**Extrusion Processing: An Advanced and Novel Technology for Development of Ready-To-Eat (RTE) Products**

**ABSTRACT**

Ready-to-eat snacks and breakfast products are demanded rapidly day by day in the world market. To fulfill the RTE demand of consumer the novel, fast producing, versatile, uniformity, environmentally friendly and labour saving technology required by food scientists, manufacturers and industrialist. The extrusion processing technology is the latest novel technology which fulfils all these requirements. Extrusion cooking of foods is an operation in which raw food ingredients are forced to pass, in one or multiple varieties of situation of mixing, heating and shearing, through a die of specially designed to shape and puff dry the ingredients. Two or more raw food ingredients are combined to develop nutritious end products by the application of extrusion technique. Thermo-mechanical and shearing action during extrusion cooks raw mixture so that physico-chemical changes of the materials occurto carry out starchgelatinization, protein denaturation and enzyme inactivation, microorganisms and many otherfactors against to nutrition; all theseoccur in a shear situation, producing a plasticized continuous mass. In the present paper reviews the current development of RTE snacks in combination of different ingredients as well as the effect of extrusion process variables on physical, functional and textural properties such as expansion ratio, bulk density, hardness, crispness, water absorption index, etc. of extruded products. The control of process variables to produce nutritional balanced product is also important.

**Keywords:** Extrusion cooking, functional quality, process variable, RTE, starch.

**1. Introduction**

Food is an essential part of everyone’s lives. The type of food for any society or the group largely depends on the availability of edible raw materials, its preparation and food habits. In recent years RTE snack foods have become popular and commercially available worldwide including India. Some of such RTE products are puffed and popped grains, popcorn, potato chips, wafers, flakes, granules, potato puffed cubes, extruded foods etc. and have become integral part of the food habits. The growing demand of such snack and breakfast foods is due to changing food habits of children and teenagers, extended working hours, increasing number of single person households, different eating times, different food choices by individual family members, economic or buying power and more number of working women, *etc.* (Haritha *et al.,* 2014). The marketing potential exists for snacks or RTE foods production will meet the increasing demands of snacks and their need to be healthy (Euromonitor, 2002).There is an exhaustive list of RTEbreakfast cereals or thesnackfoods prepared using single component of cereals, pulses, fruits, vegetables or with composite mixture of multi-components. Consumers want snacks or RTE foods that taste good, smell good, feel good, look good and in addition, nutritionally superior or healthy. Snacks prepared from single component do not fulfil all these requirements especially the nutritional quality. On the other hand, there exists possibility of incorporating desired proportion of suitable or selected ingredients to enrich the nutritional level of end product which can easily be accomplished using extrusion technology. This provides an opportunity to manipulate the proportion of different ingredients in the blend to prepare end products of desired or pre-determined quality standards not only to meet the demand of the consumers but at the same time balanced composition of the products. The use of extrusion cooking technology in the preparation of RTE snacks, breakfast cereals, baby foods, pet foods and other especially texturised food products has been initiated in the year 1930. The extrusion technology improves the digestibility of the food and bioavailability of nutrients (Singh *et al.,* 2010 and Gu*et al.,*2008).

Food extrusion is a high temperature short-time cooking process which involves simultaneous thermal and pressure treatment along with mechanical shearing, resulting in changes such as gelatinization of starch, denaturation of protein, inactivation of enzymes and anti nutritional factors, improvement in digestibility and biological value of proteins and complete cooking of the extrudates to obtain ready-to-eat products (Singh *et al.*, 2007). Physico-chemical changes occur during extrusion cooking which includes binding, cleavage, loss of native conformation, fragment recombination and thermal degradation etc. (Joy-steel *et al.*, 2012). The final product quality mainly depends on extrusion process variables. This suggests proper adjustment of process variables to produce desired quality products (Chessari and Sellahewa, 2001). Feed moisture, screw speed, die configuration, feed rate and extruder barrel temperature had significant effect on physical and functional qualities of extruded products (Chiu *et al*., 2013; Oke *et al*., 2013). Feed moisture and barrel temperature are the most prominent effect on quality of extruded product. In order to improve the protein content of extruded foods in India, research and development on incorporation or fortification of legumes like soybeans, grams, green gram, etc. in extruded foods is being focused which will fulfill the nutritional balance of the products.

**2. Advantages of extrusion cooking**

In recent years the extrusion cooking technology has gained popularity in the preparation of different types of food products. Researchers (Riaz *et al.*, 2007;Belwal and Deshpande, 2017) have analysed the process of extrusion cooking of different food products and indicated its superiority over the other traditional methods of product development. The superiority of extrusion cooking for the preparation of food products over the other traditional food/feed processing methods could be briefly narrated as follows:

1. **Versatility:** Extrusion technology can be used easily to prepare number of products by combining varying levels of different ingredients which may be difficult otherwise with other processing methods.
2. **LowCost:** The requirement of labour and work place is comparatively less for extrusion processing and the method also utilizes raw materials effectively for processing and forming which in turn reduces the overall processing cost and finally the product cost.
3. **Productivity:** The unit can be operated continuously to its maximum capacity with a set of operating conditions thereby enhances the productivity.
4. **Product quality:** The method of extrusion uses very high temperature for short time which helps in maintaining the heat sensitive components in the product with minimum degradation of nutritional quality. Moreover, it also helps in destroying some of the anti-nutritional undesired factors such as enzymes, micro-organisms *etc.*
5. **Environmentally-friendly:** This method of food processing do not require excessive water in the whole processing operation due to which excessive waste water as effluent and other pollutants are not produced which is a major problem in other methods of processing.
6. **Energy efficient:** It works on optimum moisture content of the input ingredients which is comparatively lower than any other method of processing due to which the product does not require much of energy for final drying and finishing of the product.
7. **Less space:** The entire system of extrusion processing can be installed and operated efficiently in a smaller space.
8. **Automated control:** The extruder systems are such that all the controls can be fixed together and made automatic which not only helps in maintaining the product quality uniform but also reduces the manpower requirement.

**3. Types of food extruder**

Depending upon their use extruders are of several designs. On the basis of construction extruders are two type namely single screw and twin-screw type. The single screw extruders are in use since as early as 1870 in the field of development of rubber products and sausage. In 1881 continuous twin-screw was used for colouring and shaping chewing gums. Subsequently with the advancement of technology extruders have been used in the food industries in the year 1930 to produce pasta using mix semolina flour with water. The simulation and modeling work of twin-screw extruder was reported first time in 1984 (Yacu, 1984). The development of extruded plastics in the industries is closely linked with the extrusion process. A single screw was used in a cylindrical open channel as a conveying device to pump water uphill by Geek philosopher Archimedes (Ramachandra Rao and Thejaswini, 2015). Application of single screw extruder in the food industry was done first time in the history for the production of breakfast cereals, ready-to-eat snacks and other textured foods in the year of mid 1930s (Hazarika *et al*., 2013). Directly expanded corn curls were developed during 1930s and 1940s, by using extruder, which were characterized by extremely high shear rates. The single screw extruder was used commercially for the extrusion cooking and expansion of corn snacks in 1946. The first patent on an application of twin-screw extruder was filed in the mid-1950s. The success of technology was appreciated and its application spread and grown dramatically in the manufacturing of different type of food products. Later during the mid-seventies the twin-screw extruders were used commercially for the combined process of cooking and forming of food products and now-a-days it is one of the most commonly used technology in the food processing industries (Ramachandra Rao and Thejaswini, 2015; Adekola, 2016). The use of twin-screw extruders for food processing initiated as early as since 1970s which expanded largely in 1980s.

The twin-screw extruders are comparatively more expensive than single screw-extruders for the same capacity (Lusas and Riaz, 1994). Twin-screw extruder is self-wiping type of extruder and produces a more uniform flow of the product through the barrel due to positive pumping action of the screw flights. The product cannot turn within the screw as its revolution was impeded by the escape of other screw. Co-rotated twin screw extruder has better transmission function, reduced residence time and readily transport sticky food ingredients compared to single screw extruder. The most commonly used extruders in food industry are: single screw (wet and dry) and twin-screw extruders. Wet extruders require steam or water injection into the barrel (Rokey, 2000); while in dry extruders heating was accomplished by mechanical friction during processing (Said, 2000). Increaseddemand for development of new product with different shapes and sizes by twin-screw extruder which provide more flexibility and better control was realized with the time and product range. It was further classified into counter-rotating and co-rotating twin screw extruders with either intermeshing or non-intermeshing actions. The extruder of co-rotating self-wiping type is most widely used in food processing industries which require frequent product change over, uniform size and shape, product made with low density powders and the products ranges from noodles, pet treats, cereals and corn flakes, high fat aquatic feeds, corn chips tortillas, chocolate filled snacks etc. (Riaz, 2000).

**4. Extrusion process parameters influencing the product quality**

Quality of the extruded products depends on the process parameters such as barrel temperature, screw speed, screw configuration, shape and size of the die opening, D/L ratio, feed rate, feed moisture, type of extruder, etc. Much of the research findings related to effect of process variable on extrusion process and product quality have been reported in the literature. Some of the related important findings and studies have been summarized in the foregoing paragraphs to give an understanding of the subject.

**4.1. Barrel temperature**

Barrel temperature is most prominent parameter for expansion of the extrudate, it greatly influences the visco-elastic behaviour of melted starch and gelatinization of starch which is responsible for expansion of the extruded products. Expansion does not take place if the temperature remains below 100°C. On contrary, Singh *et al.* (2006) have reported successful preparation of extruded product with 20% blending of soybean (15% feed moisture content) at 85°C barrel temperature. However, it is necessary to bring the starch into completely molten state otherwise product expansion isreduces greatly or in some cases it does not expand at all. Expansion of extruded products increases with the increase in extruder temperatures up to a certain limit beyond which it adversely decreases, at very higher temperatures dextrinization takes place which is responsible for weakening of the starch structure (Ramachandra Rao and Thejaswini, 2015). Barrel or the extrusion temperature also affects the bulk density, hardness, crispness, WAI, WSI, etc*.* of extruded products.

Studies on wheat based expanded snacks and maize-millet based RTE products using twin screw extruder performed by Ding *et al.* (2006) and Sahu *et al.* (2022a) indicated that physical and functional qualities of the product significantly depends on process variables and found that the product properties were mostly dependent on barrel temperature and feed moisture. The decrease in density, water absorption index and hardness occurred with the increase in barrel temperature but it had a positive effect on expansion, water solubility index and puncture energy.

Hagenimana *et al.* (2006) used twin screw extruder at a varying range of barrel temperature from 100 to 160°C for the development of extruded products from rice flour-based blends and reported that barrel temperature significantly affected the water absorption index, water solubility index, expansion ratio, bulk density, total colour change, pasting and starch digestibility of extrudates.

Degree of superheating of water increases with the increase in barrel temperature during extrusion, which improves the bubble formation and decreases melt viscosity causing reduced bulk density and increased expansion of products (Lawton *et al.,* 1985; Omohimi*et al*., 2013; Seth *et al.*, 2015). The increase in barrel temperature to certain level also decreases the hardness of the product appreciably.

Water absorption index (WAI) is an indication of degree of gelatinization of starch and increases with temperature. At higher temperature, more disruption of starch molecule occurs and more water is bounded to it, which causes increased WAI (Kumar *et al*., 2010; Seth *et al*., 2015). WSI increased with the increase in barrel temperature. This may be due to degradation of starch molecules with the exposure of product inside the barrel at higher temperature (Sobukola *et al.*, 2013).

**4.2. Feed moisture content**

Feed moisture is an important parameter that directly affects the physical, textural, functional and sensory qualities of extruded snacks. The level of feed moisture has been varied largely in the range of 12% to 24% depending on the type of mixture of ingredients for extrusion cooking (Ding *et al.*, 2006; Pansawat *et al.*, 2008; Chakraborty *et al.*, 2014; Seth *et al.*, 2015; Sahu *et al.*, 2022a). Several studies have concluded that bulk density, hardness, water solubility index and water absorption index of the extruded products increased with the increase in moisture of the blends, whereas expansion ratio and crispness have been reported to be decreased with increasing feed moisture (Chiu *et al.,* 2013; Oke*et al.*, 2013; Sahu *et al.*, 2022a). During extrusion process, increased feed moisture may lead to reduce the dough elasticity through plasticization of the melt, resulting in reduced specific mechanical energy causing decrease in the expansion and increase in extrudate density due to improper or incomplete gelatinization (Ding *et al*., 2006). On the contrary, according to Lawton and Handerson (1972), during extrusion process higher moisture content of the feed reduces the viscosity of starch, allowing the free movement of the starch molecules and thereby enhancing the penetration of heat resulting in complete gelatinization. At lower moisture content of feed, increased shearing action inside the barrel takes place which causes more mechanical damage to starch, resulting into low WAI (Sobukola *et al*., 2013). At lower feed moisture content the drag force at the die increased which increases starch molecules to gelatinize and hence increased water absorption index. An increase in moisture content up to 18% decreases degradation of starch molecules and further increase in moisture content beyond 18% causes easy dissolution of polysaccharides to the food matrix, resulting in increased WSI (Seth *et al*., 2015).

Meng *et al.* (2010) reported higher expansion ratio, low bulk density and hardness properties of extruded product prepared with 16% to18% feed moisture of chickpea flour-based snack. Li *et al.* (2005) explicitly indicated that the increasing moisture content in the range of 21% to 23% significantly decreased specific volume and increased hardness of the extrudate.

**4.3. Screw speed**

Extruder screw speed is an imperative parameter of the extrusion cooking technology that affects specific mechanical energy requirement, torque and feed rate of the machine. Development of shear rate and residence time of feed depends largely on screw speed. With the increase in screw speed percent torque decreases but specific mechanical energy increases. Its effect on the extrudate attributes like, expansion ratio, bulk density and hardness is less prominent compared to other parameters (Nishani *et al*., 2017). The increase in screw speed improves the expansion and decrease the bulk density, which may be due to lower melt viscosity of mix and increased elasticity of dough (Seker, 2005; Ding, *et al.*, 2006; Filli, *et al.*, 2012). Colour value of product had markedly affected by screw speed of extruder while WAI and WSI of products were lesser affected by screw speed (Lo, *et al.*, 1998; Balasubramanian, *et al*., 2012). Omohimi *et al.* (2013) and Sahu *et al.* (2022a) reported the effect of screw speed on expansion ratio and bulk density of extrudates. The results showed that screw speed did not bring appreciable change as compared to barrel temperature and feed moisture. Further, the specific mechanical energy was observed to be mainly affected by screw speed of the extruder and increases with the increase in screw speed. Jin *et al*. (1994) expressed that torque required to rotate the screw is very much related with degree of fill in the extruder barrel.

**4.4. Feed rate**

Feed rate is essentially influencing the quality of extruded products in addition to smooth functioning of the machine. The screw element types, screw speed, feeding element and feed moisture influence the rate of feed in the extruder. The pressure development in the barrel, residence time, torque and dough temperature depend on the rate of feeding. The expansion index and sectional expansion index increase with the increase in feed rate up to certain limit and the further increase in feed rate adversely affects these important attributes (Adekola, 2016). On the other hand, the specific length of the product increases with the increase in feed rate. The feed rate or throughput directly affects the capacity of the machine. However, like other similar machines, its operation is trouble free if operated within the range of rated capacity. Few of the observations made by researchers are; expansion ratio of extrudates depends on its degree of gelatinization which was found to be decreased with the increase of feed rate. WAI and WSI of the products have also been observed to be influenced with the feed rate, lower the feed rate, these indices were lower (Chinnaswamy and Bhattacharya, 1983). Ding *et al*. (2006) reported the combined effect of feed rate with the feed moisture level. Increased feed rate with lower feed moisture increased the hardness of the product significantly and its magnitude was comparatively less with higher feed moisture levels. Balasubramanian *et al.* (2012) reported that the feed rate and screw speed invariably affected the firmness of the product during preparation of millet and soy blended extrudates. The feed rate did affect the hardness of extrudates which increased with the increase in feed rate and the corresponding density was also noted to be higher.

**4.5. Die configuration**

The die of an extruder is a major component of the machine. The shape of the die is determines the shape of the product to be prepared. The die allows rapid expansion puffing of the dough into different shapes and sizes depending on the die configuration. The die section is an important section which is directly related with the performance of the extruder as well as quality of the end product. The pressure drop at the entrance of die is greater for visco-elastic fluid than that of Newtonian fluids of similar viscosity. The pressure drop at the entrance of die increases with the decrease in the ratio of length to diameter of die. This also affects the flow within the die and shear stress during the operation. Therefore, it is important to select a properly designed and developed die (Adekola, 2014). The back pressure is directly proportional to the length to diameter ratio of die. The die diameter directly affects the radial expansion of the extrudate but it is not true for axial and overall expansion of extruded products.

**5. Suitable Ingredients for Extrusion Cooking Technology**

The composition of ingredients plays an important role in the preparation of extruded products and its final quality along with other factors associated with the extrusion process *viz.,* type of extruder, operational parameters, feed conditions etc*.* (Adekola, 2016). Number of studies has been conducted in the past to prepare extruded products with different combination of ingredients successfully. The combination of ingredients used by the researchers are based on many considerations, some of them are; (a) preparation of pre-determined quality products for particular targeted consumers (b) use of available potential raw materials for the production of high value products (c) preparation of nutritionally balanced extruded products (d) preparation of popular extruded products for excessive marketing (e) preparation of extruded products incorporating ingredients having medicinal values etc. Numbers of feed ingredients of food materials are used to form extruded foods. These materials are biopolymers of starch or protein, which varies in their source, age, pre-treatment and eventually cause extensive alteration in the chemical and physical nature of extrudates.

In the preparation of extruded product, presence of starch or the carbohydrates in the participating ingredients form a major component, which consists of two glucose polymers namely amylose and amylopectin and responsible for physico-chemical and functional changes during extrusion cooking. It has the properties of low gelatinization temperature, low retro-gradation tendency, no soil residues, high viscosity, non-cereal flavour, bland taste, high water binding capacity, translucent paste and good stability. Other food commodities containing or rich in protein, fiber, minerals, vitamins *etc.* could be the member of the mixtures or the raw materials used for preparation of extruded products. The ratio and combination of all such ingredients are varied suitably depending upon the requirement of end product or the targeted quality of the product.

Numerous research findings have been reported in the literature on the development of extruded products using variety of raw materials in different combinations (Nishani *et al.,* 2017). Many of them have been adopted successfully and commercialized. Cereal-legume blend based extruded products have been reported by researchers in the past (Chakraborty and Banerjee, 2009; Asare *et al.*, 2012; Sahu *et al.*, 2022a) and commercialized over the period. Cereals are the main component of extruded products suitably fortified with appropriate combination of legumes to mitigate the deficiencies of certain amino acids. In the commercial extruded snacks mostly, cereals are used due to their inherent potential expansion characteristics but at the same time they are low content of protein, fiber and minerals.

Borah *et al.* (2016) used low-amylose rice flour, seeded banana and carambola pomace blends to prepare mineral rich ready-to-eat breakfast cereal through extrusion technology. Ortiz *et al.* (2015) prepared extruded products using different blends of soybean seed and white corn flour, and concluded the amino acid profile in the final extrudate compared satisfactory with the requirement for essential amino acid suggested by FAO/WHO for adults. Deshpande and Poshadri (2011) used foxtail millet, amaranth, rice, bengal gram and cow pea as raw ingredients for the preparation of extruded products with the objective of adding value to the millets to enable their commercialization.

Chickpea, potato and whey protein concentrate were used to develop extruded product by Meng *et al.* (2010). The chickpea and potato contain high proportion of carbohydrate mainly starch which produces expanded products during extrusion. Evaluation of extruded snacks prepared from blends of acha (*Digitariaexilis*) and cowpea (*Vigna unguiculata*) flours with different ratios by Olapade and Aworh (2012). Blends of these two commodities can be successfully extruded to produce high protein-energy complementary foods. Omwamba and Mahungu (2014) carried work to develop protein-rich ready-to-eat extruded snack from a composite blend of rice, sorghum and soybean flour with the objective of improving nutritional value of the products. The prepared product had not only improved nutritional profile but also superior in textural properties. Maize, finger millet, defatted soy and elephant foot yam were combined as composite flour by using D-optimal mixture design to develop protein rich extruded product by Sahu and Patel (2021). The maize and finger millet were responsible for high expansion of the product during extrusion cooking which may be due to high starch content in the composite flour. Ganorkar and Jain (2015) reported that extruded product can be successfully prepared with the incorporation of flaxseed in rice-corn flour to produce nutritionally enriched extruded product with proper selection of other parameters. Table 1 depict that the extruded products developed from raw materials along with their composition made by previous researchers.

Table 1: Raw ingredients and their combination ratio by previous investigators for development of

extruded products

|  |  |  |  |
| --- | --- | --- | --- |
| S. No. | Ingredients | Combination ratio | Researchers |
| 01. | Corn, lentil flour | Lentil/corn ratio (10, 30 & 50%) | Lazou & Krokida, 2011 |
| 02. | Rice,Sorghum,Defatted soy | Rice:sorghum:defatted soy 65:20:15 | Omwamba & Mahungu, 2014 |
| 03. | Maize, Rice, Finger millet, Soybean | Maize: Rice: Finger millet: Soybean 50:20:20:10 | Sawant *et al.,* 2013 |
| 04. | Foxtail millet,Amaranth,Rice, Bengal gram,Cow pea | Foxtail millet: amaranth: rice: Bengal gram: cow pea 60:05:05:20:10 | Deshpande & Poshadri, 2011 |
| 05. | Maize, Finger millet, Defatted soy, Elephant foot yam | Maize 40-55%, Finger millet 20-30%, Defatted soy flour 10-25%, Elephant foot yam 10% | Sahu & Patel, 2021 |
| 06. | Oat flour, Dried green pea flour, Fenugreek seed powder, Fenugreek leave powder | Oat flour 10-50%, Dried green pea flour 5-25%, Fenugreek seed powder 0.5-2.5%, Fenugreek leave powder 0.5-2.5% | Wani & Kumar, 2016 |
| 07. | Acha (cream colour), Cowpea | Acha: cowpea 70:30 and 60:40 | Olapade & Aworh, 2012 |
| 08. | Acha, Soybean flour | Acha: soybean ratio- 100:0, 87.5:12.5, 75:25, 62.5:37.5 and 50:50 | Anuonye *et al.*, 2007 |
| 09. | Defatted soy flour, Rice | Defatted soy: rice 10:90, 14:86, 18:82, 22:78 and 26:74 | Garg & Singh, 2010 |
| 10. | Corn, Millet, Soybean | Corn 44%, Millet 36% and Soybean 20% | Semasaka *et al.,* 2010 |
| 11. | Wheat flour, Defatted soy flour | Wheat flour: Defatted soy  80:20, 90:10 | Zasypkin & Lee, 1998 |
| 12. | Broken rice, rice bran, black soybean okara | Rice flour: Rice bran: Black soybean okara 81:9:10 | Coutinho *et al*., 2013 |
| 13. | Maize and Defatted soy flour | Maize: Defatted soy 90:10, 80:20, 70:30 | Veronica *et al.*, 2006 |
| 14. | Yam, Rice and Corn flour | Yam:Rice: Corn flours ratio 10:40:40, 25:37.5:37.5 and 40:30:30 | Seth *et al.,* 2015 |
| 15. | Brown finger millet, Maize, Rice, Full fat soy, Bengal gram, Skimmed milk powder | Brown finger millet: Maize: Rice: Full fat soy: Bengal gram: Skimmed milk powder 20:50:20:10:0:0, 30:50:10:10:0:0, 40:50:0:10:0:0, 10:50:0:0:20:20, 20:50:0:0:10:20, 30:50:0:0:0:20, 40:50:0:0:0:10 | Sawant *et al.*, 2013 |
| 16. | Soybean, Corn flour | Corn : Soybean 100:0, 79.7:20.3, 50:50, 20.3:79.7, 0:100 | Ortiz *et al.,* 2015 |
| 17. | Rice, Sorghum, Defatted soy flour | Rice: Sorghum: Defatted soy flour 65:20:15 | Omwamba & Mahungu, 2014 |
| 18. | Rice, Beans, Soy, Millet, Salt, Glyceryl monostearate, water | Rice: Beans: Soy: Millet: Salt: Glyceryl monostearate: Water 10:16:16:20:0.5:6:31.5 | Navam *et al*., 2014 |
| 19. | Carrot pomace, rice, Pigeon pea, | Rice: Carrot pomace and Pigeon pea 90:10, 85:15, 80:20, 75:25, 70:30 | Kumar *et al.*, 2010 |
| 20. | Rice, Defatted soy, Garlic powder | Rice- 47.5 to 67.5%, Defatted soy 30%, Garlic powder 0 to 20% | Haritha *et al.*, 2014 |

**6. Effect on Nutritional Quality**

**6.1. Product Moisture**

Product moisture of extruded products varies with the variation in process parameters, feed moisture and ingredient composition. Barrel temperature had significant effect on product moisture of the extruded product. At higher temperature moisture loss increased as it exit the die. This may be due to higher vapour pressure difference between inside the barrel and at the exit of extruder die. Screw speed and feed moisture had positive influence on product moisture. At high speed of screw, holding time for cooking reduced. Increase in moisture content of feed during extrusion causes lowers the dough’s elasticity and viscosity reduced, which retards the gelatinization and product moisture raises (Asare *et al.*, 2010; Sobukola *et al*., 2013; Sahu *et al.*, 2022b).

The extruded snacks (RTE) contain low moisture foods and the variation in moisture content directly influences the textural properties, and subsequently, the less crispy snacks are not acceptable. Crispness of cereal products directly depends on their moisture content or the water activity (Martinez-Navarraete *et al*., 2004). Heidenreich *et al*. (2004) studied the textural parameters of extruded rice crisps which were adjusted to water activities in the range of 0.05 and 0.65 and found that crispness was more influenced when the sample exceeds a critical water activity value >0.5. Final moisture content of the product depends on the feed moisture as well as the extrusion process conditions. The product moisture increases as feed moisture content increases but decreases with increase in barrel temperature and screw speed (Omohimi *et al.*, 2013).The extruded snacks developed with high feed moisture resulted with a higher bulk density, WSI, hardness and lower expansion, WAI, lower puncture energy (Garg and Singh, 2010).

**6.2. Protein**

Protein is very important for growth, body building and repairing maintenance in living beings including humans. Proteins are complex biopolymers that are composed of a series of amino acids which includes twenty-two amino acids. Among these the most essential amino acids are isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine. Digestibility of protein in extruded is higher than without extruded products. This is probably be due to denaturation of proteins and inactivation of antinutritional factors that impair digestion. The nutritional value in vegetable protein is typically increased by mild extrusion conditions, owing to an increase in digestibility (Colonna *et al.*, 1989; Areas, 1992). An advantage of extrusion processing technology is the demolition of antinutritional parts, particularly trypsin inhibitors, haemagglutinins, tannins and phytates, which restrain protein digestibility (Armour *et al.*, 1998). The effect of process variables on protein digestibility very significantly and the findings are summarised in Table 2.

Table 2: Protein digestibility changes with process variables during extrusion cooking

|  |  |  |  |
| --- | --- | --- | --- |
| Processing variable | Protein digestibility | Product | References |
| Barrel temperature | Increased with increase in temperature | Yam starch based pasta, Maize-millet based soy fortified extruded product,  Protein rich products | Sobukola *et al.* (2013); Sahu *et al.* (2022b);  Maurya and Said (2014) |
| Screw speed | Increased with screw speed | Yam starch based pasta,  Corn gluten-whey blend | Sobukola *et al.* (2013);  Camire *et al.* (1990) |
| Feed moisture | Decrease with increase in feed moisture | Mucuna beans extrudate | Omohimi *et al.* (2013); |
| Feed ratio | Increased with increase in protein content | High protein glutinous rice-based snack,  Maize-millet based soy fortified extruded product | Chaiyakul *et al.* (2009);  Sahu *et al.* (2022b) |

Processing variables significantly affected on protein in the extruded product. Proteins are denatured at high temperature during extrusion enabling the improvement in digestibility and retard the antinutritional portion. During extrusion reduction of bitter taste from soy protein occurs which improves the acceptability of the product. It also reduces the undesirable volatile compounds (Maurya and Said, 2014).

**6.3. Carbohydrate**

It is one of the most important nutritional components in the food which is responsible for energy providing to the body. Changes of starch during extrusion cooking are responsible for development of expanded or puffed product. Starch undergoes several significant changes, which include gelatinization, melting and fragmentation. Hardness, crispness, density, expansion ratio and other product parameters are affected by the degree of gelatinization of starch (Lai and Kokini, 1991). According to Qu and Wang (1994) extrusion cooking is one of the important operation in which gelatinization of starch occurs at much lower levels of moisture content (12% -22%). Gelatinization and dispersion of starch granules occurs during extrusion, which results in the formation of a continuous phase of melt inside the extruder (Huber, 2001). During extrusion process, the molecular weight of amylase and amylopectin molecules decreases. The greater molecular weight reduction occurs in corn flour due to its larger amylopectin molecules (Politz *et al.*, 1994). During extrusion, fragmentation of the amylopectin is 10 times greater than that of amylose and hence reducing the molecular weight of amylopectin containing raw material (Colonna *et al*., 1984). Pea and rice blends fortified with guar gum, locust bean gum and fenugreek gum at the level of 5, 10, 15 and 20%, was utilized for production of extruded snacks and studied the effect of extrusion on complex carbohydrates such as galactomannan gums. All these three gums produced good expanded products with lower glycemic index. The mean sensory scores indicated that all the products containing gums up to 15% levels had good expansion and less glycemic index (Ravindran *et al.,* 2011). The barrel temperature and screw speed had positive significant effect on carbohydrate content of snacks whereas feed moisture content had negative effect (Omohimi *et al.,* 2013).

**6.4. Fat**

The fat acts as a lubricating effect and also affects the products quality during extrusion. During extrusion it was chemically affected as oxidation, hydrogenation, isomerization or polymerization (Cheftel, 1986). Inactivation of lipase and lipoxidase occurs during extrusion which guards against oxidation during storage. Many of the extruded snack foods may contain less than 6% lipids, because high levels of lipid produce slippery action and prevents proper pressure and temperature generation during extrusion which prevent puffing or expansion. Thus, small lipid levels (up to 5%) help steady extrusion and improve the texture. Expanded extruded snacks can thus be considered as low calorie foods (Singh *et al.,* 2007). Omohimi *et al.*, (2013) explained the effect of process variables on fat content of extruded snack products developed from Mucuna beans and found that none of the process variables have affected significantly on fat content of extrudates. The increase in fat content of meat analogue extrudates with barrel temperature was due to exposing the internal matrix to thermal energy thus melting of fat and the level of fat increases into the final product.

**6.5. Dietary fiber**

Dietary fiber is the edible portion of the carbohydrates that are resistant to digestion and absorption in human intestine. It includes polysaccharides, lignin, oligosaccharides and associated plant substances. When extrusion was carried out at mild conditions, the fiber content of product affected insignificantly while at severe conditions, major effect was observed on fiber content (Singh *et al.,* 2007). There were no significant changes in crude fiber with feed moisture content, which may be due to a reduction in starch gelatinization at high feed moisture content during extrusion (Sahu *et al.*, 2022b). At more typical conditions, the increasing trends in dietary fiber content were found and mainly owing to increase in soluble dietary fiber and enzyme-resistant starch fraction. Depending on process conditions 50-75% of total fiber was soluble in the extruded product but only 40% fiber was soluble in the raw flour (Bjorck *et al.,* 1984). The soluble type of dietary fiber, increases glycemic control, decreases hyperinsulinemia, and lowers plasma lipid concentrations in patients with type 2 diabetes (Chandalia *et al.*, 2000) and most importantly consumption of dietary fiber had shown to reduce the risk of diseases such as cardiovascular disease, stroke, hypertension, diabetes, obesity, and certain gastrointestinal diseases. Thus, extrusion processed food product with high in dietary fiber content may have potential to act as preventative as well as ameliorative effects on such diseases depending on the consumer health status.

**6.6. Vitamins**

The chemical structure and composition of vitamins vary significantly; their stability during extrusion also varies.The degradation levelof vitamins depends on different parameters during food processing operations and their storage, like moisture, temperature, light, oxygen, time and pH (Singh *et al*., 2007). Increase in barrel temperature from 125°C to 200°C reduces all trans-β-carotene in wheat flour by over 50% (Guzman-Tello and Cheftel, 1990). Cereals constitute an important source of B-vitamins. During extrusion 20% to 40% losses of vitamin C was observed, which may be due to enhanced oxidation at high temperature (Cheftel, 1986). Reduction in the temperature and shear within the extruder protects most vitamins (Killeit, 1994).

**7. Conclusion**

Extrusion processing is a novel technology in food processing which produces a variety of breakfast/snack products with versatility and advantages for the production of eco-friendly, low cost, nutrient rich, energy efficient and convenience ready-to-eat food products.Texturized protein food has been developed and marketed throughout the world by the use of extrusion processing technology. Extrusion processing variables have significantly affected on physical, functional, textural and nutritional qualities of extruded products. These factors are barrel temperature, screw speed, die configuration, L/D ratio, feed moisture content, feed compositions and type of extruder. This variable also minimizes the anti-nutritional factor and increases the starch gelatinization, protein denaturation and digestibility of the final product. Careful operation required to maintain the quality of products. It also helpful for fortification of nutrient in raw ingredients to obtain required nutritional balance end products. There are so many portions required for further research related to extrusion processing and its effect on qualities of product.

**Disclaimer (Artificial intelligence)**

Option 1:

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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