Advances in Food Extrusion technology

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Abstract

Extrusion is a versatile technique that may provide a wide range of food products and ingredients, expanding production prospects. Additionally, it might offer affordable, wholesome foods that are sustainable, safe, and tailored to the specific needs of each consumer. Extruded snacks are becoming increasingly popular among all age groups. With the increment in market demand for novel and nutritional food products, advancement in this technique is needed. Extruder modification for commercial use in the food processing industry has made major strides. Some of the novel advancements include extrusion assisted by supercritical fluid, extrusion-based 3-D printing and hot-melt extrusion. Hot-melt extrusion is used to produce food that is widely used in meat substitutes, cheese, cocoa, and other products. Extrusion assisted by supercritical fluids is utilized to create nutrient-rich, heat-sensitive goods. The latest development in extrusion technology is 3-D printing, and the commercialization of both products and technology is bright for new extrusion technologies.

Keywords: Extrusion, Hot melt extrusion, 3-D printing, Supercritical fluid extrusion

Introduction

Significant rises in lifestyle diseases have prompted consumers to investigate new food consumption guidelines. Food quality and safety concerns prompted the development of a brand-new food industry with premium, innovative foods. Now adays want food to be accessible, secure, sanitary, nutritious, tasty, and visually beautiful. Using extrusion techniques, it is possible to create a wide range of food products with minimal processing costs, continuous production, high throughputs, and higher product quality while maximizing energy efficiency (Grasso, 2020).

The process of extrusion cooking involves forcing a material to flow through a shaped hole (die) under different conditions to produce a variety of products. This technique has been used for more than 50 years. Food extruders are currently used as high temperature-short time bioreactors that transform raw materials into modified intermediate and completed products, as opposed to earlier uses that were limited to mixing and creating macaroni and ready-to-eat cereal pellets (Alam *et al.,* 2015). Extrusion alters the final product by caramelizing, mixing, cooking, heat and mass transfer, plasticizing, shearing, kneading, shaping and forming (Yu, 2011). Extrusion cooking is preferred over traditional cooking/processing methods due to its versatility, high productivity, low operating costs, energy efficiency, and shorter cooking times. It also produces a variety of products with distinct textural advantages, such as expansion, crispiness, and general mouthfeel (Brennan *et al.,* 2011).

In order to create food items effectively and sustainably with desirable functional qualities, extrusion machinery has undergone a number of modifications and changes (Prabha *et al.,* 2021). Some of these include hot melt extrusion, supercritical fluid extraction, and extrusion-based 3D food printing. Another use of extrusion technology that is receiving a lot of attention is the creation of environmentally friendly, biodegradable packaging materials utilizing biopolymers.

Principle and process parameters

Extrusion is a process that involves multiple unit activities using a universally applicable operational concept. Compression, combining, shearing, kneading, and high-temperature heating are used to transform food ingredients into a molten substance. These molten components are expelled via a small die to produce semi-cooked or completely cooked food items with the least degree of nutritional loss (Fellows 2009). In the extrusion process, the feed hopper is used to feed raw materials into the extruder barrel, and the screw is used to deliver the food as well. Smaller flights inside the barrel limit food volume, which improves compression. Food is placed into the barrel and the crevices between the screw flights, which causes compression. As you move down the barrel, a semisolid, plasticized substance forms. Due to the frictional and electric heat in this area, the temperature increases quickly. Food is subjected to increasing pressure and shearing once it reaches the area of the barrel with the smallest flights. At the discharge end of the barrel, one or more limited apertures (dies) are eventually pushed open when the food exits under pressure from the die. Rapidly, the finished product cools down as the moisture flashes off along with the expansion of the final product. By altering the die, it is possible to make a variety of forms, including rods, spheres, doughnuts, tubes, strips, and shells. (Rizvi *et al.,* 1995).

Characteristics and quality attributes of extrusion

i. Expansion

Crispiness, an organoleptic quality of puffed extruded products, its relationship to starch and protein interaction (moisture 14–20%, temperature 120–160 °C) is quite significant. The amount of feed moisture, barrel temperature, and screw rotation speed may all be changed to achieve the required level of extrudate expansion. As feed moisture increases, extrudate expansion ratios decrease and vice versa. Most starch, along with proteins, fats, and other substances, has an impact on melt behavior and expansion. A decrease in expansion could be caused by the addition of protein, and the protein to starch ratio is also significant in changing extrudate expansion.

Expansion can be described as a collection of several physical phenomena that take place quickly, such as bubble nucleation and growth, coalescence, and final setting. After a final collapse, the melt matrix turns glassy (Moraru and Kokini 2003). More specifically, starch melting produces a viscous fluid that flows through the die, followed by elastic recovery that causes the extrudate to inflate and water flash evaporation that causes bubbles to develop (Kristiawan *et al.*, 2016). The difference in pressure between the matrix's inside and outside is what causes bubbles to develop. The bubble extends in both directions, resulting in the expansion of the extrudate (Moraru and Kokini 2003).

ii. Bulk density

Temperature, moisture and screw rotational speed in fluence the bulk density. Sectional expansion is accelerated and density is reduced when the screw rotates faster. A rise in temperature accelerates the evaporation of moisture. Furthermore, an increment in screw rotational speed results in enhancement of sectional expansion and reduction in density (Tiwari and Jha 2017). In extrudates of rice, wheat, and spelt, for instance, sample plasticization, which occurs as moisture levels rise, forms a protective layer that compresses the sample and raises its density and hardness (Kojić *et al.,* 2022).

iii. Hardness

It is linked to expansion, and less expansion results in denser products; hardness is influenced by the moisture content of the feed, the speed at which the screw rotates, and the temperature; feed rate has varying effects; as feed moisture increases, so does apparent density of extrudates. With increased feed moisture, the apparent density of extrudates increases, demonstrating a strong correlation. A denser, more fracture-resistant product was produced as the moisture content increased (Lazou and Krokida 2010a; Bisharat *et al.,* 2015;). A relative drop in extrusion temperatures results in a reduction in hardness. Extrusion at higher temperatures produces more expanded products that are crispier and expanded along with smmother texture (Bisharat *et al.,* 2015).

iv. Hydration properties

They are based on the water absorption index (WAI) and water solubility index (WSI), and they depend on the particle size and composition of the feed material, the pretreatments used, and process factors. Various factors like raw materials, extrudate expansion and processing conditions affect the WSI and WAI. The hydration properties depend on the size and shape of starch granules. The low moisture extrusion procedure subjects' starch to high temperatures and mechanical shearing. The starch granules undergo partial depolymerization and lose their structural integrity during such a vigorous process, altering their functional qualities (Andriana, 2022).

v. Color

The acceptance of foods by customers is significantly influenced by colour. The color of extruded food products is profoundly affected by the raw ingredients used and extrusion process variables. At high temperatures, lightness or darkness depends on the Maillard process, caramelization, the presence of pigments, and pigment degradation (Leonard *et al.,* 2020). Extruded products were made lighter (L*) by lowering the feed composition and screw rotating speed while increasing the extrusion temperature. Likewise, the increased screw rotational speed causes the value of a* to decrease and the b* value to increase (Andriana, 2022).

vi. Pasting properties

Temperature, feed moisture and mixing blend substantially affect the pasting properties of starch. Screw rotational speed and feed rate have a lesser impact. As they affect viscosity, pasting profiles (viscosity curves) are an effective tool for the quick and frequent assessment of extrudate cooking quality. They are also crucial when choosing novel food processing additives (thickeners, emulsifiers), as they have a significant impact on viscosity (Andriana, 2022).

vii. Thermal properties

DSC thermograms might be used to assess the melt-onset temperature, peak temperature, finish temperature, and transition enthalpy. These thermograms are additionally beneficial for the estimation of process energy demand and energy required to dissolve the hydrogen bonds in biopolymers, which determines the melting point and the degree of starch gelatinization. The investigation of protein denaturation, amylose-lipid complex dissociation, and starch gelatinization is made easier by the presence of two endothermic peaks. Feed rate has an influential effect on glass transition temperature (Andriana, 2022).

viii. Lipid oxidation

Lipids are the key components in several raw materials and have a significant impact on the extrusion process. They can alter the textural properties and stability of extrudates during storage by acting as plasticizers or emulsifiers (Rao and Artz, 1989). Some formulations explicitly include lipids. Both natural and added lipids become liquids during hot extrusion and are then finely disseminated by mixing and shearing. However, they are spread out on the biopolymers if the amount of lipid exceeds a critical point.

Effect of extrusion cooking on different foods

Cereals

The most important source of calories is cereal grains. Cereals are considered a staple food and offer more food energy than any other food category. With the noteworthy exception of oats and maize, which contain significantly higher levels of lipids (7-9%) than the 1-2% in other cereals (FAO, 1999; Riaz, 2010), most cereals have a similar composition that is commonly low and high in protein and carbs, respectively (FAO, 1999; Riaz, 2010). Flaking, puffing, toasting, shredding, or extruding are common methods of cooking and modifying RTE cereals.(Varsha and Pavani, 2016). It is necessary to remove the bran and germ, leaving only the starchy endosperm during the process. When producing high-fiber meals, it can be required to stipulate that bran or other dietary fibres be included as a product requirement. Plant proteins have been mixed with wheat bran, a byproduct of wheat milling, to create enlarged snacks and breakfast cereals with greater nutritional and fibre content (Onipe *et al.*, 2015). Cereals that include a larger percentage of lipids may leak dough within the extruder barrel, rendering them unsuitable for expanded meals (Ilo *et al.*, 2000 and Riaz, 2010).

Pulses and oilseeds

Trypsin and chymotrypsin inhibitors, lectins, saponins, cyanogenic chemicals, and other substances found in legumes have antinutritional effects when consumed. Legume flour incorporation may lead to improvement in nutritional value, physical characteristics, and flavor of the product. Meat analogs and Texturized vegetable proteins can be formed from legume protein concentrate or isolate (Hulse, 2012). The process parameter used to create the texturized meat analogue standardized the barrel temperature (120.12 °C), feed moisture (47%), and screw speed (119.19 rpm). While modifications in screw speed had no impact on the texturized meat analogue, increased feed moisture throughout the process enhanced density, water absorption index, oil absorption index, and swelling power but decreased lateral expansion (Omohimi *et al.*, 2014). Due to the increased barrel temperature, the essential amino acid content of products made from Bambara groundnut and sorghum malt was decreased, although higher feed moisture improved the preservation of important amino acids. (Jiddere and Filli, 2015).

Extruders are being used more frequently in the oilseed industry as a result of innovative designs that broaden their scope of use. When the screw speed (75 rpm), seed input flow rate (19 kg/h), and pressing temperature of 120 °C were maintained at the predetermined settings, the sunflower seed produced the maximum oil output (85%) (Kartika *et al.*, 2007). The oil's acid and iodine levels were unaffected by the working conditions, and less than 13% of the oil was left over.

Fruits and vegetables

In the formulation of extruded products, fruit and vegetable fractions could be incorporated that enhance the nutritional value of the extruded products. fruit powders were incorporated into the extruded snack, which improved the nutritional composition of the snack. The expansion and density of the extrudates were significantly affected by the addition of fruit powder, but the fiber content of the extruded snack was higher than that of the snacks (Potter *et al.,* 2013). The extruded snacks included carrot pomace, and the process parameters were optimized for moisture content (19.92%), screw speed (249.1 rpm), and die temperature (114.3 °C). According to sensory investigation, ready-to-eat expanded products might include up to 11.75% carrot pomace (Kumar *et al.*, 2010). Extrudates made from rice flour, pulse powder, and carrot pomace were manufactured under ideal circumstances, and colour, hardness, microstructure, -carotene, and vitamin C levels were evaluated. The L- and b-values of rice extrudates made from carrot pomace increased with increasing extrusion temperature, but the a-value, crispiness, β-carotene, and vitamin C values decreased (Dar *et al.,* 2014).

Animal products

Extrusion cooking was used to create fish- and meat-based products, and the main process variables that impacted product quality were high barrel temperature, feed moisture, protein and starch concentration, and screw speed (Surasani 2016). Byproducts from the cooking of crabs were used to create a calcium-rich expanded snack. higher calcium content (from 5.1 to 52.4 mg g1) and higher pH (from 6.1 to 8.8) were the results of increasing crab processing by product level (Murphy *et al.,* 2003). The 30% blanched dried lizard fish powder in the extruded fish snack had the highest protein content (28.790.35%), while the lowest protein content (5.810.18%) was found in the control extruded snack. A 10% addition of blanched dry fish powder is the maximum that can be used in an extruded snack item. However, according to Ganesan *et al.* (2017), adding more than 10% of blanched dry fish powder reduced consumer acceptance.

Table 1: Nutritional changes during extrusion cooking

Food component	Process	Changes
Starch	Gelatinization	Deterioration and impact on the product's digestion

Proteins	Denaturation	Decreased protein solubility and improved digestibility and enzymes lose their biological activity following exposure to high temperature and shear
	Texturization	Imitate the structure and texture of meats
Lipids	Cooking	Form amylose-lipid complexes and modifies the physicochemical properties
Mineral	absorption	Phytates and other inhibitory substances, such as condensed tannins, are destroyed
Fiber	Water solubility	Physicochemical and structural changes to insoluble fibre fractions might cause them to be reallocated to soluble fibres.
Vitamins	Thermal treatment	During thermal treatments at 100 °C heat-sensitive vitamins will be lost.

Advancement in food extrusion

Hot melt extrusion

The earliest application of HME was in the plastics industry; later, it was expanded to include the food sector for the production of cereal-based food products. To improve the stability and bioavailability of food and pharmaceuticals, hot-melt extrusion is an effective method for creating solid dispersions by changing their physico-chemical features and thermal and mechanical characteristics. Gelatinize starches, enhance solubility, and denature protein , HME has established itself as a reliable industrial process in the food processing industry. Its widespread use is based on its capacity to increase digestibility, deactivate enzymes, bacteria reduce anti-nutritional factors (Alam *et al.*, 2016). Drugs with molecular dispersions of active biocompounds, polymers, or lipids can be created for targeted drug d elivery using HME, which has a wide range of significant applications in the pharmaceutical sector (Maniruzza man *et al.*, 2012). The essential elements of a basic hot melt extruder are

1 A structure that supports the drive system.

2 An extrusion barrel.

3 A screw that rotates mounted on a screw shaft

4 a die for extrusion that determines the product's shape.

One or two screws moving in the same or opposing directions in a still barrel make up the standard extruder used for HME. The molding of the barrel is done by dividing the scetion to reduce the time of molten materia (Maniruzzaman *et al.*, 2012). The barrel's sectioned pieces are then connected or clamped together, and the materials are formed using the endplate die that links the barrel to the end. Depending on the specifications for the various purposes, the extrudate's shape may take the form of rods, pellets, tablets, etc. Extruders with twin screws are frequently utilized in the hot melt extrusion process. Three zones—a feed zone, a compression zone, and a metering zone—make up a standard twin-screw extruder. Mixing and continuous feeding from the hopper are two tasks performed by the feed zone. The compression zone uses unique screw components including interrupted flights and kneading blocks to try to create more mixing. The majority of the melting, homogenization, and shearing of the extrudate occur in the compression zone, making it a suitable shape for entry into the metering zone. In order to produce food with a consistent composition, the food particle is melted and mixed at a constant temperature in this last zone (Fang *et al.*, 2003). HME has a number of well-known applications, including the ability to improve the solubility of hydrophobic compounds and the ability to microencapsulate medications to conceal their taste (Maniruzzaman *et al.* 2012). Ramirez *et al.* (2020) developed a novel dietary health supplement rich in flavonoids epicatechin, manufactured from cocoa, after discovering the potential of these compounds against the risk of atherosclerosis pathology. Hot-melt extrusion has been demonstrated to be a superior alternative to current technologies including spray drying, cocrystallization, and freeze-drying in terms of target delivery, repeatability, and taste-masking properties. Hot melt products have a very low tendency to recrystallize because of their enhanced thermodynamic stability (Huang *et al.*, 2019). During the hot-melt extrusion procedure, the native crystallites melt and water is dispersed throughout the granules. Alam *et al.* (2019) looked at the functional characteristics of these pellets as a possible source of protein in food, despite the fact that hot melt extruded insect-based pellets are routinely utilised in the pharmaceutical business. The pellets were made using either insect flour alone or insect flour combined with cornflour in this way. A corotating twin-screw extruder with a screw speed of 100 rpm, a water rate of 0.03 kg/h, and a die zone temperature of 70 °C was used to extrude the pellet. The hot-melt extrusion process increased the pellets' solubility, stability, and dispersion characteristics. However, given how the insects were fed, the application of extruded insect pellets for commercial purposes is yet in the future. Ottoboni *et al.* (2017) conducted a similar investigation to ascertain how extrusion affects the digestibility of five blends, comprising H. illucens (HI) larvae or pupae and wheat flour, at a single barrel temperature of 60 °C and a single screw speed of 60 rpm. The production of snacks derived from insect flour utilising HME could be a long-term answer to the world's increasing protein need. Pharmaceuticals, feeds, cheese creams, and meat replacements are a few more applications for HME (Ramirez *et al.*, 2020).

Nutraceutical meals with encapsulated bioactive ingredients have been produced using the hot-melt extrusion method. A straightforward interaction between bioactive components (flavours, vitamins, colours, and essential oils) and wall components (maltodextrin, maize starch, mannose, and b-cyclodextrins) is obtained when wall materials are plasticized. Combining plasticizers with affordable carrier agents lowers the glass transition temperature while conserving the bioactive components that are heat-sensitive (Zuidam and Heinrich, 2010). The solvent-free method ensures excellent throughput while reducing oxygen exposure in the extrusion channel. The opportunity to further examine how HME may be used to produce products with smaller particles, greater solubility, and better antioxidant capabilities has been provided by these discoveries. However, further research is needed to establish the toxicity and bio accessibility of HME chemicals before they are employed in the food industry.

Supercritical fluid extrusion

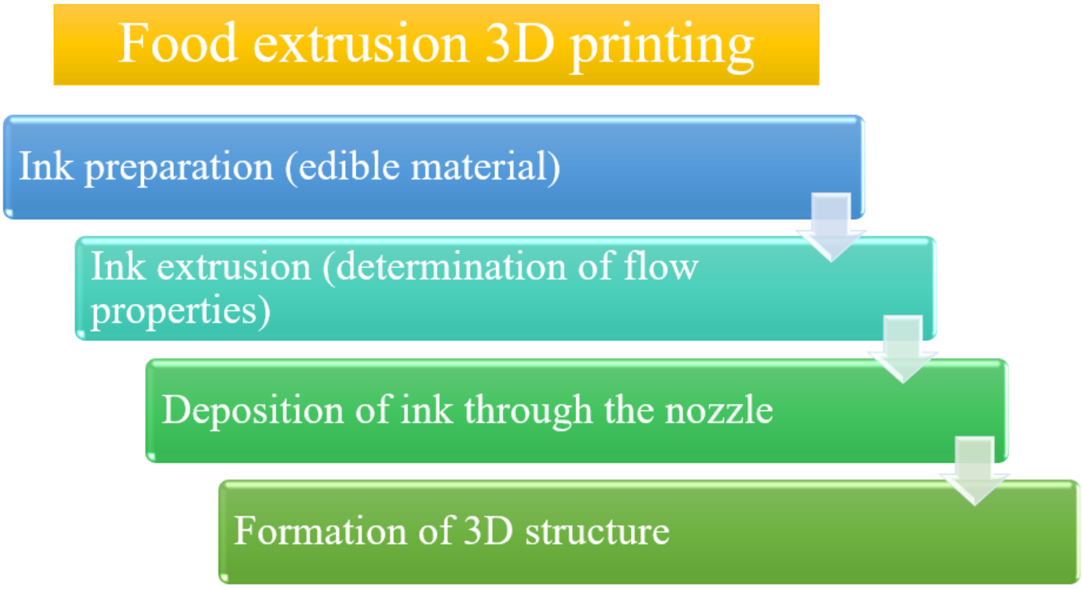
The concept of supercritical-aided with extrusion cooking (SC-CO2 Extrusion) was first put forth by Rizvi *et al.* (1992). This process used to create an end product that was more uniform and had a smoother surface. Supercritical carbon dioxide extrusion, in comparison to steam (water) extrusion, gives more expansion and can function as a leavening agent, lowering the time required to generate leavened dough (Rizvi *et al.* 1992). Supercritical fluid is injected with feed containing flavorings, colorants, and volatile micronutrients (Rizvi *et al.,* 1995). Water is added to the components to act as a plasticizer, and steam is utilized to heat the contents for cooking. By causing water to flash off in the cooling region subsequent to cooking, the steam aids to reduce product puffing and lowers the product's temperature. By employing a cooling zone, which lowers the temperature production during SC-CO2-based extrusion results in the development of shelf stable rice soy chips supplemented with micronutrients and spirulina accomplished by enhanced nutrition retention and and sensory acceptance (Bashir *et al.,* 2017). SC-CO2-based extrusion was performed for generation of cereal based healthy puffed snacks supplemented with fruit pomace and whey (Paraman *et al.*, 2015). The goods had a lower density and were high in vitamin C, polyphenols, and dietary fiber. The final extrudates had a greater retention rate (84% and 74%) of the apple pomace's total phenolics and antioxidants. Yoon and Rizvi (2020) conducted a similar work with Greek acid whey which is concentrated, was used in place of water in the creation of extruded snacks made from milk concentrate. Greek acid whey significantly enhanced the functional (crispiness, crunchiness, and hardness), nutritional, and sensory characteristics of the product when compared to commercially available extruded goods. When whey protein-based snacks are extruded under standard circumstances (high temperature, pressure, and shear), the browning caused by the high protein and carbohydrate content results. Supercritical CO_2 was used as a blowing agent to develop maize based extruded snacks comprising of defatted hemp cakes, camelina, hazelnut, and pumpkin (Panak Balenti *et al.,* 2019). The procedure significantly improved the snacks' physical (bulk density, crispiness, fracturability, and expansion ratio) and sensory qualities. It also has excellent practical implications for use at home because the product can be expanded briefly by microwave heating. N_2 injection was also employed in addition to SC-CO2 to enhance the expansion and textural characteristics of extruded snacks that are high in protein and fiber. The physical microstructure of the extruded product (red lentil puffed snacks) significantly improved after N2 was injected at 300 KPa during extrusion. This led to the creation of a product with a decreased density and plenty of tiny, evenly spaced cells (Luo *et al.*, 2020). Due to their taste, shelf life, and economic viability, the snacks created in this way can be used in various nutritional programmes, such as mid-day meals in our nation.

Extrusion-based 3D food printing

3D food printing is a developing technology that has the potential to alter the eating habits of consumers. Extrusion-based printers (Fab@home) were primarily used by Cornell University researchers to introduce 3D printing into the food industry (Periard *et al.*, 2007). Layer-by-layer deposition is a novel method used in extrusion-based 3-D printing to produce computer-aided designed food products on a platform (Zhu *et al.*, 2019).

Due to the growing market demand, revolutionary changes are taking place in the food industry. Consumer demand for 3D food printing is rising as a result of the technologically advanced modern world's potential to change food production by combining culinary innovation with digital capabilities (Hussain *et al.,* 2021). The first usage of 3D printing in the food industry involved printing a 'cake mix' using paste extrusion of a mixture made of starch, sugar, corn syrup, yeast, and cake icing (Yang *et al.,* 2001). Later, chocolates, cake icing, processed cheese, and sugar cookies were produced using extrusion-based 3-D printing.

Food printing uses an extrusion method that builds complex 3D food products layer by layer using a robotic building system that is digitally controlled (Huang *et al.,* 2013). The process commences with loading of material, pushing the material out of the nozzle in a controlled manner, moving the material stream according to a predefined path, and finally forming a coherent structure by bonding of the deposited layers (Sun *et al.,* 2018). Screw-based extrusion, syringe-based extrusion, and air pressure-based extrusion is used for 3D printing of food. The ingredients are mixed and fed into the cartridge in the screw-based extrusion process. Materials are then transported with the aid of a screw tube and passed through the nozzle tip. In the syringe-based extrusion process, printable materials are deposited in a syringe tube with one plunger inside. The plunger is connected to the stepper motor, which aids in driving the plunger in a linear motion. The printable material is prompted to pass through the nozzle tip by a step motor. In air pressure-based extrusion, printed materials are kept inside the cartridge tube while air pressure is created by a compressor. Compressed air is used to forcibly push the printed materials through the nozzle tip onto the printer bed.



Outrequin *et al.* (2022)

Extrusion-based printing materials are classified into two categories: naturally extrudable printing materials (such as confectionery, dairy products, and hydrogels) and artificially extrudable printing materials (such as plants, meat, and animals) (Voon *et al.,* 2019). Extrusion-based food printing possesses processing parameters similar to those of extrusion cooking along with printing-related parameters such as the stage moving speed and printing layer thickness (Sun *et al.,* 2018). The printing process and quality of the final product are significantly influenced by the rheological properties of food ingredients, which are crucial in determining printing performance and self-supporting abilities (Jiang *et al.,* 2019).

The preferred values for flow stress f (140-722 Pa), yield stress y (32-455 Pa), and storage modulus G' (1150-6909 Pa) were found in starch suspensions with concentrations of 15–25% (w/w) heated to 70–85 °C. According to Chen *et al.* (2019), this resulted in outstanding extrusion processability and sufficient mechanical integrity to attain high resolutions (0.804–1.024 mm line width) for the preparation of customised starch-based meals.In one of the studies, a variety of food components, including cold swelling starch, milk powder, rye bran, oat and faba bean protein concentrates, and cellulose nanofibers, were shown to be applicable for 3D food printing. This work serves as a foundation for the development of wholesome, personalized 3D printed foods in the future. The pastes comprising 10% cold swelling starch + 15% skim milk powder, 60% semiskim milk powder, 30% rye bran, 35% oat protein concentrate, or 45% faba bean protein concentrate produced the best printing results. To obtain good form stability after printing, a high yield stress was necessary (Lille *et al.,* 2018). This study demonstrated the three-dimensional printing capabilities of rice dough and the compatibility between 3D printing and steaming technology of 3D rice products. The best shape, highest precision, and most compact microstructure were exhibited by the 3D-printed waxy rice product with a flour-to-water ratio of 100:90 (3DWRD-3), followed by the Indica rice product (3DIRD-2) and Japonica rice product (3DJRD-4) with flour-to-water ratios of 100:85 and 100:95, respectively. Furthermore, the 3D printed products were steamed to study the compatibility of 3D printing. 3DWRD-3 swelled while steaming because waxy rice had the highest amylopectin content. It also demonstrated the lowest shape stability and the highest in vitro starch digestibility. However, the opposite behavior was observed in steamed 3DIRD-2 and 3DJRD-4, suggesting that indica and japonica rice could be potential 3D printing materials. (Liu *et al.,* 2020).

Highly fibrous, rigid and denser microstructure foods such as meat (pork) are usually nonprintable in nature. Therefore, in order to enhance the printability of these foods, hydrocolloids such as xanthum gum and guar gum were added. Addition of hydrocolloids resulted in improved rheological, textural, and microstructural qualities (Dick *et al.,* 2020).

Biopolymer extrusion

Biopolymers have been widely used in food, medicine, materials, and energy resources due to their renewable, affordable, and multifunctional qualities (Avella *et al.,* 2009). The term "biopolymer" (also known as "biodegradable polymer" or "biobased polymer") refers to materials whose physical and chemical characteristics is such that they completely degrade when exposed to microbial enzymatic action and anaerobic and aerobic processes (Abhilash and Thomas 2017). The use of biopolymers as a packaging material is one of the most significant inventions as they may act like other polymers such as polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polystyrene (PS), etc. (Mangaraj *et al.,* 2019). To increase the shelf life and track the freshness of food, biopolymer-based packaging systems with active and smart features are also being used as release systems and sensors (Salgado *et al.,* 2021). Extrusion is used to make bags, films, tubes, fibers, and foams and in food industries. The polymer is continuously heated and under pressure, which causes it to melt and be forced through a small orifice. Type of biopolymer used and the processing parameters during extrusion have an impact on the final product's quality (Ashter 2016). Biopolymers are produced using the twin-screw extrusion (TSE) process (Prabha *et al.,* 2021).

In this investigation, polycaprolactone (PCL) composite films containing varying concentrations of grapefruit seed extract (GSE) as an antibacterial agent were produced using twin-screw extruders. According to the in vitro analysis, the antibacterial efficiency of the PCL/GSE composite films improved with increasing GSE concentration, with a 5% concentration showing the strongest inhibitory action against Listeria monocytogenes and a 5.8-log reduction in bacterial count. The films were examined for cheese packaging, and soil burial testing was used to gauge the samples' biodegradation. The findings validated the potential of these composite films as bio-degradable material for food packaging with antibacterial properties (Lyu *et al.,* 2019). Reactive extrusion is a processing technique that uses enzymatic or chemical reactions to modify polymers during extrusion, such as through grafting, crosslinking, polymerization, and polycondensation. The extruder in reactive extrusion serves as both a processing tool and a chemical or bioreactor (Chen *et al.,* 2021). The extruder's thermomechanical action and the enzyme action in the extrusion reaction work together to improve production efficiency (Zu *et al.,* 2020). Reactive extrusion has been used to create biodegradable films using cellulose acetate/corn starch blends (Herniou *et al.,* 2019). This type of extrusion has also been utilized to develop starch/polylactic acid composite films as alternatives to petroleum-based products (Palai *et al.,* 2019).

Product developed by the extrusion process

Fortified food products

Incorporation of by- products, produced during food processing, for the development of value-added products can lead to the fabrication of fortified foods. Extrusion (HTST), is one of several technologies that can be used to produce snacks with good nutritional profile and widespread taste appeal without compromising the quality of final product. To boost the nutritional profile of extruded snacks, flour mixtures can be supplemented with fruit pomace and vegetable peels, comprising of fiber, vitamins, and minerals. Extrusion cooking is used to transform these byproducts into new food products with improved physical, chemical and nutritional properties.

At 170-210 °C mass temperature and 13% feed moisture, 2-20% of the sucrose was lost during extrusion when protein-enriched fortified cookies were prepared (Noguchi *et al.*, 1982). Raffinose and stachyose, two oligosaccharides, can cause flatulence and reduce the nutritional value of grain legumes (Omueti & Morton, 1996). In the extrusion process, high-starch fractions of pinto beans containing raffinose and stachyose dramatically decreased (Borejszo & Khan, 1992). To reduce iron-deficient anemia in children from underprivileged communities, a fortified extruded meal comprised of chickpea, bovine lung and maize was developed (Moreira-Araújo *et al.,* 2008). In this investigation, maize extrudates were made from fortified maize flour was used to prepare extrudates of maize by using traditional and cold extrusion processes at varied barrel temperatures and feed moisture contents (Boyasi *et al.,* 2012). In an investigation, the impact of extrusion (at 140 °C and 160 °C) on the concentration of α-galactosides (raffinose, stachyose, and verbascose), inositol phosphates (IPs), trypsin inhibitors, and lectins in various formulations of lentil flours enriched with nutritional yeast was assessed. The amount of total α-galactosides increased by up to 85% as a result of extrusion. After extrusion, the quantity of IPs was greatly reduced, and the amount of TIA and lectins was also significantly reduced (by more than 90%). Extrusion has been shown to have a positive impact by boosting helpful prebiotic compounds and lowering non nutritional elements (Ciudad-Mulero *et al.,*2020).

Table 1: Extruded products and extrusion effect on the different product parameters

Food product	Extruder type	Effect of extrusion	Reference
Texturized meat analog	Single screw extruder	Decrease in feed moisture Increase in feed moisture content increases density, water absorption index, oil absorption index, swelling power but decreases lateral expansion	Omohimi *et al.,* 2014
Extruded sorghum maize composite flour	Co rotating twin screw extruder	Increasing sorghum level increases slowly digestible starch Increase in barrel temperature decreases slowly digestible starch	Licata *et al.,* 2014

House cricket (*Acheta domesticus*) added extruded product	Single screw extruder	Addition of *Acheta domesticus* powder increased protein content but reduced expansion and crunchiness	Igual *et al.,* 2020
Corn grits extruded products	Counter rotating twin screw extruder	While apparent density increased with residence time and feed moisture content, it decreased with product temperature. Porosity and expansion ratio dropped with escalating feed moisture content and residence time.	Thymi *et al.,* 2005
Extruded maize extruded snacks with supplemented soy protein	Twin screw extruder	In contrast to its negative effects on the Expansion Ratio, crispness, and Water Solubility Index, feed moisture had a positive effect on bulk density, hardness, and the Water Absorption Index. Bulk density, hardness, and water absorption index were negatively impacted by barrel temperature and screw speed, but expansion ratio, crispness, and water solubility index were positively impacted.	Sahu *et al.,* 2022

Meat analogue

The texture, color, flavor, and form of meat analogues are comparable to the characteristics of meat. In India, affordable and widely available vegetables, grains, and pulses can be exploited for manufacture of meat alternatives. It can enhance the nutritional value of meat substitutes. Attainment of fibrous structure during the development of plant-based proteins is the most challenging part of the process. Therefore, extrusion with high moisture content, is one intriguing technique that is widely employed worldwide for this purpose (Prabha *et al.*, 2021). Fibrillary textured extrudates were developed by combining microalgae and soy concentrates. Extrudate nutritional profile was enhanced by integration of microalgae, as it provided vitamins B and E in the product. It was concluded that high moisture extrusion cooking is a good alternative for the production of meat substitutes from microalgae and soy concentrate (Caporgno *et al.,* 2020). For the production of fibrous (anisotropic) structures, texturization of renneted casein-based gels by sheet die extrusion was performed, which could be used in texturized protein-rich products (Kern *et al.,* 2020). *Bacillus subtilis* was used to ferment Texturized Vegetable Proteins (TVP) extruded at 40% and 50% feed moisture levels at 37 °C to study the impact of fermentation on TVP. Cohesion and springiness did not change during the process of fermentation. A study showed that a novel food product from TVP-based B. subtilis fermentation may be made by extrusion at a 50% moisture level prior to fermentation (Maung *et al.,* 2020).

Starch modification

Raw ingredients that are frequently used in food extrusion typically have starch as a major constituent. Starch can be broken down through the thermomechanical process of extrusion, which causes gelatinization, melting, and deterioration of the starch by affecting its structure, crystallinity and morphology (Ye *et al.,* 2018).

In one of the investigations, the stability of rice starch that had been altered using improved extrusion cooking technique (IECT) over freeze-thaw cycles (FT) was examined. The FT stability of rice starch modified by IECT was studied and compared with that of unmodified rice starch. The findings revealed that rice starch FT stability was enhanced by the IECT treatment, which was due to suppression of starch retrogradation by the given treatment (Ye *et al.*, 2016). The effects of "improved extrusion cooking technology" (IECT) on the molecular structure, as well as the short- and long-term retrogradation properties, of rice starch were investigated. In the following order: high speed/high temperature > low speed/high temperature > high speed/low temperature > low speed/low temperature, the IECT reduced the size of the starch molecule. Amylopectin was primarily degraded, but amylose degradation was minimal. IECT directly affects the retrogradation of starch (Liu *et al.,* 2019).

Advantages, disadvantages and challenges of food extrusion

Extrusion cooking is a high-temperature, quick cooking method that enables the management of microbes and antinutrient elements. It can be utilized to produce unique puffed snacks that offer regulating nutritional enhancement and quality attributes (flavor, color, texture, mouthfeel, and bioactive) by selecting the appropriate materials and manipulating process parameters. Additionally, it can be used to make fibrous plant-based proteins, texturized proteins (such as structural meat analogues and extenders), high-fiber foods, high-protein snacks, and flours with certain qualities. Coextruded snacks and bars with a crispy exterior and a creamy core have gained market appeal thanks to improvements in extrusion cooking technology, unique ingredients, and recognizable inclusions (Dey *et al.* 2021; Patil and Kaur 2018; Prabha *et al.* 2021). Hot-melt extrusion, which also extends the shelf life of food products, enables the fabrication of food components with extruded encapsulated flavors and bioactives. Hot-melt extrusion may additionally benefit the food industry by masking undesirable colour, flavour, and taste, preserving volatile ingredients, incorporating functional and nutritional components, and site-specific release of encapsulated ingredients at a regulated pace (Lazou and Krokida 2017; Prabha *et al.* 2021). The food processing sector can use ingredients and additions derived from natural sources through modification and reactions free of solvents and other chemicals thanks to reactive extrusion. A variety of natural biomolecules can be polymerized, grafted, branched, and functionalized using this economical processing method to create goods that are valuable in the food sector. It should be noted that the preparation of functional food ingredients by reactive extrusion technology is becoming more commercially successful (Pereira *et al.* 2022; Xu et al. 2020). A new technique that has captured the interest of both the scientific community and business is extrusion-based 3D printing. It is a very promising technology that makes it possible to build intricate and unique foods. It demonstrates traits such as adaptability, accuracy, minimal waste production, and tremendous design freedom. Despite having all these benefits, its application in the food business is restricted because of the expensive cost, lengthy production process, and vast output (Baiano 2020). Additionally, by using extrusion, wholesome foods can be created to address societal requirements, such as reducing malnutrition and food poverty (Egal and Oldewage-Theron 2020). It could offer food personalization while providing a quick reaction to consumer needs for nutritious foods for particular consumer groups such as elderly individuals, pregnant women, and children. Such requirements drive the food business to be at the cutting edge of understanding food extrusion techniques. As a result, professionals from the scientific community, academia, and business are now participating in extrusion food processing. Additionally, one of the most commercially effective technologies for constructing food products on a large scale is food extrusion.

Conclusion

Food extrusion is a significant method of processing that has been used to produce a variety of textured meals, breakfast cereals, and ready-to-eat snacks. Compared to conventional methods, extrusion cooking offers a number of advantages to the feed and food processing industries. In the past thirty years, there has been a significant advancement in the design and modification of extruders for commercial use. Cryogenic and supercritical fluid extrusion provides considerable potential for the structural modification of carbohydrates, proteins, and other nutrients. Various extrusion technologies aid in retention of nutrients, bioavailability, and digestibility by minimizing the requirement of heat and energy during processing. Supercritical fluid shall be used for development of extruded pellets. The snacks manufactured in this way can be expanded by microwaves in a fraction of a second. These snacks shall be made quickly and easily at home without addition of chemical additives, thereby making it more appealing to the customers. During supercritical fluid extrusion, it's quite difficult to maintain the temperature below 100˚C. Experimental and modelling investigations are required to improve conceptual understanding of the process and technical expertise before scaling up for industrial applications. With growth of the digital culinary industry, 3-D food printing opens up new possibilities for creating fascinating food structures without sacrificing their nutritive value or sensory qualities (such as color, taste, or flavor). The food industry is looking to create unique, functional goods with added value that are made from plant-based products such as bran, soybean hulls, bagasse, fruit and vegetable peels, and pomace. The functional foods manufacturers can take advantage of extrusion technology's ability to blend various raw components into unique foods. To meet the growing demand for healthy food options without cholesterol and the expanding veganism trend, inventive food manufacturers are turning to meat analogs to find sustainable practices in the field of food packaging where extrusion technology outstands for developing biodegradable packaging materials from food-based biopolymers.

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