THE IMPACT OF EXTRUSION PROCESS VARIABLES ON THE NUTRITIONAL VALUE AND SENSORY PROPERTIES OF FUNCTIONAL SNACKS

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ABSTRACT

Extrusion is a food manufacturing process in which preconditioned ingredients are fed into an extruder where they undergo different operational units such as mixing, kneading and shaping. Ingredients goes through the tightly fitting screw rotating within the stationary barrel where they are conveyed, mixed and heated. The product exits the extruder through a die where it changes texture and shape by the release of steam & forces. A variety of food extruders are developed as there is a minimum loss of vitamins and other nutrients due to high temperature and short time processing. The aim of this review is to give comprehensive overview of the extrusion process and its evolution in food processing over time and the role of extrusion parameters in changing key product qualities such as color, texture and shape and its potential for future advancements.

KEYWORDS: Extrusion process, Product Quality, Manufacturing operations

INTRODUCTION:

Extruders were developed in 1870's to make sausages while in 1970's single screw extruder were developed to mix semolina flour with water to make pasta. In 1940's and 1950's evolution occurs, and twin-screw extruders were introduced. Three major types of extruders are being used Pistor, Roller and screw extruders. Among them screw extruders gained attention in food industry. (1) Extrusion gained attention in recent years due to its role in the food industry. Extrusion is a process in which different ingredients go through preconditioning and then fed through a hooper into an extruder. There is a barrel in which screws are there to move food through it. There are smaller flights along the barrel which compress the material by restricting its movements. At the end of extruder there is a die, passing through screws and different

operational units. It comes at the end to pass through die of different shape with high pressure or force. To give the product desired shape. Food goes through different processes which can

be mixing, heating & shaping. Food extrusion is a versatile technique used to make simple food stuffs to complex meat analogues. (2)

Extrusion techniques continue to expand through various industries to find out new ideas and drive innovation and development of new processes and new products. In the food industry it's use is in cereal industry where cereals go through kneading, mixing, texturizing and different processes to get the final product or ready to eat products. Products can be made in different ways. Final product can be influenced by various factors either changing the screw speed, temperature, moisture feed or formulation. Extrusion technology is environmentally friendly. In the 1980's it became more prominent after it's use in aqua-feed industry and paper-milling industry. Extrusion high intensity processing due to high mechanical energy inputs makes it cost effective in comparison to other processes. (3)

Fig 1 (4)

Classification of Extrusion Technique:

Extrusion is further categorized based on its processing and parameters to make products of desired shape, texture and quality. All extrusion techniques, no matter what the parameters are, work on the same principle which is combination of mechanical shear, pressure and temperature. In which material is fed through hooper into extruder and preconditioned ingredients go through many operational units includes mixing, kneading and shaping and reach the die to leave extruder with desired shape. Based on method of operation and construction, it has different categories. (5)

Hot Melt Extrusion It is basically an extrusion technique in which the temperature is above 100°C. At specific temperature and pressure, the material is converted into molten material. High temperature is applied for smooth flow of the product. The hot melt extrusion method basically originated in mid-19th century for making of plastic bags and sheets and other products in plastic industry. (6) It can be used in plastic, rubber and food industry. It produces modified and sustainable food products. It is cost effective and reduces capital investments.(7)

Cold extrusion is basically when temperature is kept below 100°C. Cold extrusion breaks the secondary bonds with low temperature and specific screw speed improving functional properties of products. It allows products to retain their original qualities. (8) Cold extrusion is also used in metal industries. It is produced in several stages. At temperature below 100°C it is passed through extruder at high pressure maintaining color, flavor and originality of the products. (9)

Supercritical extrusion is a process in which CO2 is in its supercritical state means it is heated above its critical temperature 31°C and pressure 73.8rtm is combined with extrusion process to produce food products with better expansion and flavor and improved texture of final product. (10) Technology using supercritical CO2 does not have any drawbacks because it is neutral for environment as it is toxin or pollution free. (11) It is a hybrid technique using SCCO2 with low temperature and shear does maintaining originality of product with minimal loss of nutrients. (12)

3D-printing Extrusion is the extrusion process in which 3D products are formed. It can be personalized, flexibility in design and minimum waste. While layers by layers materials are settled causing less human interaction. In food 3D extrusion the food ink is injected into extruder and extruder forces the ink in nozzle and nozzle make specific paths. (13)

Based on screw there are two types of single screw and twin-screw extruders. Both are used in many industries like food processing, pharmaceuticals and many more.

Single screw extruder is a type of extruder which uses single screw, and it works well with food materials which are less complex like pasta. Its design is simple and basic. With each rotational speed changes in intensity, temperature and pressure occurs. (14) Twin screw extruder have two screws instead of one. It is used for food products which are complex like functional snacks. It has greatly modified screw profiles. (15)

Extrusion	Food products

Cold Extrusion	Pasta, Fruit and vegetable pastes
Hot Extrusion	RTE cereals & snacks
SC-CO2 Extrusion	Baked goods, functional foods formulation
Single Screw Extruder	Snacks, bread, noodles
Twin Screw Extruder	Meat Analogues and products with high components

Process:

Extrusion allows manufacturing food products. Raw materials are fed through hooper, and it goes into extruder where there is a rotating screw fixed in a barrel. There are small flights as screws rotate and help material to pass by. These flights compress the material and restrict the movement. Food goes through different processes mixing, kneading, texturizing and shaping and reaches the end of diet with high temperature, pressure and force. Dies come in different shapes and when product leaves die releasing all the steam the product gets into desired shape. Raw material qualities and extruder operational circumstances are important as well as diet diameter, pressure, and temperature. (16)

Food goes through three sections Feed section, Metering section and Compression section. (17) • In Feed section raw material is introduced and process starts

- In Compression or Transition section food processing processes starts like mixing, kneading and shear is provided
- In the Metering section pressure is applied refining the product until it reaches the die.

Equipment's:

Food goes through different processes and operational units in extruder which are required for production of desired food product. These equipment's are mentioned below (18)

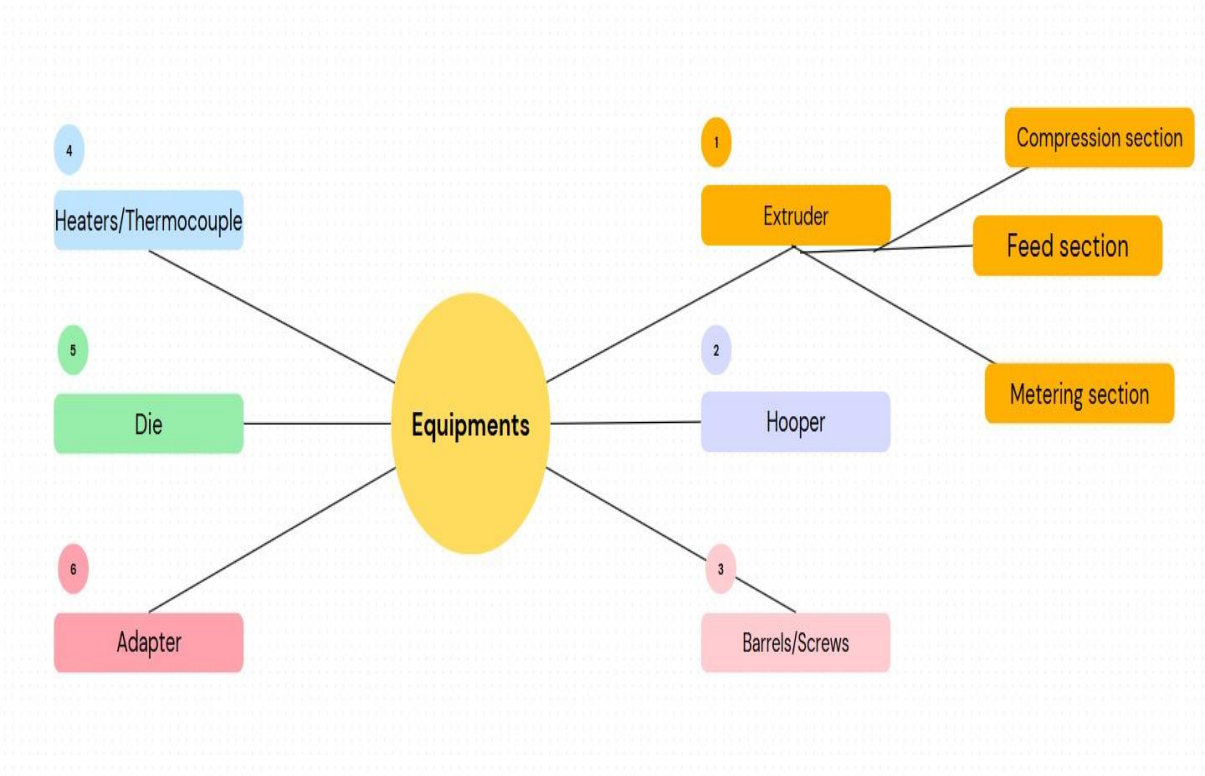

Fig 1(19)

Overview of Literature

Study	**Objective**	**Methodology**	**Findings**	**Reference**
Extrusion as a tool to enhance the nutritional and bioactive potential of cereal and legume byproducts (2023)	To improve nutritional and bioactive properties of cereal and legume by products by optimizing extrusion parameter	Literature review. Data was collected from online databases google scholar and Scopus	Improved antioxidant activity Protein digestibility Antinutrient elimination Increased bioavailability of bioactive compounds	(21)

Use of orange juice processing waste to produce films using blown film extrusion for food packaging (2024)	The objective was to see potential of orange peel a byproduct in making of LLDPE films using blown film extrusion.	Experimental study was conducted. Twin screw extruder was used. Orange peel powder was prepared by freeze drying and milling.	OP films can be successfully made. More OP material can be incorporated to reduce byproducts. Other optimizing processes can be used for improved mechanical properties.	(22)
Second-generation snacks prepared from quinoa with probiotic. Physicochemical properties, *in vitro* digestibility, antioxidant activity and consumer acceptability (2024)	The objective was to produce rice-based snack with high protein content to replace unhealthy snacks in market.	Experimental study was conducted. Twin screw extruder was used. Quinoa and BC30 were obtained commercially.	Expansion & amylose increased while bulk density decreases with addition of quinoa Different formulations were prepared one with 30% HPQF was highly acceptable.	(23)
Legume Flour or Bran: Sustainable, Fiber-Rich Ingredients for Extruded Snacks? (2020)	To investigate the impact of legume flour and bran on sensory and textural properties of extruded snacks. To produce co extruded snacks from chickpea, green pea and rice.	Experimental study design was conducted employing twin-screw extruder. Seven formulations were tested. Hedonic scale was used to perform sensory analysis	High fiber with mild crumbliness and flavor was observed in snacks. Sensory attributes were acceptable.	(24)

Impact of tomato pomace powder added to extruded snacks on the *in vitro* gastrointestinal behaviour and stability of bioactive compounds (2022)	To investigate physical, textural, sensory properties and in vitro absorption or digestibility.	Experimental study was designed. Co-rotating twin extruder was used. TPP and cereal mix blend was produced. Cereal mix (corn starch & semolina, wheat semolina)	Phenolics and carotenoids levels increased Acceptable physical and sensory properties making tomato pineapple pomace a functional ingredient TPP enhanced snacks increased bio accessibility.	(25)
3G extruded snacks enriched with catechin for high antioxidant capacity (2024)	To investigate how temperature and moisture content affects extruded snacks enriched with catechins on physical characteristics.	Experimental study was conducted. Co rotating twin screw extruder was used. Rice flour, distilled water and catechins were added in formulation.	Lower moisture, higher temperature & catechin led to higher expansion Catechin improved textural properties (crispiness) Higher antioxidant capacity was observed.	(26)
Physical and Paste Properties Comparison of Four Snacks Produced by High Protein Quinoa Flour Extrusion Cooking (2022)	To investigate effect of hyper protein quinoa with 27% moisture content on physical, textural and pasting properties.	Experimental study using single screw extruder. The four-formulation composed of corn, rice, quinoa flour and cornstarch.	Increased protein content. Higher hardness and lower fracturability Change of color and decrease of viscosity	(27)

Effect of the Addition of Soybean Residue (Okara) on the Physicochemical, Tribological, Instrumental, and Sensory Texture Properties of Extruded Snacks	The objective was to enhance physical & textural properties of extruded snack added with soybean residue.	Experimental study was conducted & co rotating twin screw extruder was used. Eleven formulations with added okara, bean & rice flour together with corn grit & calcium carbonate.	Extruded snacks with good nutritional properties (high fiber & high protein) and desirable sensory qualities (optimized color, expansion & bulk density) were produced.	(28)
(2022)				
Composition, bioactive constituents and glycaemic index of brown ricewatermelon seeds extruded snacks as stimulated by extrusion conditions (2023)	The objective was to develop rice-watermelon seeds extruded snacks. Examining effects of extrusion conditions on glycemic index, composition & bioactive constituents.	Experimental study design. Co-rotating twin-screw extruder was used. Glycemic index measured using RSM. Five samples with watermelon seeds & brown rice flour blends were prepared.	Protein content, fat content, ash content, crude fiber & carbohydrate content increased. Total phenolic & flavonoid, DPPH increased. Glycemic index reduced.	(29)

Use of insects and pea powder as alternative protein and mineral sources in extruded snacks (2020)	The aim of study was to evaluate physicochemical & nutritional properties the extruded snacks enriched with *Alphitobius diaperinus*, *Tenebrio molitor*, and pea protein powder	Experimental study design. Single screw extruder was used. Formulations enriched with corn grit, pea protein powder & insects' powder.	Ingredients are practical alternatives in extrudate formulation. Improved nutritional qualities.	(30)
Extruded Corn Snacks with Cricket Powder: Impact on Physical Parameters and Consumer Acceptance (2022)	Objective was to investigate effect of CP powder on extruded corn snacks physical & sensory properties.	Experimental study design. Single screw extruders were used. Formulations were produced enriched with corn grit, baking powder & CP powder.	Sensory qualities were improved including color making it brighter. Decrease in expansion ratio, water absorption index and an increase	(31)

			in water solubility index.	

Planning an experimental technology of expanded snacks (2014)	The aim of study was to produce nut added snacks with added by products of high nutritional value. To develop collagen containing food additive.	Experimental study design was performed using single screw extruder fed with CO2. Four formulations containing starch, nuts, pulse, cereal flour & CO2 extracts of spices. Added by products of poultry, sub-cheese whey & chitosan.	CO2 injection improved product quality & reduced processing time.	(32)
Second-generation snacks with high nutritional and antioxidant value produced by an optimized extrusion process from corn/common bean flours mixtures (2020)	The aim of study was to develop optimized expanded snacks by optimization of extrusion variables and corn-common bean flours mixture.	Experimental study design. Twin screw extruder & RSM was used. Four formulations were produced using corn flour & common bean flour.	Increased mineral content, expansion & antioxidant activity. Functional foods are healthy alternative to unhealthy foods in market.	(33)
Nutritional and bioactive components of rice-chickpea based snacks as affected by severe and mild extrusion cooking	The goal of this research was to develop rice-chickpea based snacks and compare effects of severe & mild extrusion cooking.	Experimental study design. Single screw extruder was used. Four formulations were developed.	Mild extrusion conditions are better than extreme extrusion conditions to produce nutritional snacks.	(34)

(2022)			Phenolic & flavonoid content and antioxidant activity was increased.	
Extrusion of a CurcuminoidEnriched Oat FiberCorn-Based Snack Product (2019)	The purpose of the study was to develop extruded snacks fortified with oat fiber-corn flour & curcuminoid and the effect of screw speed & moisture feed on snack.	Experimental study design. Co rotating twin screwier was used. Two formulations one with & without curcuminoid were produced.	21% moisture content was favorable for density & expansion. No negative effect of screw speed on extrudate.	(35)
The Effects of Fortification of Legumes and Extrusion on the Protein Digestibility of Wheat Based Snack (2016)	Research focus is to investigate the effects of adding legumes to wheat-based snacks.	Experimental study design. Single screw extruder was used. Thirteen formulations were developed. Legumes (lentil, chickpea, yellow pea & green pea) are added at different levels.	Increase in protein content & digestibility. Decrease in fat and moisture content. Legume has greater potential to be used as an ingredient on commercial level.	(36)

Development of an Expanded Snack of Rice Starch Enriched with Amaranth by Extrusion Process (2019)	The purpose of the study was to develop extruded snack from by-product of rice milling enriched with amaranth.	Experimental study design. Single screw extruder was used. More than ten formulations were made with varied amounts of flour.	At higher starch and amaranth ratio gelatinization and expansion ratio increased.	(37)
		Native starch, modified starch & amaranth were added.		
Recent Progress on Improving the Quality of BranEnriched Extruded Snacks (2021)	The aim of study was to review literature on compositional characteristics of bran and its effect on snacks produced by extrusion.	Comprehensive review on the quality of extruded snacks and effect of bran on sensory and physical properties.	Based on literature it is desirable to incorporate bran to enhance nutritional value of extruded snack.	(38)
Protein blends and extrusion processing to improve the nutritional quality of plant proteins (2023)	The purpose of the study was to improve protein profile by blending plant protein with other protein sources by extrusion.	Experimental study design. Twin screw extruder was used. Different formulations were developed. Protein blends were produced with pea, quinoa, bean & oats.	Increased protein digestibility Reducing trypsin inhibitor activity.	(39)

Development of Cellular High-Protein Foods: Third-Generation Yellow Pea and Red Lentil Puffed Snacks (2021)	The objective of study was to investigate how extrusion & microwave processing effects extruded snack's physical & thermal properties.	Experimental study design. Yellow pea & red lentils extrudate was developed using co-rotating twin screw extruder.	Microwave heating accompanied partial or mild extrusion cooking can give best results. MH enhances thermal and physical characteristics of food product.	(40)

Pulse-based snacks as functional foods: Processing challenges and biological potential (2021)	The objective of study was to review literature on incorporation of pulses in extruded food products and their potential outcome.	Comprehensive literature review on pulse-based snacks. Sensory acceptance of pulse-based snacks What different methodologies and experiments were conducted	Pulse based snacks are good alternative in food industry due to their high nutritional profile, low cost and sensory characteristics.	(41)
Optimum extrusioncooking conditions for improving physical properties of fish-cereal based snacks by response surface methodology (2014)	Purpose of study was to investigate effect of different extrusion parameters and fish feed content on expansion & bulk density.	Experimental study design. co-rotating twin-screw extruder was used. Five formulations were developed RCS was used to find out the effect	Successful production was seen with temperature 110 degree Celsius, screw speed 480 rpm, moisture 18% & fish flour 20%.	(42)

Investigation on mild extrusion cooking for development of snacks using rice and chickpea flour blends (2021)	The purpose of study was to use mild extrusion parameters to develop snacks by using extrusion technique.	Experimental study design. Twin screw extruder was used. Screw speed, temperature, moisture feed and proportions used were independent variables.	The optimum conditions such as 102 °C barrel temperature and 281 rpm were considered best. Products can be stored in laminated pouches.	(43)
Novel fibre-rich lentil flours as snack-type functional foods: an extrusion cooking	The aim of the study was to investigate the impact of extrusion on bioactive compounds in lentil flours.	Experimental study design. Twin screw extruders were used.	Reduction in phytates and protease inhibitors was observed.	(44)
effect on bioactive compounds (2015)	To provide consumers with gluten free lentils.		Increase in levels of alpha galactosidase was observed. Extruded lentil flours snacks are functional snacks.	
Third generation snacks manufactured from orange byproducts: physicochemical and nutritional characterization (2015)	The objective of study was to evaluate effect of temperature & moisture content on physical & nutritional properties of extruded snacks.	Experimental study design. Single screw extruder was used. Formulations were developed. (Orange vesical flour, potato starch,	Temperature (128-130 °C) affected expansion & bulk density Carotenoids were affected by moisture content (22-24%)	(45)

		nixtamalized corn flour& monoglycerides)		
Development of multigrain ready-toeat extruded snack and process parameter optimization using response surface methodology (2023)	The main purpose of the study was to develop RTE extruded snacks.	Experimental study design. Formulations were developed by using rice, corn, pearl millet, green gram & cowpea bean. Different extrusion parameters were kept as a variable	Acceptable physicochemical properties and sensory qualities were found to be acceptable. 120 °C temp and 350rpm screw speed were the best ranges with green gram & cowpea combination.	(46)
Nutritional characterization of the extrusion-processed micronutrientfortified corn snacks	The study focused on developing extruded snacks enriched with fiber, protein & micronutrients.	Experimental study design. Single screw extruder was used. Formulations were developed using corn,	Increased protein & dietary fiber. Corn snacks showed high content of calcium, magnesium, potassium & iron.	(47)
enriched with protein and dietary fibre (2022)		soybean & chickpea flour with fortification of iron, zinc, vitamin A & C.	Amino acids decreased.	
Sulfur compounds reduce potato toxins during extrusion cooking (2011)	The aims of study were to add sulfur-containing compounds before extrusion to reduce toxins such as glycoalkaloids.	Experimental study design. Single screw extruder was used. HPLC & colorimetric were used.	Reduction in glycoalkaloids. Reduced carboxypeptidase inhibiters.	(48)

Anthocyanins and Functional Compounds Change in a Third-Generation Snacks Prepared Using Extruded Blue Maize, Black Bean, and Chard: An Optimization (2021)	The objective of study was to investigate the effect of extrusion cooking on bioactive compounds and microwave expansion by using specific formulation.	Experimental study design. Twin screw extruder was used. Formulations were developed by using black bean, blue maize & chard.	Combining extrusion and microwave expansion increases withholding of bioactive compounds thus offering benefits for human health.	(49)
Antioxidant potential and quality characteristics of vegetable-enriched corn-based extruded snacks (2015)	The purpose of this study was to examine nutritional and sensory properties of extruded snacks.	Experimental study design. A co-rotating twin screw extruder was used. Formulation used corn flour, broccoli flour & olive paste.	Phenolic content and antioxidant activity increases. Appropriate processing and careful handling required for good sensory properties.	(50)
The impact of extrusion on the nutritional composition, dietary fibre and in vitro digestibility of gluten-free snacks based on rice, pea and carob flour blends (2017)	The objective was to develop high nutritional value extruded snacks with different blends.	Experimental study design. Formulations were developed using rice, pea & carob flour blends.	Soluble protein, resistant starch & fat was decreased Increased protein digestibility High fiber content in extruded snacks.	(51)

Texture, sensory properties and functionality of extruded snacks from pulses and pseudocereal proteins (2022)	The purpose of this study was to examine how low extrusion cooking affect different characteristics of final product.	Experimental study design. Protein extract from peas individually or in combination with protein rich flours were examined.	Textural and sensory qualities were acceptable. Protein content increased Hardness and density increased Smaller sectional expansion.	(52)

Impact of Extrusion Parameters

There are various extruder parameters Moisture, feed flow rate, formulation, screw speed and barrel pressure. Among which temperature and feed formulation are considered the most important parameters which affect the quality and other properties of final product. Low moisture causes extrudate expansion. Optimized control of all these parameters lead to successful production of desired product. In an experiment soluble fiber increased when parameters were high in temperature, low in moisture content and screw speed. In extrusion process, product expansion describes product quality. (53) **Temperature:**

Temperature is an important parameter of extrusion process. Its optimization is important in terms of uniform properties of final product but for that consistent temperature should be maintained throughout the process. Temperature effects the final mechanical properties of extrudate. High temperature improves the flow. While low temperature increases the viscosity. Temperature range should be based on various factors including raw material. (54) In 2015, a study was conducted to see if cereal bran loses the antinutritional components in extrusion and they kept temperature as a variable. High temperature eliminates the anti-nutritional components. Reduction of anti-nutritional components was observed. Oxalate, phytins, trypsin inhibitor reduces with temperature range 140 °C. Bulk density and darkness of color increased with the increase in temperature.(55)

Experiment was performed on cassava flour. In which temperature and screw feed were variables and it was observed that increase in temperature increases the expansion of extrudate.

Decrease in temperature also decreases molecular degradation of amylose and amylopectin.(56) Temperature needs to be optimized as overcooked extrudate can be recognized by browning and more browning leads to more loss of lysine which in turn decreases protein digestibility. Feed rate should be managed along with temperature as increase in feed rate decreases the transfer of heating leasing to minimum loss. (57) When temperature of melted ingredients in extrusion process is low it increases the die swell. Which increases the materials' resistance to flow towards die causes spring back once as it exits the die. Leading to expansion of product. While higher product reduces die swell offering control over shape and size of extrudate. (58)

Screw Speed:

There are two types of screw in extrusion process. Single screw extruder and twin-screw extruder. Both are used in the food industry but for different types of materials as both have different structures.

Single screw extruder is used to make pasta, noodles and other food products. It is low in cost and has an easy structure. Viscosity and density of extrudate increase with the increase in screw speed and use of single screw extruder. Viscosity is the resistance to flow which eases in mixing and other food processes while density is the texture of product basically. It showed good effects on dairy proteins specifically expansion and has mixed effect on shear strength and expansion. While twin screw extruder is used for different food products and have more complexed structures. It increases yellowness, expansion ratio, gelatinization of starch and firmness. It increases cooking time but decreases cooking loss. In almond oil experiment lowest loss of oil was observed at highest screw speed. Twin screw extruder gives product good structure. (59) Melt pressure is directly proportional to screw speed so when screw speed increases melt pressure automatically increases. High screw speed means energy loss will be low while energy efficiency, product stability and production rate will be high. So, screw speed is an important parameter and should be kept as high as possible. (60)

Experiment was conducted on rice by using twin screw extruder. A positive relation between speed of extruder and expansion was observed while it was negatively linked with the bulk density and viscoelastic properties. Hardness of product was reduced with increase in screw speed. Viscoelastic properties means that product will be less stable with the increase of screw speed shear forces increases. As stated, earlier optimization of screw speed is important to maintain the final product quality. (61)

Moisture Feed:

Moisture feed is an important factor which affects physical properties, viscosity, expansion and texture. It maintains the homogeneity of the material. During maize grit extrusion, a decrease in expansion rate was observed. Thinner cells lead to more water absorption, so moisture feed decreases water hydration. Water hydration is basically how much water is absorbed by material. Hardness and expansion have an inverse relationship so with the increase in hardness expansion decreases. Moisture feed increases the hardness. (62)

High moisture feed decreases the rate of protein degradation and decreases the viscosity. The study conducted concluded that formulation with lower moisture feed can be used to develop food products from lentils with high protein, digestibility and viscosity. (63) A study conducted in which starch-lipid complexes were made and effect of feed moisture was observed. By optimizing feed moisture successful complexes were made with increasing digestibility. Feed moisture depolymerized and denatured protein increasing its digestibility. Increasing feed moisture content will increase hydrophobicity thus increasing protein flexibility which will produce desirable properties in final product such as emulsion and foaming properties.(64)

Pressure

Pressure is one of the extrusion parameters. Increase in pressure, decrease in extrusion frequency or the number of extrusions to reach constant flow rate. Higher pressure reduces the material resistance to flow making it easier for material to pass through die. Vesicle size decreases and pore size increases with the increase of pressure.(65) Pressure controls the breakdown of the product thus giving it more refined structure. Pressure gives material more stable mechanical properties and increasing strength. Pressure gives material a texture increasing pressure can lead to hardening because of deforming.(66)

Food components

Extrusion cooking is a multi-functional process affecting nutritional and non-nutritional components such as carbohydrates, proteins, amino acids, fiber and other nutrients.

Protein

Extrusion cooking increase digestibility of protein by denaturing protein and inactivating anti nutritional factors. Temperature and moisture feed significantly affects protein. Higher temperature increases digestibility of protein by increasing protein availability. Extrusion

improves nutritional value. Low temperature doesn't break protein structure as evidenced by extrusion experiment on pea. Changes amino acids availability but not protein content. (67) Protein may aggregate at high temperature, or it is denatured while high moisture content decreases the degree of denaturation. Thus, decreasing protein aggregation.(68)

Carbohydrates

During extrusion process sugars breakdown into glucose and fructose which can further participate in Maillard reaction thus enhancing sensory qualities by enhancing flavor and color. Sugar undergoes Maillard reaction to enhance nutrition and sensory qualities of extrudate. (69) Carbohydrate have role in crispiness and expansion of the final product. They undergo gelatinization thus increasing the expansion without compromising the quality of final food product. (70)

A study conducted in which analog rice was taken as a sample, and it was observed that the highest carbohydrate makes it a staple food. The higher temperature will increase the carbohydrate as it increases amylase and amylopectin molecules.(71)

Starch

Starch plays a key role in cooking and gel formation. Extrusion gelatinizes starch increasing its digestibility. Shear and temperature enhance starch breakdown into glucose and dextrin which can be used in syrups. Overall affecting product nutritional quality. Extrusion minimizes lipid oxidation. Extruded products have more digestibility. (72) Starch content is decreased in peas by extrusion but increase in starch content was observed in lentils and chickpeas. During extrusion increase in starch content and digestibility was observed due to cell disruption and conversion of complex carbohydrates into reducing sugars.(73)

Fiber

Vitamins

Extrusion process may cause decrease in vitamins as some vitamins are sensitive to heat while some as D and K being more stable. After extrusion specific amounts of vitamins can be added to compensate for losses during extrusion process. Vitamin A and E are least stable. Its digestibility increases after passing through extrusion. An experiment was performed on rats. (77) Vitamins are sensitive to heat, so various factors decide its stability. But Vitamin B, C, folate, A and E are heating sensitive so careful handling is required. Due to sensitivity of Vitamin A,E and C their shelf life isn't long for extruded food storage.(78)

Type of process, time of process, temperature of process, storage and product composition are the factors which decide vitamin status of food. Ascorbic acid and folate being the most sensitive. It is reported that if parameters are not optimized it can lead to loss of vitamins. It can be altered by various processes including thermal processing. It also depends on quantity and bioavailability of that specific vitamins. (79)

Minerals

Extrusion has some positive effects on minerals as it increases mineral absorption while there is no loss in minerals as they are heat stable. It may increase iron content and decrease inhibitors like phytate. Increase digestibility was observed with retention of folate. (80) A study was conducted in which extruded porridge was made. Key findings were calcium, magnesium, iron and zinc digestibility increased as iron-mineral chelating effect decreased. Citric acid enhance magnesium solubility by reducing its interaction with mineral inhibitors.(81)

A study was conducted in vivo, in which an extruded pea diet was fed to rats. Increase in calcium, magnesium, iron, copper and phosphorus was observed. When compared to raw material, an increase in phytic acid was observed. Extrusion reduces the lectin activity in legumes. Extrusion increase the absorption of all minerals.(82)

The purpose of review was to investigate the role of extrusion parameters in affecting the sensory quality and physicochemical properties of extruded snacks. Based on study it was concluded that extrusion has potential to produce snacks with high nutritional profile and higher consumer acceptance.

Nutritional quality

Findings suggest that with the use of optimized extrusion techniques nutritional quality of final food product increased. In 2023, Nadia dodge conducted a study in which it was concluded that optimized extruded conditions increase protein digestibility and decrease ANF's. (39) This aligns with the study conducted in 2015 by G I Bisharat who concluded that by using optimum extrusion technique and correct blend formulation phenolic content and antioxidant activity & protein increased. (50)

In 2019 W Leonard conducted a study by producing snacks from food processing by products. This approach leads to environment friendly and cost-effective snacks making them accessible to a wider population. (77) This study aligns with the experimental study

conducted in 2022 in which tomato pomace was used leads to increase in phenolics & carotenoids content. (24)

Sensory properties

The impact of extrusion on sensory properties was also investigated. Concluding that with the increase in temperature crispiness increases and texture of extruded snacks was acceptable increasing consumer acceptance rate. Color changes also occurred.

A study was conducted in 2020 which concluded that mild crumbliness and flavor was observed and sensory qualities were acceptable. (24) This study aligns with the results of study conducted in 2022 in which tomato pomace was used results concluded that sensory qualities were acceptable. (25).

Economic & environmental considerations

A worth mentioning area is that sustainability of extruded products. By products were used to produce extruded food products reducing food waste and economically feasible. It not only increases fiber & antioxidant content but also acceptable in terms of sensory properties. Experiment was conducted by Eva Almenar in 2024 to use orange juice byproduct to produce LLDPE films. (22) This study aligned with the experimental study conducted in 2022 by Merve Tomas to use tomato pomace for snack production increases phenolic and carotenoids content. (25)

Limitations and future directions

Despite promising results of use of optimized extrusion conditions still there were limitations to study reviewed. As there is in vitro study on how access nutritional bioavailability. But still there is lack on data available and longitudinal studies to investigate long term effect of extruded snacks on human health. Other processing techniques along with extrusion should be developed to reduce vitamin loss as Vitamin A, B, C & E are heat sensitive.

Conclusion

Extrusion is a versatile technique in the food industry that is used to produce food extrudate by passing it through extruder under different operational units and processes. Wide range of food products can be produced from inexpensive raw material with minimum processing time. Food products can be of high quality, high throughput & low cost. This paper provides insights on how various byproducts can be used for processing which can be environment friendly, economic rounder as reducing byproducts & of high nutritional value. What various extrusion

parameters and feed formulation influence the sensory & physicochemical properties of final product. Future research should be more focused on using byproducts and further investigating effects of different parameters on textural & nutritional quality of product. Extrusion technology holds potential for becoming the most effective food processing technique in the future.

Conflict of Interest:

All the authors have no conflict of interest.

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