Annals of Arid Zone 63(2): 61-76, 2024

Optimization of Extrusion Parameters and Feed Composition for Enhanced Quality of Millet Extrudates

Soma Srivastava[1], Dilip Jain[1] and Neeraj Gupta[2]

[1]*ICAR-Central Arid Zone Research Institute, Jodhpur 342 003, India*

[2]*Division of Post Harvest Management, Chatha, SKUAST-Jammu, J&K 180 009, India*

Received: December 22, 2023 Accepted: April 4, 2024

****Correspondence***
Soma Srivastava
soma.sriv8@gmail.com

Citation
Srivastava, S., Jain, D. and Gupta, N. 2024. Optimization of extrusion parameters and feed composition for enhanced quality of millet extrudates. Annals of Arid Zone 63(2): 61-76

https://doi.org/10.56093/aaz.v63i2.146682

https://epubs.icar.org.in/index.php/AAZ/article/view/146682

Abstract: Extrudates prepared from cereal grains, such as corn, wheat, rice, and other starch-rich grains, are the second-largest contributors to the global ready-to-eat snack market. These cereals contain optimal characteristics, like amount, type and particle size of starch/protein which are important for starch gelatinisation, viscosity and flow characteristics. These factors contribute to the rheology and organoleptic characteristics of the extrudates. In recent years, there has been a significant push in the utilization of the millets for development of extrusion products as they are ready-to-eat and considered as healthier. Major issues with 100% millet incorporation are dark colour, lower expansion, harder and denser extrudates and lower shelf life. In case of millets feed moisture (9-12%), barrel temperature (120-150°C) and screw (123-460 rpm) speed have favorable impact on expansion ratio and bulk density. Addition of starch containing cereals, legumes and hydrocolloids like sodium alginate and carboxymethylcellulose enhances expansion, lighten color and increases nutritional and health benefits. The aim of this review is to highlight the potential of extrusion technology for development of millet products, role of extrusion operating conditions and their effect on product parameters. The review also provides detailed insights about application of extrusion based 3-D printing, hot melt extrusion, hydrogel forming extrusion, centrifugal co-extrusion and extrusion-based encapsulation for the development of innovative millet based novel product development.

Key words: Extrusion, starch, rheology, hot melt extrusion, centrifugal coextrusion, millet, 3-D printing, expansion ratio, hydrocolloids.

Millets are pseudo-cereals majorly cultivated and consumed as a staple food by the Asian and African populations (Seth and Rajamanickam, 2012). Popular types of millet are pearl millet, finger millet, proso millet, barnyard millet and foxtail millet (ICRISAT, 2017). They are also referred to as functional grains due to their abundant health benefits. India is the largest producer of millet in the world (FAO, 2019) with pearl millet taking >25% share of the total millet production in India. Superior quality of fats (2-5%) being rich in ω-3, 6 and 9 fatty acids, carbohydrate (60-70%) with low glycaemic index, high protein (7-11%) and fibre (2-7%), rich in minerals like calcium, magnesium, phosphorus, iron, zinc, polyphenols, flavonoids contribute to nutritional superiority of millets over commonly consumed cereals like wheat, rice and maize, etc. (Devisetti *et al*., 2014). Millets contain significant phytonutrients which exhibit anti-diabetic, anti-inflammatory, antifungal, antioxidant and blood clot inhibiting properties (Yadav *et al*., 2014). Insoluble fibre act as a prebiotic, supports growth of good bacteria, regulates bowel movement and reduces the risk of colon cancer by supporting the production of short-chain fatty acids. Celiac disorder is lifelong autoimmune enteropathy (Newinski, 2008) characterised by intolerance to the gluten. Following a strict gluten-free diet for life is the only treatment (Naqash *et al*., 2017; Saleh *et al*., 2013). Millets are naturally gluten free. Extrusion technology of millets has the potential to develop food products with lower in fats and calories which could add important nutrients to the human diet. Extruded snacks being the second highest contributor in the snack market have a huge potential to double their share in the upcoming years. Extrusion technology of millets have huge potential for paradigm shift in the current snack food market.

Extrusion cooking is a thermo-mechanical technique of processing a group of food ingredients (uncooked mass) by forcing them through a die/orifice of the desired cross-section at a predefined rate, for optimum cooking at a high temperature, pressure and shear developed by a barrel encased screw (Alam *et al*., 2016). This cooked mass upon moving out through the narrow opening puffs in a variety of shapes depending on the die due to sudden release in pressure which causes rapid water evaporation (Prabha *et al*., 2021; Kowalski *et al*., 2018). This HTST (high-temperature short-time) technique is carried out by combining thermal and mechanical shear energies which causes crucial physicochemical and nutritional transformation such as lipid oxidation, protein denaturation, starch gelatinization, degradation of anti-nutritional factors flavour generation, enhancing dietary fibre solubility and mineral bioavailability in raw material (Prabha *et al*., 2021). These necessary structural, chemical and nutritional changes are combined effects of shearing, intense mixing, homogenization of ingredients, cooking, plasticizing, heat and mass transfer, kneading, shaping, moisture and volatile evaporation.

Application of extrusion is currently applicable for a wide range of functions such as encapsulation, shaping, mixing, flavor generation, cooling or heating, sterilization, venting moisture and volatiles, conveying and co-extrusion. Newer modifications and upgradations taken place in extrusion technology for developing food products efficiently and sustainably with retention of functional properties. Examples are 3D printing with help of extrusion, supercritical carbon dioxide aided extrusion for nutrient retention, hydrogel forming extrusion for making soft jells for elderly, hot-melt extrusion for improving solid dispersion stability and bioavailability of food and drugs. 3-D printing, is a new technology used to develop personalized and customized food products with the help of extrusion using complex geometries and formation of food structures through layer-by-layer deposition (Kim *et al*., 2019). Extrusion technology is gaining consumer interest not only in the food segment but also in the field of making eco-friendly biodegradable packaging materials using different biopolymers. This paper discusses in detail regarding the extrusion of millets and how major issues due to compositional difference while its extrusion can be ameliorated. It provides a clear understanding about the influence of these components on the important macromolecules and physicochemical characteristics of the extrudates. Review also provides insight about the various other extrusion-based technologies which can be utilized for the millet based product development.

Extrusion process and principle

Generally, a fundamental extruder consists of four significant parts: (i) a feeding system (ii) a screw or worm on a rotating shaft (iii) a cylindrical stationary barrel (iv) an extrusion die along with a cutting knife. The feeding system ensures a consistent flow of the raw material into the extrusion barrel (Rao and Thejaswini, 2015). One or two screws attached to rotating shafts convey and shear the feed against the wall of the stationary barrel (Rao and Thejaswini, 2015). At the discharge end of the barrel is a die along which blades cut the extrudates into the desired length. Die also increases the internal pressure by resisting the flow of the feed inside the barrel (Rao and Thejaswini, 2015).

First, the coarsely ground grains are pre-conditioned using steam or water and mixed uniformly. It is an essential step as it reduces the residence time of the feed in the extruder by uniformly hydrating the particles prevents the wearing of the barrel and screw and reduces the energy utilized in the process (Rao and Thejaswini, 2015). Further, the screw kneads and compresses the feed into a semi-solid plasticized mass. Due to continuous compression and shearing frictional heat is developed. Molten material finally reaches the discharged end of the barrel where the pressure increases further. When the pressurized molten material forcefully exits the die the pressure drops instantly. The product expands to the shape of the die and cools immediately due to the evaporation of moisture into steam (Prabha *et al.*, 2021).

Compositional ingredients and their effect on extrusion process

Primary ingredient for extrusion is cereal/ millet grits along with other minor ingredients such as salt, sugar, emulsifiers, leavening agents, nucleating agents, etc. Concomitant mixing, kneading, homogenization, and cooking of raw material during extrusion generate heat and mechanical shear which results in phase transformation of raw materials (Fellows *et al.*, 2009b; Ek *et al.*, 2020).

Feed properties such as type, physical state, pH of feed, moisture content, and chemical composition (quantity and nature of starch) amount of protein, fat and sugar significantly contribute to the rheology and organoleptic characteristics of the final extrudate (Fellows *et al.*, 2009b). Carbohydrates are major portion of the millets grain (60-70%), followed by dietary fibres (2-12%), proteins (5-11%), fat (1.5-5%), and minerals (2-4%). Starches are the major type of carbohydrates important in the production of extrudates. Other than starch, sugar, hydrocolloids and fibres are the other commonly used carbohydrates in minimal quantities. Starches contribute most for the expansion of the extrudates. The intrinsic properties of starches are responsible for the crispy and characteristic texture of extruded products (Ek *et al.*, 2020). Starch granules size ranges between 0.1 and 200 µm and has different shapes like smooth, angular, ellipsoidal, oval, and spherical on the basis of botanical source (Kumari and Thayumanavan,

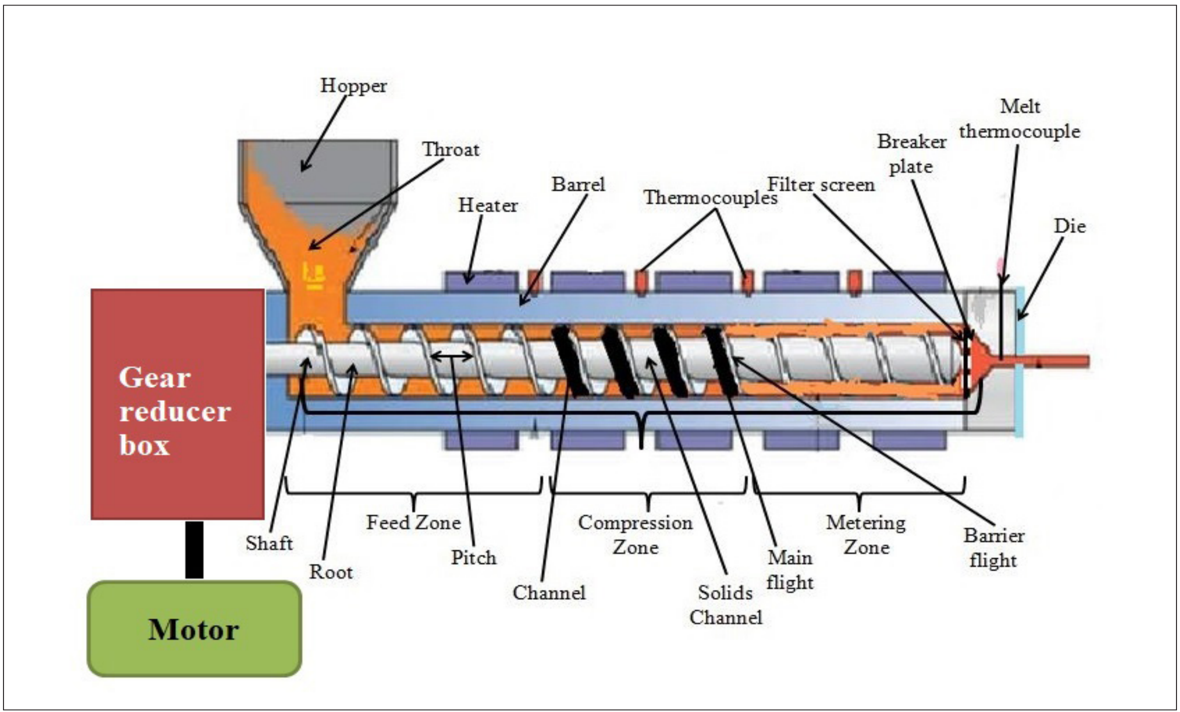

Fig. 1. Illustration of typical extruder with all parts.

1997). Vitreous region, usually in the periphery of the endosperm, whereas floury endosperm, usually in the centre of the endosperm, is white, mealy, and non-translucent. Vitreousness reflects the compactness of the starch-protein matrix. Mostly, amylopectin is the major component of starch granules, while amylose is about 20-30% of total starch. High-amylose/ amylopectin ratio influences starch digestion attributing towards resistance starch and affect the glycaemic response. Along with amylose and amylopectin, starch contains intermediate component in various forms which are available in some mutant plants (Mahajan *et al*., 2021). Starches are further classified into three A, B and C-types based on their X-ray diffraction pattern showing the degree of crystallinity. A-type starches have a lower degree of crystallinity (higher amorphous regions) due to the presence of shorter branching in amylopectin and higher amylose content. B-type has longer and densely branched amylopectin contributing toward

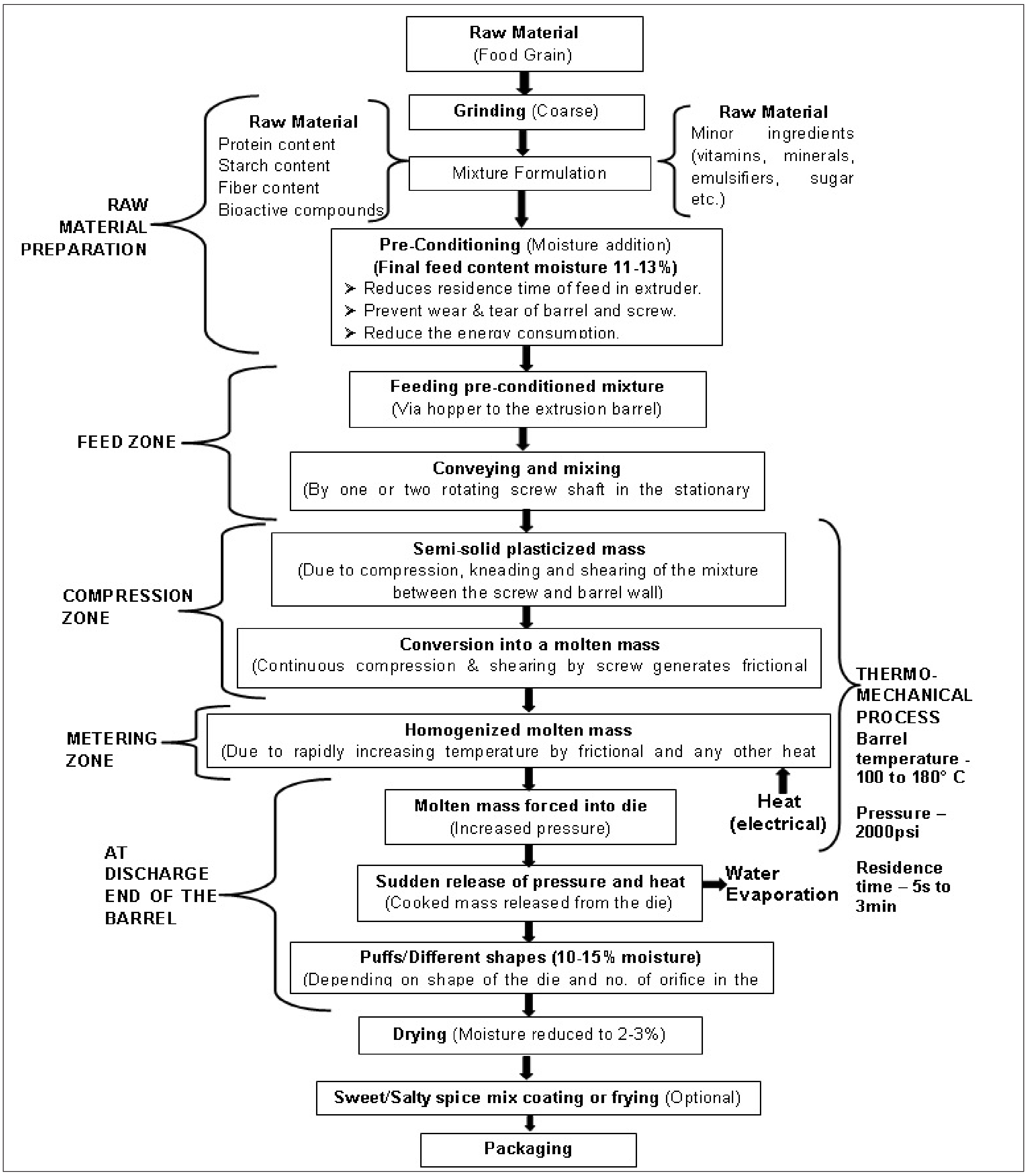

Fig. 2. Schematic representation of the process of extrusion cooking

higher crystallinity. While the C-type is a combination of A- and B-type starches (Guo *et al.*, 2020). Cereal grains contain A-type starch polymorph, B-type polymorph is found in tubers and C-type starch is found in legume seeds, and plant rhizomes. Generally, amylose contributes to 20-30% of millet starch and the remaining 70-80% is occupied by amylopectin (Mahajan *et al.*, 2021). Millet starch like any other cereal starch demonstrates semi-crystalline characteristics with A-type polymorphism, as starch granules are higher in amylose content than amylopectin which is the reason of their low glycaemic index (Mahajan *et al.*, 2021).

Phase transition of starch during extrusion

Under extrusion cooking, starch is subjected to mechanical shear and high temperature in presence of water which induces phase transition (glassy-rubbery-molten-rubbery-glassy) (Fellows *et al.*, 2009b). Phase transition is induced as the temperature inside the extruder reaches above the glass transition temperature (T_g) of starch (Fellows *et al.*, 2009b; Ek *et al.*, 2020).

This phase transition prepares the feed (mainly starch) for optimum expansion upon its exit from the die (Kowalski *et al.*, 2018). In the feeding zone, there is no mechanical shearing between the starch granules. The feeding zone involves moisture addition to the feed so that gelatinization could be initiated afterwards while sufficient time is provided for starch granules to hydrate and absorb moisture (Ek *et al.*, 2020). From the feeding zone, a moist starch mixture enters the compression zone where it is compacted and mechanically sheared due to the high rotational speed of the narrowing barrel and screw. Mechanical shearing generates heat among the starch particles which facilitates more moisture absorption and initiates gelatinization of starch. Sometimes, for appropriate gelatinization heat is also provided via external sources. Simultaneous, gelatinization and mechanical degradation disrupt the starch granules. Gradually towards the end of the compression zone glassy state of starch transforms into a rubbery state (Ek *et al.*, 2020). Continuously elevating temperature and mechanical shear in the metering zone (last

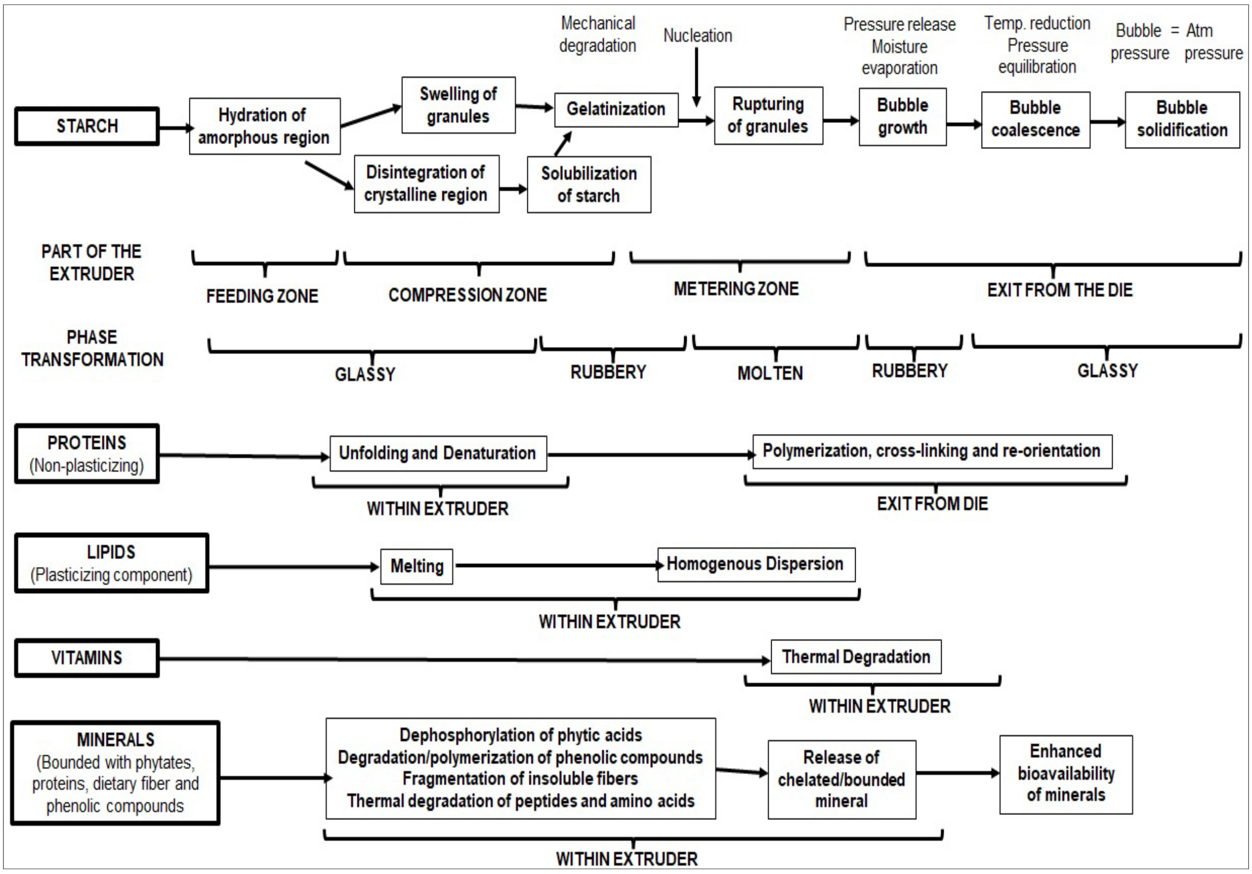

Fig. 3. Physico-chemical changes in feed components during extrusion cooking.

zone) causes the previously disrupted granules to melt. The rubbery mass transforms into a molten state when the disruption of starch completes (Kowalski *et al*., 2018). In the molten state, the starch demonstrates viscoelastic behaviour. A sudden drop in pressure and temperature at the exits from the die triggers bubble growth and moisture evaporation from the molten mass. Simultaneously during exits, heat diffuses rapidly from the molten mass to the ambient temperature transforming it into a rubbery state (Ek *et al*., 2020). The rubbery state expands steadily until a balance between the mass pressure and atmospheric pressure is attained (Ganjyal *et al*., 2014). When the temperature of rubbery mass equilibrates with the atmosphere, starch transforms back to a glassy state (stable state) with desirable shape, expansion and texture.

Feed component interaction and changes during millet extrusion

Starch: Starch granules get hydrated by absorbing water which causes swelling of granules and disintegration of semicrystalline structure depending on the moisture content and starch type (Fu *et al*., 2014). Starches undergo the process of gelatinization to transform into a viscous mass (Fellows *et al*., 2009b). Gelatinization is an irreversible phase transition of starches from glassy to a rubbery state in presence of sufficient water at critical temperature (Ek *et al*., 2020; Shevkani *et al*., 2017). It involves hydration of starch granules wherein water is absorbed and bounded by the amorphous region which swells upon exposure with heat from mechanical shear. Further, the water reaches the crystalline region, and water along with heat melts the ordered structure (loss of crystalline structure) by breaking the hydrogen bonds. Melting of the ordered structure enhances the molten mass concentration, as the more amorphous portion is available for hydration and swelling (Ek *et al*., 2020; Shevkani *et al*., 2017). Gelatinization ultimately promotes swelling and solubilization of starch (Fellows *et al*., 2009b). Moisture content in the feed and temperature of gelatinization depends on the starch type, amylose/amylopectin ratio, and presence of inhibitor (amylose lipid complex, proteins) (Fellows *et al*., 2009b; Ek *et al*., 2020). For example, the presence of amylose lipid complex restricts the entry of water which lowers the susceptibility of starch to gelatinization (Mahajan *et al*., 2021; Shevkani *et al*., 2017). The crystalline region of millet starch granules remains intact when the moisture content during heat treatment (hydrothermal treatment) is maintained below 30% (Mahajan *et al*., 2021). To initial physical modification such as an alternation in the diffraction pattern (semi-crystallinity) of A-type starch (millet) moisture content ≤ 35% along with temperature above gelatinization temperature of millets need to be applied (Mahajan *et al*., 2021). Millet starches have higher (<60°C) and broader (60-80°C) gelatinization temperature ranges owing to their higher amylopectin content (Mahajan *et al*., 2021). Additional hydrogen bonds and molecular rigidity prevents the transformation of fibres (especially insoluble type) under the thermal and mechanical shear of extrusion. In general, millet starch has lower swelling and solubilization values than potato at higher temperature range of ~90°C. Low amylose is associated with lower gelatinization temperature of starch granule in tubers which disintegrates easily at 65°C and attributes higher glycaemic response.

Proteins: Under the hot and moist environment of extrusion, proteins undergo unfolding, denaturation and molecular rearrangement (Fellows *et al*., 2009b; Ganjyal *et al*., 2014). Constant mechanical shear throughout the extruder prevents the re-alignment of the protein molecules until the mass exit from the die (Fellows *et al*., 2009b). Rapid cooling and expansion outside the die initiate polymerisation, cross-linking and re-orientation of the protein molecules (Fellows *et al*., 2009b). This re-alignment forms a fibrous structure of protein contributing to the texture of the product (Fellows *et al*., 2009b). At lower protein concentration unfolding and denaturation is favourable in producing a uniform and viscous plasticised mass for texturization of proteins but at higher concentration of proteins in the extrusion feed hinders the expansion of the final extrudate (Fellows *et al*., 2009b; Ganjyal *et al*., 2014). Denaturation and molecular rearrangement of proteins are comparatively more favourable in the production of texturized proteins. Further, extrusion improves the digestibility and biological value of proteins (Omosebi *et al*., 2018). This improvement happens mainly due to the inactivation of protease inhibitors, trypsin inhibitors, and anti-nutritional factors such as condensed tannins and polyphenols that usually form complexes with proteins. Thermal denaturation of proteins also contributes to the enhanced digestibility and biological value of proteins (Omosebi *et al*., 2018; Gulati *et al*., 2020).

Lipids: Feed temperature inside the extruder elevates beyond the melting point of all lipids (Llo *et al*., 2000). Hence, lipids melt into oils under extreme conditions of extrusion cooking. Shearing action of the screw inside the barrel ensures homogenous dispersion of oils into tiny drops (< 1 μm). These tiny droplets act as a plasticizing agent which ensures smooth passage of feed throughout the extruder (Llo *et al*., 2000). Lipid concentration and homogenous dispersion in the feed are major elements of concern. Exceeding lipid concentration beyond the critical level and non-uniform mixing post/prior extrusion results in oil separation which negatively impaction the friction factor by lubricating both screw and barrel surfaces and reducing shear inside the barrel. During extrusion cooking, higher lipid content favours its tendency to bind starch and proteins (Gulati *et al*., 2020). These starch lipid complexes are undesirable for the desired physical attributes of extrudates (high density, hardness, lower expansion. At higher concentrations, lipids are highly susceptible to oxidation due to the presence of prooxidants i.e., metals from the extruder and higher extrusion temperatures.

*Vitamins***:** Vitamins such as thiamine, tocopherol, ascorbic acid and vitamin precursor (β-carotene) are highly susceptible to oxidation and thermal degradation during extrusion cooking. Among the fat-soluble, vitamin D and K are more stable to high barrel temperatures than A and E. Loss of vitamin E amplifies on exposure to severe conditions i.e., high barrel temperature with low moisture content in feed. Extrusion conditions have a severe effect on tocopherol regardless of its natural presence or addition (artificial/natural source) in feed. Vitamin A losses during extrusion cooking are highly dependent on the form of pro-vitamin. Losses are reduced by almost 25% when vitamin A is added in form of retinol rather than β-carotene which harbours up to 75% losses. Vitamin C degradation during extrusion cooking is less severe than B vitamins (Gulati *et al*., 2020). High barrel temperature or lower feed moisture also increases the susceptibility of B group vitamins to degradation. Riboflavin and niacin are more stable to high temperature and pressure during extrusion cooking than thiamine. Vitamin losses especially at high barrel temperatures could be curtailed by increasing screw speed which shortens the feed residence time (Gulati *et al*., 2020).

Minerals and fibre: Extrusion cooking is reported to enhance the bioavailability of minerals. The foremost reason, for enhanced bioavailability, is the modification fostered by extrusion conditions in the mineral binding ability of proteins, phytic acid, dietary fibres and phenolic compounds. Extrusion cooking unleashes the chelated or bounded minerals by dephosphorylation of phytic acids, degradation or polymerization of phenolic acid, fragmentation of dietary fibres, and thermal degradation of peptides and amino acids. Lower feed moisture and high barrel temperature facilitate the thermal degradation of these mineral-binding compounds. Non-thermal degradation can also be achieved by operating the extruder at high screw speed and low die and barrel temperatures which induces high shear degradation (Gulati *et al*., 2020). Insoluble fibres generally melt at a temperature exceeding their thermal decomposition temperature. Uninterrupted exposure of heat and shear in extrusion often results in fragmentation of fibres (Ek *et al*., 2020) which is an additional advantage of millet extrusion i.e., increasing its digestibility.

*Natural toxins/anti-nutritional factors***:** Natural occurring toxins and anti-nutritional factors in cereals, legumes, and millet can be reduced or eliminated during their extrusion cooking. Extrusion cooking is reported to eliminate the significant quality of hemagglutinin, urease activity, glycoalkaloids, and alkylresorcinols. Extrusion conditions are less effective on trypsin inhibitors as they are reduced by only 70-85%. Thermal degradation, oxidation, polymerization, and various other reactions occur due to intensive mixing and shearing at high temperatures during extrusion causing severe loss of naturally present/pre-extrusion added flavour. Also, these flavour compounds tend to flash off with steam during the expansion of feed. Flavour retention can be improved by adding encapsulated flavours which are insoluble at barrel temperature and heat and shear resistant into the feed pre-extrusion. Such

Table 1. Various millet-based extrudates, extrusion parameters, physical characteristics and nutritional values

S. No.	Product	Extrusion parameters	Extrudate composition	Physical characteristics	Nutritional characteristics	References
1.	Pearl millet extrudates	Feed moisture content – 16% Die Temperature- 150 °C	Pearl millet Sodium alginate- 3%	Expansion ratio- 2.64 Density (g cm^{-3})- 0.395 Water absorption index (%)- 7.002 Water solubility index (%)- 4.982 Hardness (g)- 1110	--	Maitre *et al.* (2017)
2.	Millet-soy blended extrudates	Feed moisture- 14% Barrel temperature- 120°C Cutter speed- 15 rpm	Pearl millet- 81.68% Finger millet- 7.02% Decorticated soybean- 11.29%	Feed rate 9.5 kg/h and screw speed 250 rpm Sectional expansion index- 5.39	--	Balasubramanian *et al.* (2012)
3.	Sorghum extrudates	Feed moisture- 17% Screw speed- 400 rpm Feed rate- 15 kg h^{-1} Diameter of the die- 3 mm Barrel temperature- 105°C.	Sorghum flour- 100%	Length (mm)- 19.9 Diameter (mm)- 8.2 Bulk density (g cm^{-3})- 0.07 Expansion ratio- 10.9	Carbohydrates (g)- 82.3 Protein (g)- 10.3 Fat (g)- 1.7 Ash (g)- 3.1 Fiber (g)- 1.1 Calcium (mg)- 25 Phosphorus (mg)- 222 Iron (mg)- 4.1	Devi *et al.* (2014)
	Sorghum + Rice extrudates		Sorghum flour- 60% Rice flour- 40%	Length (mm)- 27.5 Diameter (mm)- 8.4 Bulk density (g cm^{-3})- 0.07 Expansion ratio- 11.5	Carbohydrates (g)- 83.5 Protein (g)- 8.9 Fat (g)- 1.2 Ash (g)- 3.0 Fiber (g)- 1.2 Calcium (mg)- 19 Phosphorus (mg)- 197.2 Iron (mg)- 2.7	
	Sorghum + Rice + (Bengal gram flour) extrudates		Sorghum flour- 50% Rice flour- 30% Bengal Gram Flour- 20%	Length (mm)- 27 Diameter (mm)- 7.7 Bulk density (g cm^{-3})- 0.08 Expansion ratio- 9.6	Carbohydrates (g)- 82.3 Protein (g)- 11.3 Fat (g)- 1.2 Ash (g)- 3.2 Fiber (g)- 1.2 Calcium (mg)- 28.7 Phosphorus (mg)- 257.2 Iron (mg)- 3.4	
	Sorghum + Rice + Legume mix extrudates		Sorghum flour- 50% Rice flour- 30% Legume mix (Green & roasted bengal gram)- 20%	Length (mm)- 28.2 Diameter (mm)- 8.4 Bulk density (g cm^{-3})- 0.08 Expansion ratio- 11.5	Carbohydrates (g)- 81.8 Protein (g)- 11.5 Fat (g)- 1.2 Ash (g)- 2.5 Fiber- (g)- 1.5 Calcium (mg)- 37.45 Phosphorus (mg)- 268.5 Iron (mg)- 3.3	
	Sorghum + Rice + Defatted soy flour extrudates		Sorghum flour- 50% Rice flour- 30% Defatted soy flour- 20%	Length (mm)- 27.3 Diameter (mm)- 8.3 Bulk density (g cm^{-3})- 0.08 Expansion ratio- 11.2	Carbohydrates (g)- 74.1 Protein (g)- 16.6 Fat (g)- 1.5 Ash (g)- 3.4 Fibre (g)- 1.6 Calcium (mg)- 65.5 Phosphorus (mg)- 329.0 Iron (mg)- 4.4	

Contd...

Table 1. Contd...

S. No.	Product	Extrusion parameters	Extrudate composition	Physical characteristics	Nutritional characteristics	References
4.	Pearl millet+ whey protein concentrate extrudates	Feed moisture- 14% Feed rate- 10.5 kg h^{-1}	Pearl millet grits size- 841µ Pearl millet grits- 95% Whet protein concentrate- 5%	Expansion index- 4.9 Water absorption index (g g^{-1})- 5.24 Water solubility index (%)- 19.44 Bulk density(g cm^{-3})- 0.129	Total carbohydrates (%)- 77.1 Protein (%)- 12.4 Fat (%)- 2.3 Ash (%)- 1.15 Iron (mg 100 g^{-1})- 6.65 Calcium (mg 100 g^{-1})- 44.7 Phosphorus (mg 100 g^{-1})- 207.9 Tannins (mg 100 g^{-1})- 148.0	Yadav *et al*. (2014)
5.	Soy, sorghum, millet and rice blend extrudates	--	Ragi flour- 42.03% Sorghum flour- 14.95% Soy flour- 12.97% Rice- 30%	Expansion ratio- 2.69 Bulk density (g cm^{-3})- 116.77 Water absorption index (g g^{-1})- 6.14 Water solubility index (%)- 30.9	--	Seth and Rajamanickam (2012)
6.	Millet–legume blended extrudates	Feed moisture-23.2% Barrel temperature- 121.1°C Screw speed- 123 rpm	Blend ratio (barnyard millet and red gram)- 19.9%	Density(g cm^{-3})- 0.00052 Sectional expansion index- 5.1 Water absorption index- 9.4 Crispness- 45	--	Chakraborty *et al*. (2011)
7.	Corn + Pearl millet extrudates	Feed moisture- 28% Die diameter- 4mm Barrel temperature- 135°C Screw Speed- 160 rpm	Corn - 75% Pearl millet- 25%	Expansion ratio- 1.8 Bulk density (g cm^{-3})- 0.893 Water absorption index (g/g)- 4.8 Water solubility index (%)- 4.2 Hardness (g)- 3303	Total carbohydrates (%)- 67.2 Protein (%)- 9.3 Crude fiber (%)- 5.88	Rolandelli *et al*. (2020)
	Corn + Sorghum extrudates		Corn-75% Sorghum- 25%	Expansion ratio- 1.9 Bulk density (g cm^{-3})- 0.933 Water absorption index (g g^{-1})- 4.4 Water solubility index (%)- 4.3 Hardness (g)- 3777	Total carbohydrates (%)- 67.3 Protein (%)- 9.4 Crude fiber (%)- 5.1	
8.	Protein Maize based breakfast cereal	Feed moisture- 9.75% Barrel temperature- 125°C Screw speed- 461 rpm	Quality protein maize- 72% Finger millet- 18%	Expansion ratio- 3.12	Protein (%)- 9.6 Fat (%)- 1.5 Fibre (%)- 3.4 Ash (%)- 2.4 **β-carotene (mg/100g)- 2** Iron (mg 100 g^{-1})- 3 Calcium (mg 100 g^{-1})- 122	Prakash *et al*. (2021)
9.	Finger-millet and horse-gram in rice matrix extrudates	Feed moisture- 11.36% Die head temperature- 130.52°C Screw speed- 329.08 rpm	Rice flour- 40% Finger millet flour- 50% Horse gram- 10%	Bulk density (g cm^{-3})- 0.248 Expansion ratio- 2.927 Water absorption index – 5.949 Water solubility index (%)- 10.835 Hardness (N)- 84.415 Crispness- 33.182	Total phenolic content (mg GAE 100 g^{-1})- 401.235	Patil *et al*. (2017)

Contd...

Table 1. Contd...

S. No.	Product	Extrusion parameters	Extrudate composition	Physical characteristics	Nutritional characteristics	References
10.	Pusa pearl puffs	Feed moisture-13% Barrel temperature-128°C Feed speed-470 rpm	Pearl millet flour Quality protein Maize Green gram flour (10% carrot powder, 2% bittergourd powder, and 5% aonla powder can be added)	Bulk density (g cm^{-3})-0.139 Expansion ratio- 4.56 Hardness (N)- 1.88 Crispness- 440	Phytic acid (mg 100 g^{-1})- 377.31 Total polyphenols (mg 100 g^{-1})- 302.12 Protein (%)- 13.02 Fat (%)- 5.26 Carbohydrates (%)- 73.13 Fibre (%)- 3.07 Ash (%)- 2.59 Iron (mg 100 g^{-1})- 5.24 Zinc (mg 100 g^{-1})- 3.13	IARI final report – NAE project (2011-16)
11.	Pearl millet + Mung bean extrudates	--	Pearl millet- 90% Mung bean- 10%	Bulk density (g cm^{-3})-0.072 Expansion ratio- 0.83 Water absorption index (g/g)- 4.33 Water solubility index (%)- 33.30 Swelling power (%)- 2.48	Total phenolic content (µg GAE g^{-1})- 6996.10 Antioxidant activity (%)- 21.30 In vitro protein digestibility-65.99	Kaur *et al.* (2020)
	Sorghum + Mung bean extrudates		Sorghum- 80% Mung bean- 20%	Bulk density (g cm^{-3})-0.091 Expansion ratio- 0.87 Water absorption index (g/g)- 4.08 Water solubility index (%)- 35.99 Swelling power (%)- 2.34	Total phenolic content (µg GAE g^{-1})- 4811.40 Antioxidant activity (%)- 23.08 In vitro protein digestibility-70.23	
	Sorghum + Chickpea extrudates		Sorghum- 80% Chickpea- 20%	Bulk density (g cm^{-3})-0.097 Expansion ratio- 0.92 Water absorption index (g g-1)- 4.12 Water solubility index (%)- 33.00 Swelling power (%)- 2.48	Total phenolic content (µg GAE g^{-1})- 4010.76 Antioxidant activity (%)- 23.43 *In vitro* protein digestibility-75.45	
12.	Pearl millet + African walnut + food grade corn starch	Feed moisture-15% Barrel temperature-60°C Feed speed-470 rpm	Pearl millet flour- 80% African walnut flour- 10% Corn Starch- 10%	Bulk density (g cm^{-3})- 0.57 Expansion ratio- 6.23 Water absorption index (mL/g)- 6.31 Oil absorption index (mL/g)- 6.06 Residence time (s)- 16.5	Moisture content (%)- 9.41 Protein content (%)- 11.61 Crude fibre (%)- 2.27 Crude fat (%)- 3.20 Ash (%)- 2.27 Carbohydrate (%)- 70.98	Sobowale *et al.* (2021)

flavour capsules can be formulated using the extrusion technique (Huang *et al.*, 2021).

Millet incorporation in extrudate formation and effect on physical parameters

The expansion ratio and density of extrudates are the most important physical indices for the degree of puffing of the extrudates. The expansion ratio is inversely proportional to density. A greater level of puffing in the extruded product is highly desirable. Higher expansion and lower bulk density in extrudates are favourable to incorporating crispiness and crunchiness from the consumer's point of view. Maitre *et al.* (2017) carried out a series of experiments to understand the impact of different hydrocolloids and various process parameters on the characteristics of the pearl millet extrudates. Three different types of hydrocolloids i.e., carboxymethylcellulose), sodium alginate and gum acacia were added to the mixture before extrusion. During the extrusion process parameters such as feed moisture content and die temperature were kept variable while feed rate was maintained constantly. It was observed that with the addition of three types of hydrocolloids, parameters such as expansion ratio and water absorption index increased while density, water solubility index and hardness decreased. The most effective out of all three was sodium alginate. It was concluded in the study of Maitre *et al*. (2017) that decreasing moisture content and increasing die temperature and hydrocolloid concentration in the mixture has a positive impact on the expansion ratio while the density of the extrudates is reduced simultaneously. Reduced feed moisture and increased temperature during extrusion restrict the flow of the mixture across the barrel due to the high viscosity of feed which increases the shearing rate and residence time of the feed. Higher shear for a long time enhances the degree of gelatinization and expansion. Feed with lower moisture content is highly viscous due to which pressure difference is higher, resulting in higher expansion. Hydrocolloids tend to change the visco-elastic characteristic of starch which increases the expansion ratio. Visco-elastic characteristic is again dependent on the type of starch that persists in the extrusion feed material.

Devi *et al*. (2014) extruded a mixture of sorghum and legume mix (green gram and roasted Bengal gram), rice and soybean. Developed extrudates were ground into powder to which 15% malted ragi flour was added to develop complementary food such as porridge and infant feed of low density. A complementary mix was highly acceptable among sensory panellists. The least expansion was recorded in rice, sorghum, and Bengal gram extrudates. Extrudate mix with higher starch contents expands more while one with higher protein content expanded less. Expansion and bulk density of sorghum and sorghum mixed with other grains extrudates was comparable. The highest expansion and lowest bulk density were reported in soybean and legume mix extrudates (Devi *et al*., 2014).

Yadav *et al*. (2014) enhanced the nutritional quality of pearl-millet extrudates by incorporating whey protein concentrate (WPC). During trials, whey protein concentrate was added at different concentrations. Enhanced protein concentration was observed to harm the expansion and bulk density. It was stated that a higher level of protein disturbs the water distribution in the extrudate matrix as a large number of sites are available for cross-linking due to which extensibility of the starch matrix is reduced. Proteins are also reported to decrease the pressure difference (lowers the expansion) as protein lowers the shear inside the extruder. The addition of WPC also resulted in increased hardness and breakpoint index while lowering water absorption index and water solubility index. Lowered water absorption index (WAI) and water solubility index (WSI) were suggested to be due to dilution of starch by increased levels of protein which denatures at extrusion temperature. A more rigid network in the extrudate matrix was explained as the reason for higher hardness and breakpoint index. WPC was observed to improve the visual appeal as it contributes to a whiter colour. All the observed mentioned negative effects of WPC on pearl millet extrudates were not very significant up to 5% WPC incorporation, therefore Yadav *et al*. (2014) suggested 5% WPC incorporation in the extruded snacks.

Seth and Rajamanickam (2012) formulated soy-fortified millet (ragi and sorghum) extrudates. It was observed that higher concentrations of fibres and protein of millets such as ragi and sorghum bind water more tightly than starch. This tight binding inhibits water loss during extrusion and thereby decreases expansion and increases bulk density. However, it was reported that due to the lower proportion of soy no significant effect on bulk density and expansion. Water absorption index and water solubility index were reported to be positively and negatively respectively, impacted by the composition (Seth and Rajamanickam, 2012).

Chakraborty *et al*. (2011) prepared extrudates by combining barnyard millet and red gram at varying blend ratios. These varying compositions of the mixtures were extruded at the different moisture content of the mixture, screw speed, barrel temperature and die head temperature. Increased values of all the processing variables were observed to enhance the density of extrudates except screw speed and blend ratio which decreased the density with increasing value. It was suggested that protein and starch molecules tend to stretch during extrusion which weakens their bonds, this leads to a puffed product. At higher screw speed and blend ratio residence time of extrudate mixture is reduced and lowers millet starch for gelatinization. Section expansion index enhanced with increasing values of blend ratio, moisture content, die head temperature and barrel temperature. However, section expansion decreased at higher screw speed which is due to incomplete expansion with lower residence time at higher screw speed (Chakraborty *et al*., 2011).

Rolandelli *et al*. (2020) studied partial replacement of corn flour with 25 % whole grain mix flours (pearl millet, quinoa, red sorghum and canary seed with 10-11% moisture content (d.b.) and its effects on protein agglomeration and formation of protein lipid complexes during production of extrudates. Important benefit of whole grain flour incorporation was development of gluten free snack products. The addition of millet and sorghum had no significant effect on expansion ratio and bulk density in comparison to the control (corn extrudate). Rolandelli *et al*. (2020) reported that the water absorption index of extrudates was enhanced with the incorporation of sorghum, pearl millet and canary seeds which may be due to higher protein and fibre which results in higher water retention and binding of water, respectively. With the addition of the high crude fibre flour of sorghum and pearl millet, the cell structure of the expanded product is weak due to which sorghum and millet blended extrudate were the least hard in texture. While presence of isolate protein agglomerates in control (maize) samples negatively affects the Organoleptic properties resulting in brittle and less crunchy product. However, with addition of 25% pearl millet flour lesser proportion of protein agglomerates were noticed with big pores formation due to starch melting with formation of protein-lipid complexes and amylase-lipid complexes. The presence of lipids close to air cells again showed higher susceptibility for oxidation. Scanning electron microscopy (SEM) analysis report depicted that the addition of millet produced extrudates with a more porous inner structure along with multiple air cells of variable sizes. All extruded blends with millet as compositional element were observed to have darker than the control sample (Rolandelli *et al*., 2020).

Prakash *et al*. (2021) developed breakfast cereal by combining maize, finger millet and carrot powder. It was observed that the expansion ratio of the breakfast cereal increased with increasing temperature, screw speed and feed moisture. The initial rise in expansion ratio was suggested to be due to a reduction in the viscosity of molten mass which increases gelatinization of starch and prevents degradation of starch, whereas the subsequent increase in temperature above 125°C and moisture content above 9%, decreases the expansion ratio of breakfast cereal extrudates due to degradation of the starch molecule. The addition of finger millet up to a level of 5% increased the expansion ratio. With the addition of finger millet at a concentration of 25%, extrudates started darkening. Therefore addition of 20% finger millet in the extrudate mixture yields breakfast cereal with acceptable expansion and colour.

Patil *et al*. (2017) developed innovative extrudates using rice, finger millet and horse gram. All operational variables were found to have a significant effect on expansion ratio, WAI, WSI, hardness, total phenolics and antioxidants. Bulk density was observed to decrease and increase, respectively with decreasing feed moisture and increasing screw speed. At higher feed moisture, the molecular configuration of amylopectin and plasticization of the mass is altered which reduces elasticity and bubble growth due to which bulk density increases. Higher screw speed contributes in two ways i.e., by breaking the amylopectin networks and lowering the residence time of molten mass in the barrel which enhances the elasticity and expansion. The expansion ratio of the extrudates was significantly affected by barrel temperature and feed moisture. At higher temperatures, starch granule disruption and superheating of water are elevated which favours bubble formation and expansion by lowering mass viscosity. Lower feed moisture increases the shearing effect which increases the pressure differential between atmosphere and bubble in mass inside the barrel, due to which moisture evaporation at the die-end increases, thereby increasing the expansion ratio. WAI of the extrudates increases with increasing feed moisture, decreasing screw speed and barrel temperature as starch degradation is reduced which increases the water absorption capacity. Patil *et al*. (2017) stated that increased moisture decreases WSI due to its lubricating effect

Table 2. Physical properties of extrudates from different composition of pearl millet and maize

Properties	Pearl millet : Maize				
	0:100	30:70	50:50	70:30	100:0
Moisture content (%)	8.14	6.5	6.0	5.95	5.75
Expansion ratio	4.64	4.24	4.05	3.95	3.73
Density (kg m^3)	62.01	63.50	66.07	67.59	72.25

which reduces the frictional/shearing effect of temperature and screw speed on the molten mass, causing lesser degradation. Thermo-mechanical damage (depolymerization and degradation into smaller molecules) caused by higher temperature and screw speed enhances the WSI. Higher feed moisture decreases the expansion ratio due to which extrudates are harder and less crispy. Higher temperature and screw speed yield extrudates with thinner wall thickness and more expansion which make them less hard and crispier also rich in total phenolic content and antioxidant activity.

Sobowale *et al*. (2021) studied the combined effect of feed composition, feed moisture content and barrel temperature on functional properties, proximate composition and physicochemical properties of pearl millet-based extrudates. Pearl millet Extrudate enriched with the maximum amount of African walnut flour (10%) demonstrated the highest crude protein and fibre content but increase in bulk density with proportional reduction in expansion ratio was noted due to the higher fibre and protein content of African walnut flour. Usually, fibres and proteins bind the moisture in the feed during extrusion cooking which hinders moisture evaporation at the die exit, resulting in lower expansion and higher bulk density (Yadav *et al*., 2014). The highest water absorption capacity was demonstrated by 100% pearl millet extrudate which was suggested to be due to the presence of larger starch fragments.

Fig. 4. Single screw extruder developed at ICAR-CAZRI, Jodhpur.

Advancements in single screw extruder technology for millet extrudates: ICAR-CAZRI's experimental study

a) Development of pearl millet based extrudates: Single screw extruder was used for extrusion cooking of pearl millet. Extruder consisted screw barrel assembly having length of 120 mm, diameter 34 mm, pitch of 15 mm at feeding zone and 5 mm at compression zone, die opening of 3 mm and feeding hopper of 1-1.25 kg capacity mounted over barrel. A rotating cutting blade is attached at outlet of die. A 3-phase induction motor of 5.5 kW of 1450 rpm and extruder assembly was fixed in metal frame both connected with belt-pulley assembly which rotates screw at 400 rpm and cutting blade through gear assembly. Pearl millet and maize grits at 13-14% moisture level can be extruded successfully for production of millet extrudates.

0:100 30:70 50:50 70:30 100:0

Fig.5. Extruded product with different ratios of pearl millet : maize.

Expansion ratio of the extrudates gradually decreased with increasing concentration of pearl millet in the extrusion mixture. Least expansion was reported in 100% pearl millet based extrudates.

b) Development of pearl millet and arid legume based extrudates: To overcome the major problems of lower expansion and higher length of pearl millet and maize (70:30) based extrudates trials were carried out by addition of arid zone-based legumes (mung bean and moth) at varying concentration levels (5, 10, 15 and 20%). Incorporation of legumes at varying concentration significantly enhanced the expansion along with decreased elongation. Pearl millet-maize-legume based extrudates were somewhat round in appearance rather than elongated unlike pearl millet-maize based extrudates. Values of all the parameters for both the legumes were almost similar. Addition on legume exhibited negative impact on length of extrudates while imposed a positive impact on expansion ratio, density and diameter which results into highly desirable extrudates which are lighter, puffier and crispy.

c) Physical properties of pearl millet and arid legume based extrudates: The initial experiments were conducted with the composite grits of pearl millet by addition of maize into the ratios of 70, 50, and 30% on weight basis. The raw mixtures were conditioned to moisture content of 13-14%. The initial moisture content of extrudates obtained after extrusion cooking ranged from 8.14 to 5.75%. Volume, projected area and diameter of the extrudates decrease on increasing the concentration of pearl millet. Reduction in these parameters can be directly related to reducing expansion ratio. Expansion ratio was 4.64, 4.24, 3.95, 3.73 for 30, 50, 70 and 100% pearl millet extrudates. Also, due to reducing expansion, extrudates increased in length and elongation ratio. It was observed that pearl millet concentration above 70% is unacceptable due to lower expansion. Hence, concentration of pearl millet was maintained below 70% in the pearl millet- maize- legume based extrudate. For expansion to acceptable level maize as a source of starch was kept above 25%.

Conclusion

Feed properties such as type of starch, amylose to amylopectin ration, feed moisture, pH, protein and fat content in the feed mixture affect the rheology and organoleptic characteristics of extrudates. Starch showing C-type polymorph is better for extrusion in comparison to A and B-type polymorph which occurs in millets and legume seeds, respectively. The expansion which is the predominant indicator of the textural and physical quality of extrudates is affected by the rheology of the feed mixture which is primarily related to type and amount of starch. In most studies favorable parameters for millet extrusion are reported as feed moisture (10-15%), barrel temperature (105-120°C) and higher screw speed also for increasing the expansion and reduction in bulk density. Several changes occur in the visco-elastic behavior of starch during extrusion. It undergoes phase transition from glassy to rubbery, rubbery to molten, molten to rubbery, and again rubbery to glassy state which leads to the physicochemical transformation of feed. The addition of some hydrocolloids such as CMC, sodium alginate, and guar gum are reported to increase the expansion because they absorb more moisture, increases viscosity and gelatinization of starch inside the barrel. An increase in viscosity leads to high shear which results to increased expansion ratio. Millets generally show higher cold paste viscosity

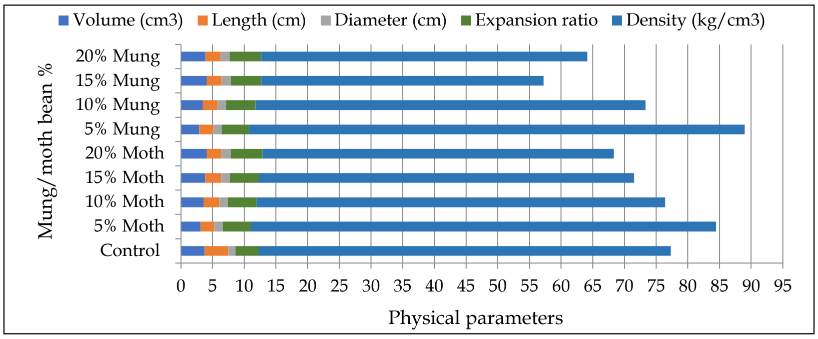

Fig. 6. Physical parameters of extrudates prepared from pearl millet and arid legumes.

which shows retrogradation and formation of resistant starch that is the reason behind lower glycaemic index of millet extrudates. The shape of starch granules are spherical or polygonal and pinholes are not present in the millet starch granule surface so the enzyme does not enter inside the granule easily. This phenomenon favours the slower release of glucose and reduces the Glycaemic Index (GI) of millet products. At higher barrel temperatures water is super-heated, aids in breaking the amylopectin networks for efficient mixing and lower residence time promotes expansion due to the sudden release of pressure once molten mass exits the die. However, after a certain level, higher feed moisture, barrel temperature and screw speed negatively impact the expansion, as the starch granules are degraded. With the increase in expansion ratio hardness decreases and crispiness increases. Studies indicated that incorporation of millet alone results in a dark colour, harder and denser texture due to their high fibre content and absence of starch matrix. Mixing millets with grains like corn, rice and legumes up to a certain level i.e., <30% highly increases the expansion. Incorporation of hydrocolloids like sodium alginate or CMC in extrudate mixture not only enhances the expansion ratio but also lightens the dark colour of millet extrudates. It was concluded that extrusion enhances the in-vitro digestibility of proteins because the processing denatures complex proteins, inactivates trypsin inhibitors, lipase and reduces the quantity of protein binding compounds such as phytic acid and tannins. The change from insoluble fibre to soluble fibre is another advantage which affects its digestibility. Major problems of lower expansion in 100% millet extrudates can be reduced by the addition of legumes or other cereal grains in certain proportions i.e. 5-15% in the extrusion mixture to obtain extrudates of desired quality and functionality. Newer techniques of extrusion like 3D printing, hot melt extrusion and hydrogel forming extrusion are also an innovative approach and gaining popularity these days. These technologies will soon capture the global markets through bulk production, novel product formulation opportunities and new consumer experiences. There is a need for further research for developing extrusion-based low-cost 3-D printers at the commercial scale, which is rapid and can provide consistent results in terms of material quality and printing time, nutritional value as well as food safety and quality requirements in extrusion based products.

References

Alam, M.S., Kaur, J., Khaira, H., and Gupta, K. 2016. Extrusion and extruded products: changes in quality attributes as affected by extrusion process parameters: A review. *Critical Reviews in Food Science and Nutrition* 56(3): 445-473.

Balasubramanian, S., Singh, K.K., Patil, R.T. and Onkar, K.K. 2012. Quality evaluation of millet-soy blended extrudates formulated through linear programming. *Journal of Food Science and Technology* 49(4): 450-458.

Chakraborty, S.K., Singh, D.S., Kumbhar, B.K. and Chakraborty, S. 2011. Millet–legume blended extrudates characteristics and process optimization using RSM. *Food and Bioproducts Processing* 89(4):492-499.

Devi, N.L., Shobha, S., Alavi, S., Kalpana, K. and Soumya, M. 2014. Utilization of extrusion technology for the development of millet based complementary foods. *Journal of Food Science and Technology* 51(10): 2845-2850.

Devisetti, R., Yadahally, S.N. and Bhattacharya, S. 2014. Nutrients and antinutrients in foxtail and proso millet milled fractions: Evaluation of their flour functionality. *LWT-Food Science and Technology* 59(2): 889-895.

Ek, P., Kowalski, R.J. and Ganjyal, G.M. 2020. Raw material behaviours in extrusion processing I (carbohydrates) In: *Extrusion Cooking* (Ed. G.M. Ganjyal), pp. 119-152. Woodhead Publishing, England.

FAO 2019. http://www.fao.org/faostat/en/#data/QCL/visualize Accessed on 29-07-2021.

Fellows, P.J. 2009b. *Food Processing Technology: Principles and Practice*. 2nd edn. Ch-14 Extrusion. pp. 294-297 Woodhead Publishing Limited, England.

Ganjyal, G.M., Kyungsoo, W., Sukh, D.B. and Clodualdo, C.M. 2014. US Patent 8,741,370, filed April 27, 2005, and issued June 3, 2014.

Gulati, P., Brahma, S. and Rose, D.J. 2020. Impacts of extrusion processing on nutritional components in cereals and legumes: Carbohydrates, proteins, lipids, vitamins, and minerals. In: *Extrusion Cooking* (Ed. G.M. Ganjyal), pp. 415-443. Woodhead Publishing, England.

Guo, K., Zhang, L., Bian, X., Cao, Q. and Wei, C. 2020. A-, B-and C-type starch granules coexist in root tuber of sweet potato. *Food Hydrocolloids* 98: 105279.

Huang, K., Yuan, Y., and Baojun, X.A. 2021. Critical review on the microencapsulation of Bioactive compounds and their application. *Food Reviews*

International. https://doi.org/10.1080/87559129.2021.1963978

IARI final report- NAE project. 2011-16. Pilot scale processes for coarse cereal based functional foods through extrusion processing Page-61 https://www.iari.res.in/files/Divisions/PHT/Final_Report_NAE_IARI_2016-18052017.pdf Accessed on 30-07-2021.

ICRISAT 2017. Small millets https://www.icrisat.org/ Accessed on 15-07-2021.

Kaur, J., Singh, B., Singh, A. and Sharma, S. 2020. Geometric physical and functional properties of selected pulses and millets for the formulation of complementary food products. *International Journal of Chemical Studies* 8: 2854-2858.

Kim, H.W., Lee, I.J., Park, S.M., Lee, J.H., Nguyen, M.H. and Park, H.J. 2019. Effect of hydrocolloid addition on dimensional stability in post-processing of 3D printable cookie dough. *LWT* 101:69-75. https://doi.org/10.1016/j.lwt.2018.11.019

Kowalski, R.J., Hause, J.P., Joyner, H. and Ganjyal, G.M. 2018. Waxy flour degradation impact of screw geometry and specific mechanical energy in a co-rotating twin screw extruder. *Food Chemistry* 239: 688–696.

Kumari, S.K. and Thayumanavan, B. 1997. Comparative study of resistant starch from minor millets on intestinal responses, blood glucose, serum cholesterol and triglycerides in rats. *Journal of the Science of Food and Agriculture* 75(3): 296-302.

Llo, S., Schoenlechner, R. and Berghofe, E. 2000. Role of lipids in the extrusion cooking processes. *Grasas y Aceites* 51(1-2): 97-110.

Mahajan, P., Bera, M.B., Panesar, P.S. and Chauhan, A. 2021. Millet starch: A review. *International Journal of Biological Macromolecules* 180: 61-79.

Maitre, A., Rathod, R.P. and Annapure, U.S. 2017. Effect of hydrocolloids and process parameters on the extrusion behaviour of pearl millet grits. *International Food Research Journal* 24(4): 1538-1544

Naqash, F., Gani, A., Gani, A. and Masoodi, F.A. 2017. Gluten-free baking: Combating the challenges-A review. *Trends in Food Science & Technology* 66: 98-107.

Newinski, M.M. 2008. Advances in Celiac disease and gluten free diet. *Journal of American Dietetic Association* 108: 661-672.

Omosebi, M.O., Osundahunsi, O.F. and Fagbemi, T.N. 2018. Effect of extrusion on protein quality, antinutritional factors, and digestibility of complementary diet from quality protein maize and soybean protein concentrate. *Journal of Food Biochemistry* https://doi.org/10.1111/jfbc.12508

Patil, H., Roshan, V.T. and Michael, A. Repka. 2016. Hot-Melt Extrusion: from Theory to Application in Pharmaceutical Formulation. *American Association of Pharmaceutical Scientists* 17(1): 20-42.

Patil, S., Kaur, C. and Varghese, E. 2017. Optimization of extrusion process for development of antioxidant rich extrudates from finger-millet and horse-gram in rice matrix. *International Journal of Chemical Studies* 5(6): 981-990.

Prabha, K., Ghosh, P., Abdullah, S., Joseph. R.M., Krishnan, R., Rana. S.S. and Pradhan, R.C. 2021. Recent Development, Challenges, and Prospects of Extrusion Technology. *Future Foods* https://doi.org/10.1016/j.fufo.2021.100019

Prakash, O. Jha, S.K., Rudra, S.G., Jha, G.K., Sinha, J.P. and Hossain, F. 2021. Development of Quality Protein Maize based breakfast cereal. *The Indian Journal of Agricultural Sciences,* 91(2):300-304.

Rao, R.G.H. and Thejaswini, L.M. 2015. Extrusion Technology: A Novel Method of Food Processing. *International Journal of Innovative Science, Engineering & Technology* 2(4):358-369

Rolandelli, G., García-Navarro, Y.T., García-Pinilla, S., Farroni, A.E., Gutiérrez-López. G.F. and DelPilar Buera, M. 2020. Microstructural characteristics and physical properties of corn-based extrudates affected by the addition of millet, sorghum, quinoa and canary seed flour. *Food Structure* 25:100140. https://doi.org/10.1016/j.foostr.2020.100140

Saleh, A.S.M., Zhang, Q., Chen, J. and Shen, Q. 2013. Millet Grains: Nutritional Quality, Processing, and Potential Health Benefits. *Comprehensive Reviews in Food Science and Food Safety* 12(3):281-95.

Seth, D. and Rajamanickam, G. 2012. Development of extruded snacks using soy, sorghum, millet and rice blend–A response surface methodology approach. *International Journal of Food Science & Technology* 47(7):1526-1531.

Shevkani, K., Singh, N., Bajaj, R. and Kaur, A. 2017. Wheat starch production, structure, functionality and applications-a review. *International Journal of Food Science & Technology* 52(1): 38-58.

Sobowale, S.S., Kewuyemi, Y.O. and Olayanju, A.T. 2021. Process optimization of extrusion variables and effects on some quality and sensory characteristics of extruded snacks from whole pearl millet-based flour. *SN Applied Sciences* 3(10): 1-12.

Yadav, D.N., Anand, T. and Singh, A.K. 2014. Co-extrusion of pearl millet-whey protein concentrate for expanded snacks. *International Journal of Food Science* & *Technology* 49(3):840-846.

Printed in June 2024