al., 2015).

Studies on pasting properties of extruded flours reveal decreasing response of modification in pasting behaviour. The extruded flours generally exhibit lower pasting profile than native flours, except initial viscosity. High initial viscosity of extruded flours is attributed to presence of gelatinized starch, which allows rapid hydration compared to native starch at room temperature. This is important in products requiring higher viscosity under cold conditions. High pasting properties such as peak viscosity, holding strength, breakdown viscosity, final viscosity and setback of native flours indicates high integrity of their starch granules, showing greater resistance to shear during heating cycle (Sun and Xiong, 2014). Whereas, decrease in pasting properties of extruded flours reflects higher degree of gelatinization coupled with starch degradation due to net effect of heat-moisture-mechanical energy applied during extrusion process (Repo-Carrasco-Valencia et al., 2009). The absence of residual gelatinization enthalpy in flours following extrusion accounts for their higher paste stability. However, the extrusion conditions exercise different effects on the pasting parameters. Increase in temperature and screw speed generally lowers the viscosity, whereas increase in moisture increases peak and final viscosities (Waramboi et al., 2014). This has direct implications with severity of extrusion processing. If the processing is not so severe, a certain percentage of the starch granules may preserve their structure, presenting relatively high values for paste viscosity since the majority of the starch granules are in the swollen condition.

Reduced pasting properties of extruded flours have been demonstrated by several researchers. Desouza et al. (2011) reported that extrusion decreased the pasting properties of corn and rice flour and thus showed higher paste stability. Similar findings have been observed by Leonel et al. (2011) and Balasubramanian et al. (2012) in extruded cassava-orange pulp blend and legume-corn blend respectively. Siddiq et al. (2013) studied pasting behaviour of extruded pulses namely navy and pinto bean flour. They found reduced peak and final viscosities in extruded bean flours. Furthermore, the trough or breakdown was not observed for flour samples. This has been accredited to higher amounts of protein that can form a protein-starch matrix, which have more resistance to breakdown. Extrusion also has been reported to modify pasting behaviour of banana flour (Sarawong et al., 2014). The extruded banana flour showed lower pasting properties compared to native, except for setback. The flour extruded under higher moisture and low screw speed caused less starch degradation and thus exhibited the highest setback values, indicating an increase in retrogradation tendency and resistance starch formation. More recently, Waramboi et al. (2014) studied pasting profile of extruded potato flour and found lower RVA viscosities of extrudates than the non-extrudates, except initial viscosity. The authors noticed that the trend between the extrusion moisture and RVA properties could indicate varied changes to the degree of starch gelatinization.

Pasting temperature is the minimum temperature required to cook the starch and is generally tend to decrease after extrusion. Low pasting temperature and thus low thermal resistance of pregelatinized flours is mainly because of disruption of starch granules, loss of granule integrity and crystallinity (Martí et al., 2013). However, in certain cases, extrusion may increase the region of crystallinity, as a result of reorientation of the starch granules, strengthening of intragranular bonded forces, allowing the starch to require more heat before structural disintegration and thus may cause increase in pasting temperature (Sun et al., 2015).

In general, extrusion modifies the pasting behaviour of flour; producing more stable pastes with low retrogradation tendency. A unique viscoelastic behavior and higher paste stability of extruded flours can be beneficially exploited in different product formulations. Extruded flours contain gelatinized starch, which allows rapid hydration and can be used as instant starch. Extruded flours with high peak viscosity may be suitable for products requiring high gel strength and elasticity. Low retrogradation tendency of extruded flours is of interest for children’s foods and beverages.

**Applications of Extrusion Technology**

Modified functionality of extruded flours offers wide applications in food industry as thickening, gelling agents, functional ingredients and fat replacers (Mason, 2009; Roman et al. 2015a). Recent publications critically highlight the potential of extruded flours as functional snacks, breakfast cereals, as additives in breads and mayonnaises (Martinez, et al., 2014b; Roman et al. 2015b).
Extrusion for development of functional snacks  Extrusion cooking has been extensively used in the processing of wheat, corn and rice flours for development of ready-to-eat snack products. Paradoxically from a nutritional viewpoint, they are high in starch and fats and with low dietary fiber; thus with high glycemic load; known to cause childhood obesity and trigger type-2 diabetes (Brennan et al., 2013; Omwamba and Mahungu, 2014). Additionally, prevailing snacks are deficient in concentration of essential amino acids and hence have low protein and biological value (Devi et al., 2013). This calls for enrichment of snacks with high protein, dietary fibre, mineral content, phenolics so to qualify them as functional foods. Use of whole grains, millets, pulses, pseudocereals and other naturally derived ingredients is an opportunistic window in development of functional snacks.

Pulses are currently considered as functional gluten-free grains with high-content dietary fibres and complex carbohydrates, leading to low glycemic index in extrusion formulations (Asif et al., 2013). In recent years, a great deal of emphasis has been laid to evaluate the suitability of pulses (soybean, chickpea, beans, peas, lentils etc.) in extruded snacks. Extruded pulses have been reported to have good expansion and are regarded as highly feasible for the development of value-added high nutrition, low calorie snacks (Berrios et al., 2010).

Consumption of millets is known to decrease risk of cardiovascular disease and certain cancers, has favorable effects on blood lipids and glucose, improve insulin resistance (Kaur et al., 2014). Thus, millets represent an excellent vehicle for introducing higher concentrations of dietary fiber into ready-to-eat products. Inclusion of millet flours instead of purified fibre addition is a cost-efficient way of increasing dietary fiber content of extruded products (Wojtowicz et al., 2015). This has brought the research on millet based extruded snacks in for front.

Along with pulses and millets, the recent shift in use of naturally derived ingredients in extruded snacks has been essentially in a direction to lower the glycemic index and increase alpha-glucosidase inhibitory effects for alleviating type-2 diabetes. Promising grains such as amaranth, quinoa or kaniwa and food ingredients like fruits, vegetables and herbs or their by-products are being tested for developing acceptable snack (Ramos-Diaz et al., 2015). Extruded products colored with natural fruit or vegetables may appeal to consumers interested in healthy foods. In this context, dehydrated fruit powders rich in anthocyanins and carotenoids have been used to enrich extrudates with natural pigments to increase their color appeal and total antioxidant effect.

Extruded flours as ingredients to manage glycemic response and type-2 diabetes  Extrusion processing can modulate starch digestibility which seen as a critical factor in modulating glycemic response. At present, there are two parallel prevailing theories on starch digestibility of extruded products. The first theory places extruded foods in the category of high glycemic index (GI) foods (Onwulata et al., 2010). This is based on the fact that partial gelatinization and fragmentation of starch (Cabrera-Chavez et al., 2012), structural and conformational changes in protein tend to improve overall digestibility. The depolymerisation of the starch makes starch readily available to amylolytic enzymes during digestion and hence extruded snack products tend to yield a higher glycemic response compared with their unprocessed raw ingredients. On the other hand, second theory places them in the category of low GI foods. This is based on the fact that extrusion also alters the conformation of starch; smaller units of amylose and amylopectin which could cross link forming novel, indigestible linkages and therefore lower the GI (Liu et al., 2015). Formation of amylose-lipid complexes is been strongly implicated in these reactions.

GI of starch-based food undergoing the extrusion is affected by many factors such as degree of starch gelatinization, types of native crystalline structures, amylose/amylopectin ratio and complex formation between starch and protein or lipid and resistant starch (Feng and Lee, 2014). Starchy foods high in amylose content are associated with lower blood glucose levels and slower emptying of human gastrointestinal tract compared to those with low levels of amylose (Tacer-Caba et al., 2014). Also amylose content is being viewed as the main determining factor for production of resistant starch during extrusion. This is probably by increased retrogradation tendency with the formation of strong intermolecular hydrogen bonds in the amylose fraction. Apart from amylose, resistant starch (RS) is another factor that has been receiving much attention for its health benefits and functional properties. Resistant starch (RS) is starch that escapes digestion in the small intestine and may be digested in the large intestine (Zhang et al., 2016). Extrusion processing has been shown to increase both amylose and resistant starch. This is mainly due to shearing effect of extrusion, rendering the release of more starch and resulting in increased amylose content.

There are a number of studies about effects of extrusion on RS formation; most of which have been done on pure starches such as wheat starch, corn starch, potato starch (Shin et al., 2002) and cereal grains such as wheat and barley (Faraj et al., 2004; Kim et al., 2006). Increase in amylose content after extrusion has also been earlier reported by Sarawong et al. (2014) in green banana flour and Liu et al. (2015) in buckwheat starch. Authors attributed this effect to degradation of amylopectin, amylopectin–amylose interactions in the starch granules during the modifications. The extrusion produces gelatinized starch with increased retrogradation tendency, thus favour formation of RS. Some researchers suggest that high moisture during extrusion is most favourable conditions for increased yield of RS (Huth et al., 2000). High RS in extruded flours can positively influences the functioning of the digestive tract, microbial flora and blood cholesterol level thus lowering the GI and assisting in the control of diabetes (Fuentes-Zaragoza et al., 2010).

Extruded flours as hydrocolloids or gluten substitutes in baked
Table 1. Extrusion technology for development of functional snacks

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Functional ingredient</th>
<th>Feed composition</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse based extruded snacks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>Lentil flour</td>
<td>Lentil flour (100%)</td>
<td>Rathod &amp; Annapure, 2016</td>
</tr>
<tr>
<td>3.</td>
<td>Soybean &amp; Moringa oleifera leaves</td>
<td>Maize flour, soybean (10 to 30%) and Moringa oleifera (5 to 15%)</td>
<td>Rweyemamu et al., 2015</td>
</tr>
<tr>
<td>4.</td>
<td>Brazilian (carioca) bean</td>
<td>Corn flour &amp; Brazilian bean (4.8–55.2%)</td>
<td>da Silva et al., 2014</td>
</tr>
<tr>
<td>5.</td>
<td>Pinto, navy and black beans</td>
<td>Pinto beans (100%)</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>Black gram, green gram, lentil, peas</td>
<td>Corn &amp; legumes (5, 10 &amp; 15%)</td>
<td>Balasubramanian et al., 2012</td>
</tr>
<tr>
<td>7.</td>
<td>Vicia faba beans</td>
<td>Faba beans (100%)</td>
<td>Smith &amp; Hardacre, 2011</td>
</tr>
<tr>
<td>8.</td>
<td>Navy bean &amp; red bean</td>
<td>Corn starch &amp; navy bean flour (15, 30 &amp; 45%) Corn starch &amp; red bean flour (15, 30 &amp; 45%)</td>
<td>Anton et al., 2009</td>
</tr>
<tr>
<td>Millet based extruded snacks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.</td>
<td>Sorghum</td>
<td>Sorghum &amp; cowpea flour (10, 20 &amp; 30%)</td>
<td>Gbenyi et al., 2015</td>
</tr>
<tr>
<td>12.</td>
<td>Pearl millet</td>
<td>Pearl millet: finger millet: foxtail millet = 40:30:30</td>
<td>Wadikar et al., 2014</td>
</tr>
<tr>
<td>13.</td>
<td>Pearl millet</td>
<td>Pearl millet &amp; Bambara groundnut</td>
<td>Filli et al., 2013</td>
</tr>
<tr>
<td>Extruded snacks with other functional ingredients</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16.</td>
<td>Winter squash</td>
<td>Whole-grain yellow corn flours &amp; winter squash (0.43–15.57 %)</td>
<td>Delgado-Nieblas et al., 2015</td>
</tr>
<tr>
<td>19.</td>
<td>Pineapple pomace</td>
<td>Corn flour: pineapple pomace (79:21, 89.5: 10.5)</td>
<td>Selani et al., 2014</td>
</tr>
<tr>
<td>20.</td>
<td>Dehydrated vegetables (broccoli or olive paste powder)</td>
<td>Corn flour &amp; broccoli powder (4, 7, 10%) Corn flour &amp; olive paste powder (4, 6 &amp; 8%)</td>
<td>Bisharat et al., 2013</td>
</tr>
<tr>
<td>21.</td>
<td>Pumpkin</td>
<td>Corn grits &amp; pumpkin flour (5, 10 &amp;15%)</td>
<td>Nor et al., 2013</td>
</tr>
<tr>
<td>23.</td>
<td>Guava pomace</td>
<td>Rice flour: (Pulse + guava pomace powder) = 70:30, 75: 25, 80:20, 85:15, 90:10</td>
<td>Tangirala et al., 2012</td>
</tr>
<tr>
<td>26.</td>
<td>Tomato paste or skin powder</td>
<td>Rice: tomato paste/skin = 80:20 Corn: tomato paste/skin = 80:20 Wheat: tomato paste/skin = 80:20</td>
<td>Dehghan-Shoar et al., 2010</td>
</tr>
<tr>
<td>27.</td>
<td>Carrot pomace</td>
<td>Rice flour: dehydrated carrot pomace and pulse powder (CPPP) = 90:10, 85:15, 80:20, 75:25 &amp; 70:30</td>
<td>Kumar et al., 2010</td>
</tr>
<tr>
<td>28.</td>
<td>By-products from herbs and vegetables</td>
<td>Rice-legume blends &amp; 3% by-products from herbs and vegetables (yacon stem, carrot leaf, garlic, Japanese green tea)</td>
<td>Limsangouan et al., 2010</td>
</tr>
<tr>
<td>29.</td>
<td>Fruit &amp; vegetable by-products</td>
<td>Barley flour: tomato pomace = 100:0, 98:2, 94:6, 90:10, 87:3:12 Barley flour: grape pomace = 100:0, 98:2, 94:6, 90:10, 87:3:12</td>
<td>Altan et al., 2009</td>
</tr>
<tr>
<td>30.</td>
<td>Fenugreek</td>
<td>Chickpea–rice blend (70:30) &amp; fenugreek (2, 5 &amp; 10%)</td>
<td>Shirani &amp; Ganesharanee, 2009</td>
</tr>
</tbody>
</table>
products. The unique nutritional profile of non-gluten grains comprising of high dietary fibre, micronutrients, non-gluten proteins and phytochemicals deserves special attention in bakery applications (Angioloni & Collar, 2012). However, doughs form non-gluten grains lack extensibility, elasticity, cohesiveness due to gluten dilution that makes their industrial handling a greater challenge (Deora et al., 2014) and also has detrimental effect on technological and textural properties, especially low gas retention, poor crumb texture and faster staling (Mohammadi et al., 2014). At industrial levels, these defects can be overcome by using technological additives such as enzymes, modified starches and mainly hydrocolloids to make up for the viscoelastic properties of gluten (Ho and Noor-Aziah, 2013; Schoenlechner et al., 2013). Hydrocolloids bind with water, have high thickening and gelling capacity (Varela and Fiszman, 2013); accounting for improvement in functionality of doughs.

Extruded flours as pre-gelatinized starch mimic the viscoelasticity of wheat dough in non-gluten formulations for bakery products, thus can be used as interesting alternative to hydrocolloids. Positive effects of extruded wheat flour, maize flour, wheat bran, cassava flour and rice flour on technological, textural and sensory properties of gluten and gluten-free breads have been highlighted by several researchers. Rice flour extruded at 20% moisture level and 180°C was successfully used to develop gluten-free batter as a novel gluten substitute. Acidification of extruded rice flour further improved the colour of the crust and texture (Clerici et al., 2009). Rice flours extruded at high intensity extrusion treatments produced doughs with a higher elastic modulus and consistency, therefore high bread yield. However, bread showed decreased dough development, lower specific volume and more hardness (Martinez et al., 2014b). The authors concluded that correct selection of extrusion treatment and flour particle size is essential to overcome these defects. Recently, Jeong et al. (2013) showed the positive effects of extruded rice flour on improved textural quality of cake.

Besides rice flour, extruded maize flour (Ozola et al., 2011) and extruded wheat bran Gomez et al. (2011) have been also used for improving the physiochemical properties of bread. Extruded bran in combination with improver showed better results in terms of higher bread volume. Substitution of wheat flour by extruded wheat flour (5%) did not alter mixing, handling and fermentation behaviour of dough and caused no detrimental effect to bread quality, rather increased water absorption capacity of dough and bread output (Martinez et al., 2013). Use of extruded wheat flour (5%) has been shown to offset the major problem of longer proofing time, in breads made from frozen dough. Incorporation of extruded flour provides higher amount of fermentable sugars and decrease proofing time (by 52%) and baking time allowing higher bread output (Ortolan et al., 2015). Patil et al. (2016a) explored the potential of extruded finger millet flour in improving the quality of composite bread. Incorporation of extruded finger millet (20 g/100 g) in wheat flour allowed for improved extensibility, high specific volume, high loaf height and low firmness of composite bread. The findings suggested that extruded finger millet can mimic properties of hydrocolloids thus can serve as replacement for wheat flour in bread formulations. Based on above research findings it is apparent that extrusion can be exploited as an excellent tool to modify functionality of gluten-free flours for general consumer and celiac in particular. Celiac patients require a strict lifelong adherence to a gluten-free diet devoid of synthetic additives (Deora et al., 2014). Looking at this perspective, extrusion can provide quality gluten-free products for celiacs. Extruded flours (especially millet flours) can also be effectively delivered in composite wheat based diets to deliver high fibre and phytochemical content (Koletta et al., 2014; Schoenlechner et al., 2013).

Thus it seems that extrusion is more cost-effective, economic and highly adaptable technology than alternative sophisticated technologies (high-pressure processing, microfluidization) being recently investigated for modifying functionality of non-gluten doughs (Gomez and Martinez, 2015).

**Extruded flours as fat replacer** Overconsumption of fat has been linked with human health problems such as obesity, cardiovascular diseases and several types of cancer (Schwingshackl and Hoffmann, 2013). Therefore, there is an increasing tendency towards low fat foods in order to satisfy the demands of consumers, who are more concerned about health problems. Nonetheless, it is difficult to maintain the quality of food prepared with reduced fat. Fat removal severely affects the stability of oil-in-water emulsion and causes undesirable changes in physicochemical and sensory properties of foods; especially in mayonnaises (Ma and Boye, 2013). Fat replacers are generally used to improve these properties of low-fat foods. Fat replacers are ingredients or additives which usually have a thickening effect; tends to increase the viscosity of the continuous phase, slows down the droplet movement and consequently increases the stability of emulsion (Nikzade et al., 2012). Different type of gums (xanthan, konjac, guar and pectin) and soluble fibres are being employed as fat replacer now-a-days (Li et al., 2014; Su et al., 2010). Several researchers have proposed that starches modified by physical, chemical or enzymatic processes can also be used as fat replacers in low-fat mayonnaises (Teklehaiananot et al., 2013). Use of modified starches in low fat formulations is primarily because of their low cost, unique creamy texture and ability to impart desired flow characteristics (Mason, 2009). Starches modified by hydrothermal treatments such as extrusion can be interesting alternatives to prevailing fat replacers without using any chemicals (Hagenimana et al., 2006). Extrusion caused gelatinization of starches; extent being governed by moisture, temperature and screw speed. The extruded or pregelatinized flours have high water absorption, water solubility, thickening power in cold water and smooth texture than native flours (Martinez et al., 2014a). The improved functionality of extruded flours can be harvested in many food applications as...
thickening and gelling agents; allowing their utilization as fat replacer in oil-in-water emulsions.

Lee et al. (2013) reported that reduced fat mayonnaise can be formulated by replacing part of the oil with extruded waxy rice starch. Effect of extruded maize flour incorporation as fat replacer in mayonnaise also has been studied by Roman et al. (2015a). Results revealed that if the flour-water ratio of the paste is controlled, extruded maize flour is appropriate for preparing reduced-fat oil-in-water emulsion with similar rheological properties to the full fat and greater freeze-thaw stability. The group also evaluated the effect of pre-gelatinized extruded wheat flour as fat replacer (fat substitutions of 1/3, 2/3 and 3/3) in low fat cake recipe (Roman et al., 2015b). Extruded flour paste helps to minimize the sensory changes of reduced fat cakes and can be effectively used in cake formulations up to 2/3 fat replacement. Prospects of extruded flours as fat replacers can provide innovative solutions for baking industry seeking alternative ingredients with ‘green’ label.

Conclusion

Based on the literature reviewed, it can be safely concluded that extrusion is a truly a promising versatile technology and should be seen in a broader perspective as a novel way of making quality functional foods beyond the traditional extruded snacks. Extrusion offers an excellent opportunity to modify hydration properties and to improve paste stability and functionality of food matrices, by tailoring the processing conditions. Improved functionality of extruded flours can be effectively used in development of novel gluten free, high fibre, high phenolic, mineral enriched, low fat and low glycemic foods; placing this technology in segment for delivering functional foods to manage lifestyle diseases especially type-2 diabetes. Extruded flours mimic the properties of hydrocolloids and thus can be used as alternatives to synthetic hydrocolloids with ‘green label’. Such information could help snack and baking industry to develop innovative products tune to the changing needs of consumers.

Acknowledgement

The authors are highly thankful to division of Food science and Postharvest Technology, ICAR-Indian Agricultural Research Institute, New Delhi, India, for providing laboratory facilities.

References


Korus, J., Gumul, D., and Czechowska, K. (2007). Effect of extrusion on the phenolic composition and antioxidant activity of dry beans of...


