



Why Food Technology by Extrusion-Cooking?

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ABSTRACT

Thermoplastic extrusion technology has become a cornerstone in the food processing industry, offering a versatile and efficient method for producing a wide range of food products. This technology is especially significant due to its status as a "clean technology," characterized by minimal environmental impact, efficient energy use, and the ability to produce food with consistent quality and safety. The process involves the continuous cooking, mixing, and shaping of raw materials, allowing for the creation of a diverse array of products that cater to both human consumption and animal feed. One of the key advantages of thermoplastic extrusion is its ability to produce pre-cooked and instant flours, which are highly popular in consumer markets. These flours are not only convenient but also enable the production of other products, such as snacks, breakfast cereals, and even infant formulas. The abundance of extruded products on supermarket shelves, ranging from instant noodles to textured vegetable proteins, is a testament to the versatility and consumer appeal of this technology. Moreover, thermoplastic extrusion is particularly beneficial for small, medium, and large enterprises alike. The technology is adaptable, with a variety of equipment available to suit different scales of production. This flexibility, combined with the relatively low labor requirements, makes it an attractive option for businesses of all sizes. The process also allows for the use of diverse raw materials, including cereals, legumes, and even by-products from other industries, which can be efficiently transformed into high-value products. In the realm of animal feed, extruded products are equally important. The technology allows for the precise control of nutritional content and physical properties, resulting in feed that meets the specific needs of different animals. This has led to the widespread adoption of extrusion technology in the production of pet foods, aquafeeds, and livestock feed. In conclusion, thermoplastic extrusion technology is a pivotal innovation in food processing, offering numerous benefits across various sectors. Its clean technology status, ease of use, and adaptability make it a vital tool in modern food production, enabling the creation of a vast array of products that meet the demands of today's consumers. Whether for human consumption or animal feed, extruded products are a staple in the food industry, with their presence only expected to grow as technology advances.

INTRODUCTION

In recent years, the emergence of new products for human and animal consumption has intensified, which could be produced exclusively through the extrusion process. In particular, those produced with high levels of protein, derived from pulses, known as plant based. Several products of this type now available in supermarkets imitate pieces of meat, whether analogous

to steaks or fillets, whether chicken, beef, fish, or even imitating seafood. The upper layer of fish skin is also imitated, which is partly made with seaweed and other ingredients. Most of these achievements are related to the flexibility of modern extrusion equipment, allowing important modifications in equipment configurations, consequently bringing different degrees of transformation of the ingredients placed in the extruder barrel (Ascheri, 2023; Berrios et al, 2013). On the other hand, the area of food extrusion currently has a significant amount of scientific information in the various areas of food science and technology. In this way, allowing major advances in different items related to processed foods, such as, nutritional quality, physical properties, functionality, food safety, sensory properties, engineering of the processes adopted, and competitiveness in the globalized market. Pre-treatment of raw materials and ingredients, product/consumer relationship, typical characteristics of consumer groups, such as naturists, vegetarians, celiac, those allergic to dairy products, peanut allergy, seafood allergy, special diets, mainly reducing animal protein, among others.

The search for healthy food has become a concern for a large number of people from conglomerates in large cities. As modernity and contemporary life advance, consumers are looking for foods that could guarantee immunity to the body. Furthermore, food, even at home, has gained the status of leisure. Trend observed in most of the world's large capitals. If we were already living in a time in which stress and depression have become very common illnesses, the pandemic that in some countries is still ongoing, and in many countries is still serious. The economic chaos caused by the current Russia-Ukraine war, and the great conflict that is raging in the Middle East, has arrived to amplify all of this. In this sense, extrusion technology has contributed to the creation of innovative products that are currently available in supermarkets. This extrusion process is unique when compared to other manufacturing methods because it combines several unit operations at the same time, including hydration, homogenization, casting, gelatinization, cooking, expansion, formatting, pasteurization, molecular reorientation, and dehydration, among others. With the help of this technology, components made from whole grains with rheological properties that support 3D printing may be developed. The difficulty is in finding high-fibre foods that are diverse enough in terms of phenolic compounds, antioxidants, vitamins, and minerals to meet the daily requirements of the primary target audience's meals.

The enormous number of co-products and/or agro-industrial waste that needs to be carefully considered in order to prevent losing or discarding it is another issue.

Most of them could be treated in advance and used. With a sufficient technical-economic feasibility analysis to support its use, thermoplastic extrusion can be a valuable instrument that is already implemented in many situations. Important nutritional components, such as grape seeds and skins, can be used among these co-products. These co-products can currently be purchased as flour, which can be used in thermoplastic extrusion, particularly if they were processed in combination with other starchy substances like sorghum, corn grits, or broken rice. In this approach, a novel cuisine that also contains proteins, carbs, fibre, and vitamins might include significant bioactive micronutrients, like the antioxidants found in grape skin. Several technical-science publications that employ various culinary techniques have been published in the scientific domain with the intention of adding value to co-products resulting

from agroindustry (Mostafa, 2022; da Silva, 2023; Zuñiga-Martínez, et al., 2022; Liu, et al., 2024; Bazán-Colque, et al, 2023, Ascheri, 2024). However, for better use of extrusion technology, there is a need to know different aspects linked to its use, which will be considered in the development of this treaty.

WHAT WOULD BE THE MOTIVATION FOR AN ENTREPRENEUR TO PURCHASE FOOD EXTRUDERS FOR THEIR ECONOMIC DEVELOPMENT?

There are several motivations for an entrepreneur to invest in the food extrusion process for economic development.

Product diversification, food extrusion processing allows the creation of a wide range of food products with different shapes, textures and flavours. By investing in extrusion technology, an entrepreneur can expand their product portfolio, meet diverse consumer preferences and explore new market segments. Including expanding into the feed area, whether for farm animals, pets, and aquaculture, for example. Efficiency and productivity, food extruders, depending on their complexity, allow continuous and high-speed production, leading to greater efficiency and productivity compared to traditional food processing methods. Increased production volumes, lower labour costs, and better overall operational efficiency are possible outcomes of this (Abilmazhinov, et al., 2023).

Savings on Costs Food extrusion frequently results in cost savings through maximized ingredient utilization, decreased energy use, and waste minimization. A business owner can lower production costs and increase profit margins by streamlining production procedures and optimizing resource efficiency. Consumer preferences are always changing when it comes to market trends and demand, and there is a growing need for quick, wholesome, and creative food products. Food extrusion processing enables the creation of value-added products that align with current market trends, such as plant-based alternatives, functional snacks and fortified foods, allowing entrepreneurs to capitalize on emerging opportunities and remain competitive in the market (Liu, et al., 2024).

Food extrusion technology offers precise control over various processing parameters such as temperature, pressure and moisture content, resulting in consistent product quality and uniformity. This ensures that final products meet high standards of taste, texture and nutritional value, increasing consumer satisfaction and brand reputation. **Customization and Innovation:** The food extrusion process offers room for creativity and experimentation when developing new products. Entrepreneurs can design unique food products that cater to particular client preferences or specialized markets by tailoring formulations and processing conditions. This approach fosters distinctiveness and brand loyalty.

Purchasing food extruders might help entrepreneurs achieve their goals of expanding their businesses into new markets or geographical areas. Extrusion technology helps businesses overcome logistical obstacles and reach a wider audience by producing items that are transportable and shelf-stable, which promotes growth and profitability.

Overall, using extrusion technology offers business owners a compelling chance to raise their profitability, competitiveness, and market positioning in the ever-changing food industry. Utilizing the advantages of extrusion technology, businesses can promote economic growth by leveraging the benefits of extrusion technology; companies can drive economic development through product innovation, operational efficiency and strategic market expansion.

FOOD EXTRUSION SYSTEMS MARKET OUTLOOK (2023 TO 2033)

The market for food extruders is projected to reach a valuation of US\$59.6 billion by 2023, with a compound annual growth rate (CAGR) of 3.9%. Investment is expected to reach US\$87.2 billion by 2033, having grown during the projected period (IMF, Future Marketing Insights, 2023). A variety of benefits can be derived from different configurations of extrusion systems such as versatility, high productivity, energy efficiency, low cost and the need for not much space. These characteristics help to produce a wide variety of foods composed of different textures, appearances and colours. Low cost factors ensure less raw material consumption with a high production rate. According to FMI (Future Market Insights), growing demand for textured proteins is driving the food extruder market. Because of the growing popularity of vegetarianism and the growing number of populations wishing to operate in sustainable ways they turn to veganism. For example, demand for textured proteins is increasing at a rapid pace. Because of this, the increasing use of food extruders to prepare these products, the size of the meat substitutes market is also expected to expand. Textured proteins are more reactive and can undergo several changes during the extrusion process, the most prominent being denaturation. On the other hand, the reduction in production costs, together with the change in consumer lifestyles, is boosting the global economy. The increase in lifestyles and the increase in the population's disposable income have led to an increase in demand for ready-to-eat foods. In the food industry, this extrusion technology has mainly boosted the production of snacks, breakfast cereals, breads, flours and starches, and textured protein products. This market is expected to grow at an exponential rate during the forecast period. This is due to the growing adoption of nutritious foods, including extruded snacks, and the growing demand for textured proteins.

The need for food extruders is expected to increase throughout the forecast period due to the rising demand for convenience foods in developing nations. This is a result of the processed food industry's explosive expansion in developing nations (Table 1).

Table 1: Competitive Analysis of the Adjacent Food Extruder Market (FMI)
Food Extruder Market:

Attributes	Food Extruder Market
CAGR (2023 to 2033)	3.9%
Market Value (2028)	US\$ 72.16 billion
Growth Factor	There is a dramatic increase in the popularity of processed foods across the globe due to their convenience, taste appeal, and increased awareness about healthy eating practices.
Opportunity	Developing new extruded food products, expanding the processed food sector through government initiatives, and exploiting untapped opportunities

Key Trends	Health-conscious individuals are seeking healthy snacks in developed as well as developing countries as lifestyle diseases increase
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Plant-based Food Market:

Attributes	Plant-based Food Market
CAGR (2023 to 2033)	11.7%
Market Value (2028)	US\$ 16.35 billion
Growth Factor	Several food industry pioneers have launched products in this segment and there has been a growing awareness of the health and environmental benefits of plant-based foods over animal-based foods.
Opportunity	Increasing consumer interest in healthier food alternatives to animal-based products and diverse ingredients
Key Trends	Vegan restaurants are becoming more popular as consumers become more health conscious.

Pet Food Extrusion Market:

Attributes	Pet Food Extrusion Market
CAGR (2023 to 2033)	5.6%
Market Value (2028)	US\$ 100.73billion
Growth Factor	The increasing pet population coupled with rising spending on different pet food products by pet owners.
Opportunity	The increasing popularity of pet food extrusion equipment and the benefits of the extrusion process in pet food such as the removal of toxic compounds and microorganisms, and enhancement in food digestibility.
Key Trends	Pet owners consider their pets to be part of the family and provide nutritional pet food products.

Source: FMI: <https://www.futuremarketinsights.com/reports/food-extruder-market>, 2023.

CHARACTERISTICS OF AN EXTRUSION SYSTEM

An extrusion system requires different components for its best performance and good-quality products. In Figure 1, a typical diagram of an extrusion system is represented, which can be equipped with a barrel with double or single screws.

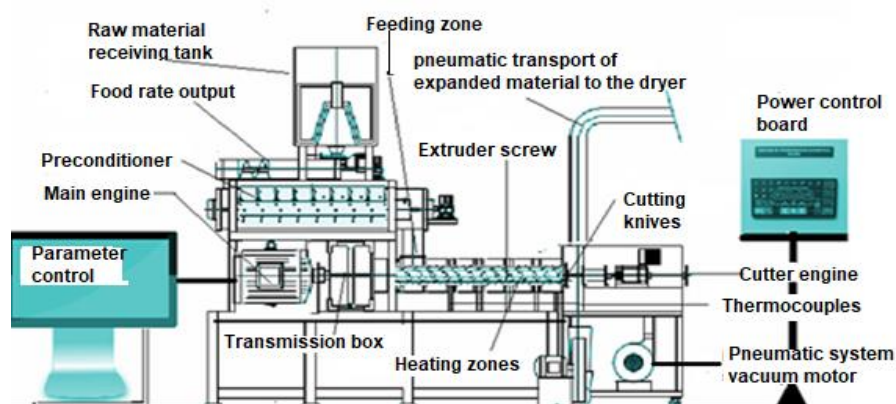


Figure 1: Representative scheme of a food extrusion system.

Source: Ascheri (2023), Questions and answers about extrusion. A simplified approach.

There are four main categories of extrusion processes: cold, hot friction, induced by steam or electrical resistance, and co-extrusion. Cold extrusion is used to gently mix and shape dough without direct heating or cooking inside the extruder. It is mainly used for the production of pasta and pastes. Hot extrusion thermomechanically transforms raw materials under high temperature and pressure conditions for a short period. This type of extrusion is mainly used to cook raw materials and mixtures thereof, as well as to produce textured plant-based foods, including the manufacture of animal feed. Steam-induced expansion defines the expansion of the melt at the die exit due to water evaporation, leading to highly expanded products. Subsequent processing determines the texture attributes of the extruded products. Examples of products produced with this type of extrusion are expanded snacks and breakfast cereals. Expanded co-extrusion combines steam-induced expansion and filling injection for expanded products with dual textures, typically crisp shell and soft filling (McHugh & Maller, 2017).

It must be considered that, depending on the characteristics and conditions of the manufacturing environment, the functionality of the extrusion equipment may be very complete or just for one purpose, a specific use in which it does not require major accessories to obtain the final product.

Analysing the diagram in Figure 1, it can be seen that there is a tank for receiving and distributing raw materials. Additionally, there is a preconditioning system. Small-expanded product factories, including producers of corn snacks, or other cereals, such as rice and sorghum, do not use a reception and pre-conditioning tank. The grit feed is directly deposited in the extruder feed hopper, that is, at the entrance to the extruder barrel, at which point the amount of water necessary to humidify the material and achieve the appropriate degree of cooking is also added. For this type of manufacturing, the control parameters are mainly limited to controlling the speed of the screw or screws, the temperatures of the heating zones, feeding rate, water flow, and the flow of the product with a certain number of dies. In some cases, equipment with a lower purchase price only has a counter-flow running water-cooling system, connected to the drinking water server, with the aim of preventing overheating of a certain zone or zones of the barrel.

On the other hand, some products resulting from extrusion, for example, aquaculture, require equipment with a greater number of accessories, as described in Figure 1, also considering that there must be a rigorously prepared stage, the pre-extrusion stage of the material. Raw material, in which the ideal particle size portion of the raw material must be reached during grinding, as the particle size of the material plays an important role in the characteristics of the final product, in addition to better performance during cooking. In this case, at the feeding rate, the pre-conditioner must be used in order to achieve better hydration, pre-cooking results and consequent improvement in cooking-extrusion. This lead, as a result, to significantly higher quality, with appropriate sinking or buoyancy levels, durability in the water, lower quantity of fine powders, and consequent durability of the barrel and screw or screws of the extrusion system, achieving better cost/benefit conditions. Alternatively, in the case of products for human consumption, adequate control will result in the physical quality of the product, texture, colour, homogeneity, and additionally gains in nutritional quality, by avoiding exceeding high temperatures or other parameters that reduce the nutritional components of the food product.

THE ROLE OF PRECONDITIONING IN FOOD AND FEED EXTRUSION

Preconditioning means conditioning or preparing a material before it is further processed. In the context of extrusion processes, preconditioning occurs immediately before extrusion within equipment called a preconditioner. The dry raw material is conditioned or prepared by adding steam, water, or both, depending on the processing needs. In which the material is subjected to a continuous mixing environment. This softens the material due to partial hydration and partial pre-cooking, due to the action of steam and the time spent inside the mixing cylinder. The conditioned material leaves the pre-conditioner and is transported by gravity to the extruder feeding area to continue the extrusion-cooking process.

WHEN IS PRECONDITIONING NECESSARY?

Preconditioning is generally preferred as part of the extrusion process. However, not all processes require preconditioning. For product formulations that require less than 18% process moisture, the preconditioning process may not be necessary. These types of products are low-moisture, highly expanded products, such as corn puffs. Due to the low process moisture requirement for such products, the mechanical energy generated by the screw inside the extruder barrel is sufficient to gelatinize or dextrinize the starch.

For formulations that need more than 18–20% moisture and longer residence times, preconditioning helps process and product quality. At higher moisture, if preconditioning is excluded, the product may not be fully cooked due to low residence time and low shear (due to high moisture content) within the extruder. Alternatively, to achieve the same degree of cooking with a preconditioner, the mechanical shear and barrel temperatures may have to be increased, and/or the L/D ratio (the length of the extruder barrel compared to its diameter) must be increased. These changes expose the product to high shear conditions and would lead to quality issues such as increased dextrinization and burning of the material. On the other hand, when working in production systems with more than 5 tons per hour, the preconditioner is essential. Therefore, recipes with higher moisture benefit from being pre-conditioned before entering the extruder for final cooking. The cooking process initiated inside the preconditioner helps to fully cook the product inside the extruder. Therefore, preconditioning would benefit any process that requires higher moisture and a longer retention time. Some of the products that would benefit from pre-conditioning include pre-cooked pasta, textured vegetable proteins, breakfast cereals, pet food, and 3G snacks (also called half products or pellets, with different formats, which can be expanded later, either in the microwave oven or by frying, for immediate consumption or subjected to packaging and storage).

Benefits of Preconditioning

Starts the cooking process, and contributes to better mixing of ingredients. Reduces wear on the extruder due to the decrease in the abrasiveness of the raw material (the raw material softens due to hydration and cooking). It allows the addition of extra ingredients such as meat paste and oil to the recipe, adding thermal energy to the process and thus reducing the need for greater mechanical energy (inside the extruder), consequently greater extruder performance due to low energy requirements. Increase the possibility of using slightly larger particle size ingredients for products such as cereals and thus bring their taste and texture closer to

traditional cooked cereal, improving product quality and extending the life of wear components inside the extruder barrel.

Physicochemical Changes During Preconditioning

The application of water and steam inside the pre-conditioner hydrates and partially cooks the raw material. Hydration (in this case) refers to the process of water imbibition by starch and protein molecules within a heated environment. The starch absorbs water and begins the gelatinization process. The increase in temperature due to the added steam also helps reduce anti-nutritional factors present in the raw mixture and helps improve digestibility. Due to hydration and increased temperature, the raw material goes from a 'glassy' state to a 'rubbery' state. This transformation occurs due to a lowering of the glass transition temperature by the addition of water, and the entry of steam increases the temperature of the raw material above its glass transition temperature. Thus, the raw material goes from a dry, hard material to a soft, malleable material that is ready to be cooked in the extruder.

Various Ingredients for Different Purposes

Let us consider the use of defatted soy flour, processing with moisture contents between 15-30%, which in this case, we could call semi-moist extrusion (SME), has well-known results, textured soy. As a result of the high shear rate, the product expands at the exit from the matrix – temperatures above 130°C – forming a spongy product, which after drying, has the capacity to absorb water, which has been used as a partial meat substitute, mainly for hamburgers, among other forms of preparation. The agricultural commodities and food processing company Archer Daniels Midland invented textured vegetable protein, in the 1960s. The company trademarked the name TVP (Textured Vegetable Protein). In this case, it is possible to use both single and double screw equipment; just have to consider that there must be a sufficient shear rate and residence time in the system to cause adequate expansion.



Figure 2: Section of a burger made with textured soy protein. Sandwich vegetable 100%.

Other food production systems, such as high moisture extrusion (HME), for meat analogues, using concentrated proteins or flours with around 70% protein, with processing of adding

water to the raw material around 65-75%, to achieve the desired fibre formation characteristics, they require a cooling system, which at the same time shapes the product. In this sense, the investment for this type of product is significantly higher than that mentioned in the previous direct expansion item.

Products made with high moisture extrusion (HME) technology (FIG. 3) seek to resemble the structure of a beefsteak, like cattle for example. Its physical and textural properties will be related to the chemical composition of the material, process characteristics and appropriate use of extrusion accessory parameters (Plattner, et al., 2024; Barnés-Calle, et al, 2024). The resulting nutritional value will be related to the quality of the material used, in this case, pulse protein flours, such as peas, chickpeas, lentils, etc., as well as the mixture and proportionality of these in a given formulation. However, the digestibility and bioavailability of vegetable protein is lower than that of meat protein and should also be better investigated, and even considered regarding different levels of processing, as high shear rates cause a greater degree of denaturation of the protein portion. Without a doubt, the ideal is to reach a limiting value, where the formation of fibres similar to that of meat is required and the nutritional value, that is, bioavailability and desirable physical characteristics reach a balance point.

According to Kołodziejczak, et al., (2022), the fact of using extrusion systems in the manufacture of products already justifies its potential, as it is a clean, environmentally friendly technology. When considering the production of meat analogues, the following advantages can be seen, such as, reduction in environmental impact, health-related aspects, supply of bioactive compounds, high fibre content, cholesterol-free, low saturated fat content and favours ethnic aspects. However, there is a need to confirm that the products available have sufficient equivalence to the nutritional values of beef, poultry or even seafood, checking that they have bioavailability values, that is, biological value that allows their name, “analog of meat”, not only in the physical aspect, but also in nutritional quality.

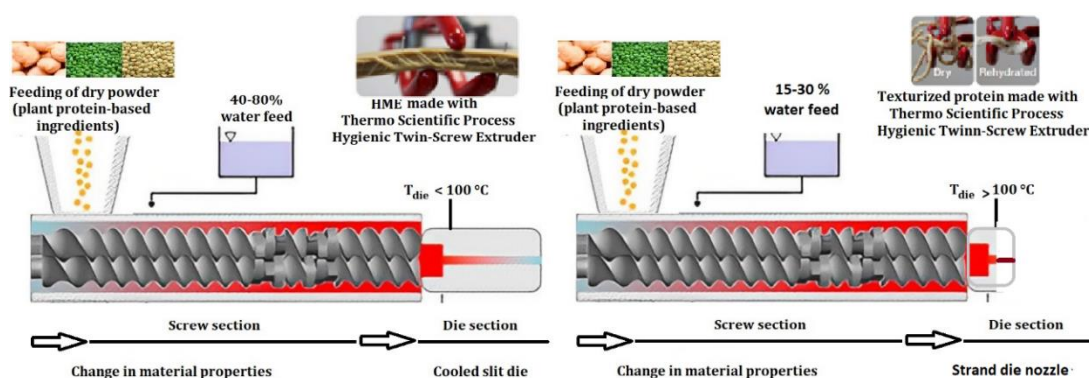


Figure 3: Co-rotational interlocking pilot scale scheme of a twin-screw extruder, presented by Thermofisher®, for the preparation of meat analogue products with high and low moisture content.

Source: <https://assets.thermofisher.com/TFS-Assets/MSD/Flyers/OV53468-Food%20Extrusion-Application%20Overview.pdf>

A traditional twin-screw extrusion system, with a certain configuration, alone is not sufficient to develop ideal characteristics for meat analogues. Experiences carried out by researchers in

the area have shown that there is a need to consider the following main requirements, which will be discussed below. Twin screw extruder, in which the central part of the screws must have a high conversion rate, with a long cooling system; degreased raw materials; protein content above 60%; processing high moisture, from 45 to 80%; temperature distribution in the barrel with security and control, low, high and low.

According to what is described on the Brabender® website, the modular design, shown in Figure 3, allows the production of textures of different sizes, independent temperature control of three heating/cooling zones throughout the matrix, comprehensive process control through 6 openings along the die for material measurements (e.g. pressure, temperature), addition of further product dimensions via modular design at a later stage possible, individual adaptation of the entire nozzle dimension according to processor needs.



Figure 3: Modular accessory with brand cold-water recirculation system Brabender®.
Source: <https://www.cwbrabender.com/en/food/products/extruder/dies/plant-protein-texturisation-modular-cooling-die/>

According to Kołodziejczak, et al. (2022) highlights, in Table 2, the advantages, risks, technological challenges, gaps to be investigated, associated with meat analogues.

Table 2: Advantages, risks, technological challenges, gaps to be investigated related to meat analogues.

Benefits	Risks and Food Safety
Reduced environmental impact	Low nutrient availability
Aspects related to health	Risk of creating dangerous by-products
-Bioactive substances	Microbiological contamination
-High fibre content	Pesticide residues
-Absence of cholesterol	Heavy metals
-Low saturated fat content	High content additional substances
Ethical aspects	

Technological Challenges	Gap Search
Improving texture through the development of new technologies or formulations	Analysis of the content of hazardous substances, heavy metals, pesticide residue, [Process Hazard Analysis (PHA), Hierarchy of Controls Analysis (HCA)]
Improvement of sensory properties	Detailed nutritional analysis

Development of safe processing and preservation techniques	Correlation between composition analyses and texture properties
Clean label product design	New ingredients and technologies

Source: Kołodziejczak, et al. (2022)

On the other hand, supercritical CO₂ (sc-CO₂) assisted extrusion constitutes an emerging method for the elaboration of foam polymer. Instead of a batch of foam, which requires the formation of a single polymer/CO₂ phase from the polymer/CO₂ solution in long cycle times, supercritical fluid-assisted extrusion overcomes this problem by providing rapid mixing and dissolution of CO₂ into the polymer melted.

Since sc-CO₂ is soluble in many polymer melts and acts as a removable plasticizer, its introduction into an extruder will allow a decrease in the processing temperature. This technique allows the use of fragile components such as active molecules or starch and protein materials. At the end of the extruder, the pressure drop will create instability and phase separation with the creation of porosity. Applications can be in the agri-food, biomedical, pharmaceutical, and packaging and many other areas.

Therefore, based on the above, with these examples, we can say that this process really allows us to develop a series of foods, with different raw materials, which only need to be adequate, both the materials to be processed and the equipment, for better results. However, there is a need to know the different characteristics that differentiate extruders and the corresponding configurations and effects caused by them.

Screw Configuration

The low-cost extruders available can be manufactured with single or double screws. These can have a short barrel or a longer barrel, depending on the processor's objectives.

One of the equipment that has become popular in companies producing expanded products is that with a short barrel, with a single, solid screw. That is, with a single purpose, what is to produce expanded cereals, such as corn, rice, and sorghum, mainly for snacks derived from corn grits.

Figure 4 shows a typical extrusion system for expanded products derived from cereal grits.



Figure 4: Extrusion system, Model DRX-50, sold by Food Machine Exportation and importation, EIRELI, containing a short barrel extruder, pneumatic transport system to the dryer/flavouring.

In the early days of simple screw extrusion, some configurations were created in order to improve cooking performance. The screw configuration of this type of equipment may vary depending on the intended use.

Figure 5 shows diagrams of solid screws with a depth of 5mm at the entrance and 2mm at the exit. (A) with one input and (B) with two inputs.

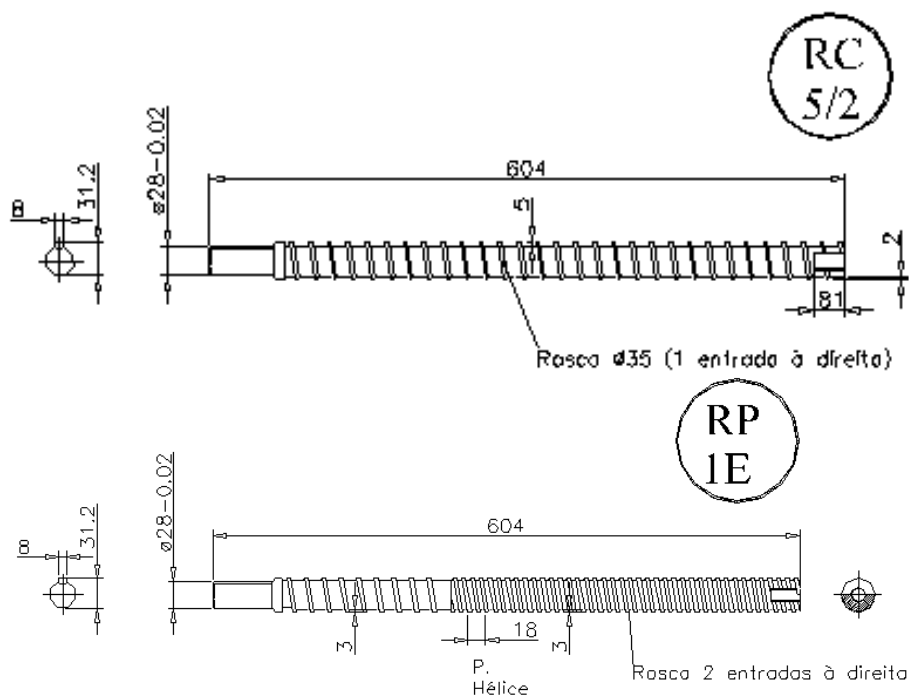


Figure 5: Diagrams of solid screws with a depth of 5mm at the entrance and 2mm at the exit. (A) with one input and (B) with two inputs.

Considering the screw design (A) in Figure 5, the applications for use are mainly indicated for typical particle size materials such as grits, as they have ideal transport characteristics from the feed entry point, at the beginning of the barrel, until the expansion of the product at the exit of the matrix.

On the other hand, the screw design (B) in figure 5 can be used with materials with finer particles than grits. For example, flour, due to the characteristic of the helices which are more open at the beginning of the screw and at a longer length extensive, precisely to facilitate feeding, and avoid clogging or accumulation of material at the beginning of the barrel.

It is worth noting that currently, there is a tendency to use twin-screw extruders. Whether these are pairs of solid, one-piece screws, or equipment that does not have interchangeable elements. Alternatively, that more sophisticated equipment, in which it is possible to adjust the shear rate, with interchangeable elements. The latter allows configuration variations that lead to increased product versatility, from obtaining simple expanded cereals, to complex procedures to obtain meat analogues, with an excellent degree of texturing, at high moisture processing.

MOST COMMON PRODUCTS MANUFACTURED BY EXTRUSION

The main and most popular ingredients in the production of expanded products through extrusion are grits derived from corn, rice and sorghum.

These expanded products can, after extrusion, be used as snacks, or subjected to grinding to obtain fine powders, aiming for use in formulations for porridges, creamy soups, instant drinks, baby food, etc.

To achieve the appropriate degree of cooking, need to pay attention to different aspects, which will be commented on separately.

Granulometric portion of the raw material, when the objective is to be expanded into breakfast cereals, these must follow a certain proportionality in the particle sizes of the grits to be processed, depending on the source, that is, corn, rice, among other cereals or pulse derivatives. Particle size of cereal and grain flours can significantly affect the results of extrusion food processing. Impact on expansion and texture, smaller particle sizes typically lead to better expansion during extrusion. This is because smaller particles provide more surface area for water absorption and gelatinization of starches, resulting in greater expansion and a lighter, more airy texture in the final product. Furthermore, obtaining consistency in the extruded product depends on a consistent and uniform particle size distribution. The overall quality of the finished product might be impacted by uneven cooking and textural changes caused by irregular particle sizes.

Conversely, when combined with water, finer particles typically have a higher viscosity, which influences the dough or batter's flow characteristics during extrusion. The ideal viscosity is required for the product to be properly extruded and shaped.

The conditions of cooking time and energy consumption, for instance, smaller particle sizes generally require shorter cooking times and lower energy consumption during extrusion processing. This is because smaller particles cook more quickly and efficiently due to increased surface area available for heat transfer.

The way different compounds interact in a composition can also be influenced by particle size and component interaction. For example, the enhanced ability of fine particles to interact with functional additives, flavours, and colours may have an effect on the sensory attributes of the final product. Cereal and grains flour particle sizes must be controlled in order to maximize the extrusion process and provide the required product properties, such as texture, appearance, and flavour.

The distinctive particle size distribution of the degerminated maize snacks, which are produced using a variety of grit types with specific granulometric characteristics, is displayed in Tables 3 through 5.

Each type responds to a certain type of texture, cells formed during expansion, crispness and other sensory parameters that define the differences between one type of snack and another. Increasing particle size produces cell extrudates slightly larger and with greater mechanical resistance (Desrumaux et al., 1998). In addition to the physical characteristics of the material, its interaction with the configuration of the screw used has a significant influence on the hardness and breaking strength of the extrudates (Altan et al., 2009), with the extruded products obtained from flour had lower hardness (11.9N) than obtained by grits (24.2N).

Table 3: Particle size distribution of degerminated corn grits.

Sieve	Retention
(US Standard/ μm)	(%)
16/1000	0.0
20/850	0.6
25/710	8.0
30/600	28.1
40/425	50.3
50/300	12.3
Pan	0.7

Source: Rokey; Huber, 1987. Snacks Food Association.
Moisture: 13.0%; Protein: 8.2%; Lipids: 0.8%; Ash: 0.4%

Table 4: Granulometric distribution of degerminated corn grits to obtain snacks with texture and fine cells.

Sieve	Retention
(US Standard)	(%)
30	0.0
40	0.7
50	47.5
60	30.1

80	15.4
100	2.4
Pan	3.9

Source: Rokey; Huber, 1987. Snacks Food Association.
Moisture: 13.0%; Protein: 6.7%; Lipids: 0.9%; Ash: 0.4%.

Table 5: Particle size distribution of degerminated corn grits to obtain snacks with a crunchy texture and larger cells.

Peneira	Retenção
(US Standard)	(%)
16	16.1
20	50.5
25	22.4
30	8.1
40	2.1
50	0.4
Pan	0.4

Source: Rokey; Huber, 1987. Snacks Food Association.
Moisture: 12.7%; Protein: 7.6%; Lipids: 0.7%; Ash: 0.3%

Breakfast Cereals

According to Miller (1994), the manufacture of breakfast cereals was one of the first commercial applications of extrusion cooking technology and remains one of the most widespread. However, the first launch as a breakfast cereal was with KELLOG'S flakes. End of the 19th century, this process, at the time, did not involve extrusion. Was made from degerminated corn (yellow corn hominy), which after a certain degree of moistening at a controlled temperature, these pass through flaking rollers, obtaining pre-gelatinized flakes sufficient for consumption, with the prior addition of a premix containing vitamins, minerals, among other nutritional and sensorial quality enrichers.

Breakfast cereal is a food made from processed grains that is generally consumed with the first meal of the day, at breakfast, especially in Western societies. The breakfast cereals market, for better understanding, can be segmented by type, distribution channel and geography. The market by type includes ready-to-cook breakfast cereals and ready-to-eat breakfast cereals. Ready-to-eat breakfast cereals dominate the entire market due to the convenience solution it offers to consumers. The market is primarily driven by consumers with busy lifestyles as these are processed grain formulations suitable for consumption without additional cooking. Ready-to-eat cereals based on whole grains are leading the market due to the added value of micronutrients in these products. Furthermore, leading companies are trying to mix organic and healthy ingredients to increase sales of breakfast cereals. These manufacturers are also using traditionally grown cereal grains, such as quinoa, to create innovation in breakfast cereal products. For example, Quinoa Crack offers a gluten-free super snack solution based on 100% quinoa, Mordo Intelligence, 2021.



Figure 5: Breakfast cereal: quinoa crack

Source: https://www.bienmanger.com/2F31211_Quinoa_Crack_French_Cereal.html

In the Asia-Pacific region, China dominates the market, contributing the largest share of this market, followed by Japan and Australia. This is due to the change in the consumption pattern of breakfast cereals and the inclination towards healthier products. Furthermore, the growing adoption of the Western lifestyle has added to the factors determining sales in the market. The development of low-carb, high-fibre, multigrain and fortified breakfast cereal products that appeal to health-conscious consumers has triggered market growth. For example, in November 2018, Kellogg's launched a new cereal, "HI! Happy Inside", which consists of fibre, prebiotics and probiotics and is specially designed to support digestive well-being. The expanding retail distribution channel is another factor expanding sales in rural and relatively small towns.



Figure 6: Breakfast cereal with fibre, prebiotics and probiotics from Kellogg's®.

Source: https://mma.prnewswire.com/media/784388/Kellogg_Company_Happy_Inside.jpg?p=original
(24/01/2023)

On the other hand, thermoplastic extrusion is used to produce breakfast cereals in the form of flakes, with some advantages and disadvantages in relation to flakes (traditional breakfast cereal, made from degerminated corn grains), a product made by Kellogg's. When made by extrusion, it may be used as raw materials of one type or of different cereals, corn, rice, sorghum, quinoa, amaranth, etc., or a mixture of them, as they are flour products, of these cereals or a suitable mixture of them, will be pre-cooked by extrusion, shaped and cut at the

exit of the die, in the shape of spheres of approximately 0.5 mm in diameter, to then be rolled into rolls, leaving them, after flocking, in a format similar to flakes corn, traditionally manufactured by Kellogg's®.

The disadvantage, in the extrusion process, is related to the degree of cooking carried out to obtain the pre-gelatinized spheres, as, if they are overcooked, the resulting flakes will have a high degree of water absorption, that is, when serving the flakes in a bowl with milk, they will quickly be soaked in the liquid, leaving a product without the crunchy characteristic of traditional cereal. This then implies strict control of parameters and processing during pre-gelatinization. With Kellogg's corn flakes, they maintain their crunchiness for longer. The disadvantage specifically for the traditional breakfast cereal patented many years ago by Kellogg's, is that this product can only be made using just one cereal, which can be corn or other cereals (here it refers only to the traditional procedure) because obviously, nowadays, the company Kellogg's, has different products made with other technological procedures, including extrusion.

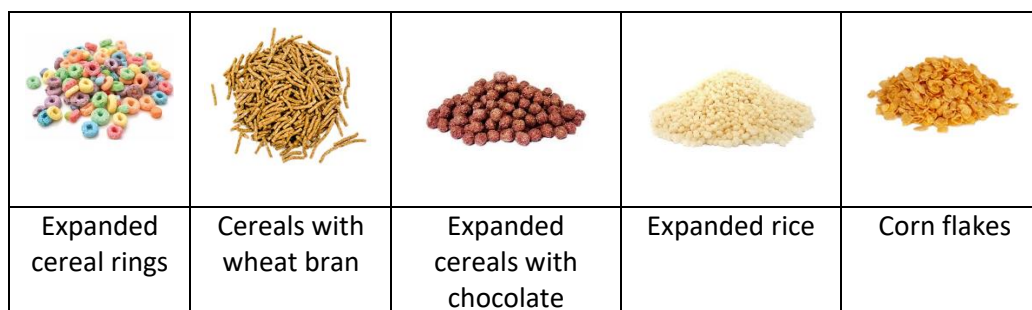


Figure 7: Different extrusion products sold on the breakfast cereal market.

Aquaculture Feed

It is important to consider that the consumption of fish, molluscs and crustaceans has increased. Surveys carried out by FAO in 2020 confirmed that there was a consumption of around 52% of aquatic animals, including fish, molluscs and crustaceans from aquaculture. In 2020, global aquaculture production reached a record 122.6 million tons, with a total value of US\$281.5 billion. Aquatic animals represented 87.5 million tons and algae, 35.1 million tons. In 2020, driven by expansion in Chile, China and Norway, global aquaculture production grew in all regions except Africa, due to a decline in the two main producing countries, Egypt and Nigeria. The rest of Africa saw growth of 14.5% compared to 2019. Asia continued to dominate global aquaculture, producing 91.6% of the total. The growth of aquaculture has often come at the expense of the environment. The sustainable development of aquaculture remains critical to meeting the growing demand for aquatic foods (FAO, 2022). In this sense, among the issues to be considered to reverse environmental problems, the production of quality feed that does not have greater effects of degradation and/or dispersion of nutrients in water could be part of the solution. This implies the use of better equipment, better formulations, and excellent control systems for processing parameters, diversification and quality of ingredients, among other factors, Plattner, et al, 2024; Arévalo, et al, 2018). Figure 8 shows different types of fish feed that float.

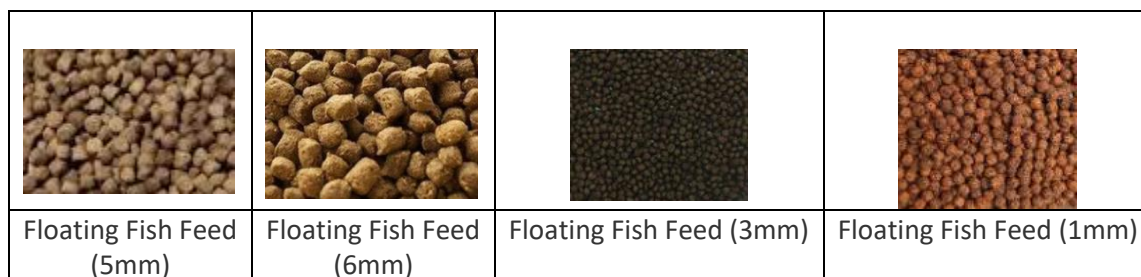


Figure 8: Different extrusion products sold in the fish feed market.

Pet Food – Pets

Another very important segment in which Extrusion Technology evolves is the manufacture of feed, mainly for dogs and cats and aquaculture. In recent years, there has been a huge growth in pet adoption, influencing the Pet Food Market.

As to the findings of an Insurance Information Institute survey, the proportion of people who own a pet increased from 56% in 1988 to 67% in 2020. As a result, this trend not only persisted but also got stronger during the pandemic. The pet market is predicted to have grown from US\$245 billion in 2021 to US\$261 billion in 2022, on a global scale. With a compound annual growth rate (CAGR) of 6.1%, this industry is expected to rise to US\$350 billion by 2027.

In the United States, \$30.3 billion was spent on pet food in 2018. This amount increased by almost 4.3% in 2019. Brazil has likewise seen this anticipated increase. According to the Brazilian Association of the Pet Products Industry (Abinpet), 60% of sales are accounted for by animal nutrition.

Considering these facts, the presence of pets has become increasingly common in different homes around the world. Because, with the premise of meeting the need for companionship, pets fill a space in the lives of young single people, couples, families and the elderly, there is an urgent need to advance knowledge on how to improve the levels of production and productivity of feed for these pets. In this sense, since the technological processes related to the feed manufacture for these animals are largely thermoplastic extrusion. Mainly due to the possibility of using a diversity of ingredients, cereals, legume grains, meat, and micro ingredients in general, so that there is balance in the use of food resources, in which competitiveness with the needs of these raw materials with human beings is avoided.

Because of the manufacture of different feeds, whether for aquaculture, pet food, or farmed animals, such as poultry, pigs, beef cattle or dairy cattle, among others, and in accordance with CAGR (6.4), the food market machines for Food Extrusion, is projected at around 100 billion dollars in 2026. Innovation and flexibility in equipment design are requirements for machine manufacturers to meet the demands of market trends. Among the main ones to be observed, lower operating costs, advances in automation, high production volumes, better product quality and longer useful life. It is important to consider that although thermoplastic food extrusion machinery is the most important technology in the transformation of raw materials, there is an entire pre-extrusion and post-extrusion infrastructure. In general, in pre-extrusion, there is processing of the raw material, such as cleaning, classifying, grinding, sieving, mixing

the formulations, weighing, etc. In the post-extrusion part, we dry the extrudates; cover them with premixes and oil, mainly for aquaculture feeds, followed by operations such as packaging and storage.

Table 6 presents the leading companies in the manufacture of food extrusion equipment.

Table 6: Main manufacturers of food extrusion equipment.

Company/Brand	Country
Bühler	Switzerland
Akron Tool & Die	USA
Baker Perkins	UK
Copernion, GEA	Germany
KAHL Group	Germany
Triottt Group	Netherlands
Flexicon	USA
Groupe Legris Industries	Belgium
The Bonnot Company	USA
American Extrusion International	USA
Shandong Ligt M&E Co., Ltd.	China
Snactek	India
Doering Sustems, inc.	USA
Schaaf Technologie GmbH	Germany
Wenger Manufacturing, Inc.	USA
Brabender GmbH & Co. KG	Germany
Jinan Darin Machinery Co., Ltd.	China

Source: <https://www.marketsandmarkets.com/Market-Reports/food-extrusion-market-221423108.html>
(extracted from WEB by 25-04-2023)

EFFECTS CAUSED BY RAW MATERIALS IN EXTRUDED PRODUCTS

Before starting any procedure for the use of raw materials, the following aspects must be considered, including for aquaculture feed.

Analyse in the laboratory or consult food composition tables to know the nutritional value of ingredients and calculate ration formulas. Obviously, every supplier of ingredients accompanies the report on the material they sell, generally containing information that concerns the processor's interest in a given food: Chemical composition, that is, value in percentage of proteins, lipids, carbohydrates, minerals, added premix, containing bioactives, amino acids, and vitamins, among others.

Control the granulometry, moisture, temperature and pressure of the raw material during the extrusion process, to avoid loss of nutrients, changes in texture and wear of the extruder parts. Avoid feed formulations with a high content of bones, limestone, salt and sugar, as these can accelerate extruder wear.

The raw materials subjected to extrusion will undergo changes as they encounter resistance at the exit from the die. Among the parameters that cause changes, we have moisture, considered one of the most important, and followed by temperature, screw speed, feed rate, number, type, shape and diameter of the matrix. However, it is important to highlight that, among the parameters mentioned above; they are all competitive with each other. This means that, for example, if we increase the moisture content during processing, and at the same time change the temperature, we will have variations in the characteristics of the extrudates, but we would not be sure whether it was due to the change in moisture or the temperature.

Considering the preparation of pasta, in most cases the moisture used can reach 30%, as the main objective is to shape the product at the exit from the matrix. In these cases, extrusion is not thermoplastic, as an example can be cited traditional pasta made from wheat. These products require cooking for approximately 11-14 minutes. However, if the case is to prepare pre-cooked pasta, in this situation the equipment and parameters change, and it is not just formatting, but cooking, so that the final product can be prepared in just a few minutes, depending on the formulation, format and characteristics of the manufactured product. It is evident that the quality, texture, among other sensorial aspects of the product will depend on the mastery of the processing parameters.

On the other hand, one of the most popular products, made by extrusion, are expanded cereals. Among them corn, widely used for the production of snacks, breakfast cereals, pre-cooked flour, porridge and ingredients for use as an input in the preparation of other foods, among other possibilities. In this sense, researchers use different methods to evaluate, and thus differentiate expanded products, depending on the treatment of a given formula or raw material used. Using thermoplastic extrusion to obtain textured soy protein, which has a similar appearance to meat and can be used as an analogue or ingredient in other products.

The expansion of extrudates is evaluated through different physical procedures, the simplest of which is the determination of the expansion index (EI).

The sectional expansion index (IES) can be evaluated by measuring the extruded diameter with a 150 mm manual calliper and the calculation carried out according to equation (1) (Alvarez-Martínez et al., 1988).

$$SEI = \left(\frac{D}{D_0}\right)^2 \quad (1)$$

Where D_0 is the diameter of the holes in the die-holder plate, for example ($D_0 = 3.8 \text{ mm}$) and D is the average diameter of a cylindrical extruded part after cooling. Where D_0 is the diameter of the holes in the insert holder plate, or also called die (for example, $D_0 = 3.0 \text{ mm}$) and D is the diameter of the extrudates after cooling.

Another parameter used to define the quality of a given product is density.

Expanded products generally have lower density than non-expanded ones. The processing parameters, the formulation, are the main elements that can have an effect on the final density of a product.

For example, when it comes to manufacturing fish feed, some feed must have the behaviour of sinking, to favour the consumption of a particular species. On the other hand, other aquatic feeds should float, thus favouring consumption.

The apparent density of the extrudates (ρ) is calculated using equation (2) (Fan et al., 1996).

$$\rho = \frac{4 m}{\pi \times D^2 \times L} \quad (2)$$

Where, m is the mass of the extrudates of length L . Twenty readings for both D and L are recommended to be recorded for each type of extrudates. The D readings were the average of three measurements: at the extremes and in the middle along L .

The expansion index becomes important when it is necessary to verify, among different treatments, for example, in multigrain mixtures, in which the proportionality of one of them, or part of them, can cause notable differences in the properties of the desired product in terms of crunchiness, texture, expanded properties.

The processing of cereals, pseudocereals, and grains in general, including some roots and tubers, can generate different types of foods, many of them already available on supermarket shelves, such as instant and/or pre-cooked flours, porridge for babies and/or food of elderly people enriched with vitamin and mineral premixes. Specific amino acids and/or bioactive, as mentioned previously.

In this sense, the producer, in order to guarantee the techno-functional characteristics, among them, the solubility indices (WSI), water absorption (WAI), paste viscosity, etc., must make use of these determinations, and thus guarantee that a given formulation or raw material, processed under specific parameter conditions for a given product.

The water solubility index (WSI) is related to the amount of soluble solids present in a dry sample and allows checking the degree of intensity of heat treatment, depending on gelatinization, dextrinization and consequent solubilisation of starch among other components of the raw material, such as protein, lipids and fibre. This index is widely used to measure the degree of solubilisation of extruded starch in drinks, soups, baby foods, among others. On the other hand, WAI is an important parameter in the characterization of extruded flours for subsequent hydration purposes. As is the case of soups and porridges, as, through this, it is possible to verify the degree of transformation that occurred during processing, making that the starch granules absorb a sufficient amount of water to characterize a product such as porridge, for example. This degree of absorption may define its palatability characteristics as a sensorial property of acceptability.

According to Anderson et al. (1969), WSI and WAI determinations are carried out by weighing approximately 1 g of sample on a dry basis, for each treatment, in centrifuge tubes, previously tared. Subsequently, 5 mL of distilled water is added, homogenized and then another 5 mL is added to wash the walls of the tubes. The tubes are then placed in a water bath at 25 °C with a mechanical horizontal shaker for 30 minutes. Then, the tubes are centrifuged for 15 min at 9000 rpm. The supernatant liquid material is carefully poured into petri dishes, previously weighed, which are subjected to drying in an oven with air circulation for 4 h at 105 °C. After this period, the plates are placed in a desiccator for 30 minutes to reach room temperature and weighed. The water solubility index can then be calculated according to equation 3.

$$WSI = \left[\frac{\text{Weight of evaporated residue (g)}}{\text{Sample weight (g)}} \right] \times 100 \quad (3)$$

After removing the supernatant, the tubes are weighed (wet residue) to calculate the WSI of the extruded material. The calculation for this index was performed according to equation 4.

$$WAI \left(g \frac{\text{gel}}{g} \text{ dry matter} \right) = \left[\frac{\text{Weight of wet centrifugation residue (g)}}{\text{Sample weight (g)}} \right] \times 100 \quad (4)$$

Research institutions, large companies, with an organized quality control laboratory, generally have a paste viscosity determiner, the Rapid Viscosity Analyser (RVA). Equipment that allows you to check how drastic or how light the thermal process of a given starchy material was during extrusion. On the other hand, a starchy material that has not undergone any heat treatment may be the object of analysis, in order to verify its behaviour and be able to compare it with other sources of starch or flour.

The principle of paste viscosity determination by Rapid Viscosity Analyser (RVA), this is an instrument widely used in food science and technology and in industry to measure the paste properties of starches and other starchy products. The viscosity profile of the paste obtained from an RVA analysis provides valuable information about the functional properties of starch and its suitability for various applications. The principles underlying measuring paste viscosity by RVA. To prepare the sample, which is usually a starch or starchy food product, it is dissolved in water or a suitable solvent to create a uniform paste. The particular requirements of the analysis may dictate changes to the sample concentration and solvent used.

Heating and Shearing: The RVA device applies regulated heating and shearing to the prepared sample. The device heats the sample in an aqueous medium at a controlled rate by continuously shearing and/or stirring it with a spinning paddle. The circumstances that are encountered when cooking or processing starch-based goods are mimicked by this heating and shearing procedure.

Viscosity Measurement, during the heating and shearing process, the RVA continuously measures the viscosity of the sample. Viscosity is determined based on the resistance encountered by the rotating paddle as it moves through the sample. The viscosity profile is

recorded as a function of time and temperature, using software, which records the data until the analysis is completed.

Paste profiles, or the viscosity profiles derived from RVA analysis, usually show multiple phases or features that correspond to distinct stages of starch degradation or gelatinization and paste production. During these stages, the sample is heated; at first, the viscosity is low. This stage is a representation of the starch granules expanding due to water absorption. Viscosity Peak: this stage relates to the sample's highest viscosity attained during heating. It shows how much the starch has gelatinized and how well it can absorb water to create a thick paste. Cooling and retrogradation, after reaching peak viscosity, the sample may undergo cooling, during which viscosity decreases as the starch, paste begins to retrograde and form a more structured gel network. Final Viscosity, this phase represents the viscosity of the sample at the end of the analysis, after the end of cooling; it provides information about the stability of the starch gel over time.

Analysis and Interpretation; the viscosity profile obtained from RVA analysis can be analysed and interpreted to evaluate various sample properties such as cooking quality, thickening capacity, stability during processing and storage, and suitability for specific food applications. Maximum viscosity, final viscosity and other parameters derived from the viscosity profile can be used to compare different starch samples or to optimize processing conditions for a specific product. In summary, RVA operates on the principle of measuring the viscosity of a starch sample as it is subjected to controlled heating and shearing, providing valuable information about its pasting properties in the hydrothermal medium and consequent functional behaviour.

Texture Analyser

Part of the definition of the extrusion process describes it as a way of achieving new shapes and textures in the products obtained. The process conditions, its applied parameters, such as temperature, moisture, screw speed, etc., are conditions for achieving variations in the textures of the products.

The texturometer is used to check, indirectly, how the product has varied depending on the processing that has been applied.

The Texture Analyser, sometimes referred to as a texture profiler or texture measurement system, is a tool used to analyse the mechanical characteristics of a variety of materials, such as consumer goods, food items, medications, and cosmetics. A Texture Analyser's functioning is based on the principles of controlled deformation and force measurement applied to a sample. An outline of the guiding principles is provided here. To guarantee uniformity between studies, samples are usually prepared in conventional sizes and forms prior to testing. This could entail modifying the sample in order to meet the demands of the particular test. Sample Mounting: After the sample is ready, it is firmly placed within the Texture Analyser. The sample may be secured in a variety of fixtures or clamps that provide tension, compression, bending, or other sorts of deformation, depending on the kind of test being performed. Test Parameter Selection: Depending on the material being tested and the attributes of interest, the user chooses the

relevant test parameters. This includes determining test speed, creep distance, and units of measurement (force, distance, time, etc.).

Using the test parameters that have been chosen, the Texture Analyser applies a controlled force on the sample. Depending on the particular test needs, this force can be applied in a variety of methods, including as compression, tension, bending, shearing, and torsion. The texture analyser records the sample's deformation in real time as force is applied. This could entail quantifying additional mechanical qualities like hardness, elasticity, adhesiveness, or brittleness, or monitoring changes in sample dimensions like length, width, thickness, or diameter.

Throughout the testing procedure, the texture analyser records information on force and deformation. Following testing, this data is usually examined with specialist software to determine the sample's mechanical properties and extract pertinent parameters. Depending on the particular test being run, they could include metrics like peak strength, breaking strength, strain at failure, area under the curve, and many more.

The interpretation and utilization of data acquired by texture analyser testing yields significant insights into the mechanical characteristics of the sample. These insights can be leveraged to assess the sample's quality, performance, consistency, and appropriateness for different purposes. Product development, quality assurance, troubleshooting, and manufacturing process optimization can all benefit from this knowledge. In conclusion, the texture analyser works based on quantifying a sample's mechanical qualities by measuring its deformation after a regulated force is applied to it. This adaptable tool is used in many different industries to evaluate the mechanical performance, consistency, and texture of materials, including biomaterials.

Differential Scanning Calorimetry (DSC)

Principles of Using Differential Scanning Calorimetry (DSC) in Processed Starches:

DSC is a popular analytical method for examining a material's thermal characteristics, particularly processed starches. DSC monitors heat flow related to chemical and physical changes in a sample as a function of temperature, which is its fundamental working principle. It measures heat flow in controlled heating or cooling circumstances relative to a reference material. Heat flow variations are a sign of endothermic or exothermic processes, including phase changes, chemical reactions, and physical transformations. Typically, processed starch samples are dried and finely crushed to guarantee consistent heating and precise measurement. Sample heterogeneity and moisture content should be kept to a minimum because they can have an impact on DSC readings. Two sample containers are often used in DSC analyses: one holds the sample and the other containing an inert reference material. Both pans are subjected to the same heat treatment (heating or cooling) under controlled conditions.

Heating/cooling program: The sample is subjected to temperature-controlled program, typically involving linear heating or cooling at a constant rate. The temperature range and heating/cooling rate are selected based on the specific sample properties and phenomena of interest. **Heat Flow Measurement,** as the sample undergoes thermal transitions such as

gelatinization, retrogradation, melting or crystallization, it absorbs or releases heat. This heat flow is detected by the DSC instrument and recorded as a function of temperature. The DSC data is analysed to extract various parameters related to the thermal behaviour of the sample. For processed starches, key parameters may include Onset Temperature; the temperature at which a thermal event begins, such as the beginning of gelatinization or melting. Peak temperature consists of the temperature at which the thermal event reaches its maximum intensity, such as the gelatinization peak. Peak enthalpy, the amount of heat absorbed or released during the thermal event, usually expressed in J/g or J/mol. Transition entropy and kinetics provides information about the change in entropy and kinetics of the thermal transition, which can be obtained by analysing the shape and width of the DSC peaks. Degree of gelatinization; for starches, DSC can be used to quantify the degree of gelatinization, which is a measure of the extent to which starch granules swell and lose their crystalline structure upon heating.

Interpretation of results, DSC data provides information on the thermal behaviour and properties of processed starches, including their gelatinization characteristics, stability and suitability for various applications in the food and industrial sectors. By comparing DSC profiles of different samples or analysing the effects of processing conditions, researchers can optimize processing parameters and develop starch-based products with desired properties.

Consequently, Differential Scanning Calorimetry (DSC) is a valuable tool for studying the thermal properties of processed starches, providing important information about their gelatinization behaviour, stability and functionality in various applications.

Evidently, each final product will have its best way of evaluation depending on its characteristics. For example, a breakfast cereal, different when compared to a meat analogue, should be analysed with the property related to that particular product.

Meat texture attributes and similar. For both meat and meat-like products, texture is one of the main characteristics that determine consumer perception and taste. Although the texture of food products can be described using multiple different attributes, here we focus on tenderness, hardness and juiciness as the most relevant for meat and meat analogues (Ilić, et al, 2022). These authors considered tenderness and softness as a crucial sensorial attribute of texture for the appreciation of meat quality. It is affected by several factors, for example, marbling, insoluble/soluble collagen ratio, race, age, sex, and pre- and post-mortem factors. However, although it is often included in meat studies, there is variability in the applied definition of tenderness.

According to ISO (International Standards Organization) 5492 (2008), softness represents a level of chewiness; therefore, it is related to the work (energy) required to chew the sample. However, some authors evaluated softness as a biting force related to hardness (Ilić, et al, 2022). According to these authors, hardness constitutes a mechanical attribute of texture related to the force necessary to achieve a certain deformation, penetration or breakage of a product. In this sense, the format and size of the sample are important factors for sensory and instrumental evaluation. In this sense, procedures to determine textural and/or sensory properties are practiced in a similar way for meat analogues (Godschalk-Broers et al., 2022).

Production Costs

When asking yourself, what would be the main topics when considering the cost assessment of a certain food product made by food extrusion? Consideration should be given to a cost survey that provides a comprehensive analysis of production costs and the factors that influence profitability. The main aspects will be discussed below.

Cost of Raw Materials

Analysis of the cost of raw materials required for the extrusion process, including primary ingredients such as grains, legumes or other raw materials. Consideration of secondary ingredients, additives and flavourings used in the formulation. Assessment of fluctuations in prices and availability of raw materials and their impact on global production costs.

Surveying the costs of raw materials for extrusion food processing involves collecting detailed information about prices, availability, quality and supply options for the primary and secondary ingredients used in the extrusion process. The systematic guide on how to conduct this research could be: prepare a list of all the raw materials needed for the food extrusion process. This may include primary ingredients such as grains (e.g. corn, wheat, rice), legumes (e.g. soybeans, lentils, peas, etc.) or other raw materials (roots and tubers), as well as secondary ingredients such as additives, flavourings and fortifiers.

Identify potential suppliers or sellers for each raw material. This may involve contacting local distributors, manufacturers, wholesalers, or farmers, as well as exploring online marketplaces and business directories. Request quotes for the required raw materials, specifying the quantity required, desired quality specifications, delivery conditions and any other relevant details. Request price quotes for different order quantities to evaluate volume discounts or bulk pricing options. Compare the prices provided by different suppliers for each raw material. Consider factors such as unit price, shipping costs, minimum order quantities and payment terms. The overall cost-benefit ratio and reliability of each supplier must be evaluated.

Evaluate the quality of raw materials offered by each supplier. Consider factors such as purity, consistency, nutritional content and compliance with regulatory standards. Request samples or certificates of analysis, reports, etc., to verify quality specifications. Then, negotiate with suppliers to secure favourable terms and pricing agreements. Opportunities for long-term contracts, price guarantees or exclusive partnerships should be explored to ensure stable and cost-effective supply arrangements.

Sourcing options should be considered, including local versus international suppliers, conventional versus organic sources, and traditional versus new ingredients. Assess the potential benefits and trade-offs of each supply option in terms of cost, quality, sustainability and supply chain resilience.

Consider market trends, fluctuations in commodity prices and supply and demand dynamics that affect the cost of raw materials. You should monitor industry reports, market analyses, and trade publications to anticipate changes in pricing and availability.

Calculate total raw material costs for the food extrusion process based on prices obtained from suppliers, including any additional expenses such as transportation, handling, storage or quality testing. Estimate the overall impact of raw material costs on your production budget and pricing strategy.

Regularly review and update cost research to reflect changes in market conditions, supplier relationships and production requirements. It is important to be proactive in optimizing raw material supply strategies to minimize costs, mitigate risks and increase overall operational efficiency.

By systematically researching the costs of raw materials for extrusion food processing, companies can make informed decisions about sourcing, purchasing and production planning, ultimately optimizing cost-effectiveness and/or cost-benefit, and ensuring the profitability of its operations.

Energy Consumption

Assessment of energy use during the extrusion process, including electricity, steam, or other forms of energy required for heating, cooling, and operating the equipment. In this case, it refers to calculating energy costs per unit of production and identifying opportunities for energy efficiency improvements. This ranges from receiving raw materials to transporting the finished products to storage and maintenance and sending them for sale (Cheng & Rosentrater, 2019). Managing energy costs in a food extrusion plant involves several steps to understand and accurately manage energy consumption. Here is a structured approach:

1. Identify energy consumption points; break down the manufacturing process into its constituent parts to identify where energy is being used. In a food extrusion factory, energy consumption normally occurs from the raw material reception area, transport system motors, electrical control systems, silos with mechanical agitators, etc. Until reaching the pre-conditioner, during the stages of heating -here we have energy in the form of steam – This item implies the use of electrical energy and fuel for its operation, to be calculated based on daily production–, mixing, extrusion, cooling (here we have the chiller, a refrigeration system that helps maintain the temperatures of the extrusion system barrel at the correct temperatures) and packaging.
2. Determine energy consumption measurement; the use energy meters or use smart energy management systems to monitor energy usage in real time. This data will help identify peak usage times, areas of inefficiency, and potential areas for improvement.
3. Analyse and evaluate the efficiency of the equipment and machines involved in the different stages of product manufacturing. Verify for opportunities to upgrade to energy-efficient models or optimize existing equipment to reduce energy consumption.
4. Consider different energy sources, if possible, in order to evaluate the energy used in the factory, such as electricity, natural gas or renewable energy sources. Compare costs and environmental impacts associated with each energy source. For example, lighting in offices and process control cabins could use solar energy sources.
5. Determine the cost of energy consumption by multiplying energy use (in kWh or other appropriate units) by the unit energy cost. This calculation must consider the fixed and variable costs associated with energy use.

6. Conduct energy audits or engage with energy management professionals to identify opportunities to reduce energy consumption. This could involve implementing energy-efficient technologies, optimizing production processes or modifying operational procedures.
7. Implement energy management strategies, that is, develop and implement an energy management plan to optimize use and reduce costs in the long term. This may include setting energy-saving goals, training staff in energy-efficient practices, and investing in energy-saving technologies.
8. Continuously monitor and review energy consumption and analyse the effectiveness of implemented energy management strategies. Adjustments may be necessary based on changes in production volume, technological advances, or fluctuations in energy prices.
9. Regulatory compliance must be considered, i.e. ensuring compliance with relevant energy regulations and standards governing energy use in manufacturing facilities. This may involve reporting energy usage data, meeting energy efficiency requirements or participating in energy saving incentive programs.

Labour Costs

Analysis of worker requirements for extrusion line operation, including qualified technicians, machine operators and maintenance personnel. These labour costs per unit of production and their comparison with industry benchmarks.

Assessing labour costs in a production system involves several steps to accurately understand and manage expenses associated with human resources. Below we show a structured approach to labour activities.

1. Identify labour activities, for this it is suggested to divide the manufacturing process into individual tasks or activities performed by employees. This may include tasks such as assembly, machining, quality control, maintenance, supervision and administrative tasks.
2. Quantify working hours, to do this you must determine the number of hours worked by employees for each task or activity. This can be done through time tracking systems, employee timesheets, or work observation studies.
3. Is necessary to calculate the labour costs associated with each task or activity by multiplying the number of hours worked by the labour rate for each category of employers. Employment fees must include wages, benefits, taxes and any other applicable costs.
4. Consider overtime and shift differentials, taking into account any overtime worked by employees, as well as any shift differentials or premiums paid for non-standard work. These factors can significantly influence labour costs.
5. Analyse labour productivity within the production system by comparing output (e.g. units produced, volume of production) with labour input (e.g. hours worked, number of employees). Identify any inefficiencies or bottlenecks that may be affecting productivity.
6. Evaluate the effectiveness of the use of labour, with the resources that are being used in the production system. This includes evaluating factors such as idle time, downtime and non-productive activities (rest or refreshment time). Look for opportunities to optimize resource allocation and improve overall efficiency.

7. Consider the costs of training and developing employees to perform their duties effectively. This may include initial training, ongoing skills development, and certification programs.
8. Evaluate opportunities for automating tasks or processes within the manufacturing system to reduce dependence on manual labour and potentially reduce labour costs in the long term. This could involve investment in robotics, automated machinery or computerized systems.
9. Continuously monitor and adjust labour costs and productivity metrics to identify trends and areas for improvement. Adjust staffing levels, workflows, and processes as needed to optimize labour costs while maintaining production efficiency and quality standards.
10. Consider regulatory compliance with labour regulations and standards governing wages, work hours, overtime pay, and employee benefits. Failure to comply with labour laws can result in legal penalties and reputational damage.

By following these steps, a production system can effectively assess and manage its labour costs, leading to greater efficiency, reduced costs and global competitiveness.

Equipment Costs

Assessment of the capital investment required to purchase, install and maintain food extrusion equipment. Consideration should be given here to depreciation, financing costs and ongoing maintenance expenses associated with the equipment.

Evaluating specific food extrusion equipment involves several steps to ensure it meets the requirements of the manufacturing process and provides the desired results. Consider the following:

1. Define requirements and objectives, this implies clearly defining the requirements and objectives of the food extrusion equipment. Here it is necessary to consider factors such as the desired production capacity, equipment or production line specifications (e.g. size/capacity, format, configuration), parameters that can be used during processing (e.g. temperature, pressure, screw speed, feed rate, etc.) and regulatory compliance (e.g. stainless steel in equipment structure). In this sense, in this item it is worth mentioning that the equipment to be acquired will be very different, in the case of purchasing an extrusion system for fish feed, than for the preparation of textured foods processed at high moisture, above 65%, in obtaining meat analogues.
2. Research available options to identify available food extrusion equipment that meet defined requirements; factors such as equipment size, configuration, features, capabilities, brand reputation and customer reviews.
3. Evaluating technical specifications involves reviewing the technical specifications of each equipment option to ensure compatibility with the manufacturing process. Pay attention to parameters such as extrusion rate, screw configuration, die design, motor power, material compatibility and control systems.
4. Evaluate the quality and durability of food extrusion equipment to ensure reliable performance throughout its operational lifetime. Consider factors such as construction quality, materials used, and engineering design and maintenance requirements.

5. Analysing safety features involves prioritizing equipment with robust safety features to protect operators and comply with safety regulations. Evaluate features such as emergency stop buttons, safety guards, interlocks, and compliance with relevant safety standards (e.g., the OSHA Occupational Safety and Health Administration).
6. Consider ease of operation and maintenance by choosing equipment that is easy to use and easy to operate, configure and maintain. Evaluate features such as intuitive controls, accessibility for cleaning and maintenance, availability of replacement parts, and technical support from the manufacturer.
7. Evaluate the energy efficiency of food extrusion equipment to minimize operating costs and environmental impact. Look for features like energy-efficient motors, insulation, heating and cooling systems, and process parameter optimization.
8. Analyse the cost and return on investment (ROI - is a metric that calculates the efficiency of an investment. It evaluates the gain obtained in relation to the amount invested), compare the cost of each equipment option with its resources, capabilities and Expected ROI. Consider not only the initial purchase price, but also long-term operating costs, maintenance expenses and potential productivity gains.
9. Seek references and testimonials, contacting other users or industry experts to obtain references and testimonials about their experience with the equipment. Learn about any challenges or benefits they encountered and how the equipment worked in real-world applications.
10. Arrange demonstrations or testing of equipment, whenever possible, to observe its performance first-hand and validate its suitability for the manufacturing process. Test equipment with representative materials and operating conditions to evaluate its capabilities and limitations. Some companies have pilot-scale environments for demonstrations, including the materials that will be manufactured by the future buyer. They also include visits to manufacturing sectors whose machines are in full operation on an industrial scale in order to evaluate their performance.
11. Consider future expansion and upgradeability, so that equipment selection allows for future expansion or upgradeability to accommodate changing production needs and technological advances. Evaluate scalability, modularity and compatibility options with accessories or additional components.

By following these steps, the food extrusion system buyer can effectively evaluate food extrusion equipment and select the best option to meet the needs of their manufacturing process, ensuring efficient production and high-quality food products.

Packaging Costs

This includes a rigorous examination of the packaging materials used to package the final food product, such as bags, boxes or pouches, as the quality and stability of the food produced depends in part on them. Each production unit must consider packaging optimization and design to minimize costs while maintaining product quality and safety.

When evaluating the quality of extrusion-processed food packaging, several key factors must be considered to ensure the packaging meets safety, functionality and aesthetic requirements. In addition, people are also wanting to see reliability and measurable progress in brands'

commitments to health, the environment and ethical aspects. That is, buyers are considering how their purchases can contribute to protecting their health and the health of the planet. In this sense, they are studying the ingredients more and looking to maximize positive benefits for both physical and emotional well-being. Consumers will look for clear and reliable guidance – this can be described on the product label – in order to understand how those ingredients will meet their needs and preferences. On the other hand, immune health will continue to be a sought-after claim in foods in general for years to come.

Here are the items to evaluate:

1. Assess the composition of the material, packaging to ensure it is suitable for food contact and complies with relevant regulations (e.g. FDA regulations in the United States, EU regulations in Europe, etc.). Check that the material is free of harmful substances and contaminants.
2. Evaluate the barrier properties of the packaging material to determine its ability to protect the food product from external factors such as moisture, oxygen, light and odours. Carry out tests to measure permeability and evaluate the effectiveness of the barrier.
3. Conduct strength and durability testing of packaging material to ensure it can withstand handling, transportation and storage without tearing, puncturing or breaking. Evaluate factors such as tensile strength, tear strength and influence resistance.
4. Check the integrity of the packaging seals to prevent leaks and maintain product freshness and safety. Perform seal strength tests and visual inspections to ensure seals are properly formed and free from defects.
5. Ensure compatibility with processing equipment, with packaging that is compatible with the packaging equipment used in the manufacturing process. Evaluate factors such as heat resistance, flow properties and compatibility with sealing methods.
6. Evaluate the print quality of any labels, graphics or branding elements applied to packaging material. Make sure the print is clear, legible, and free of smudges or fading, as this may affect the appearance and brand perception of the product.
7. Verify that packaging material complies with food safety and regulatory compliance regulations and standards applicable to the specific type of food product being packaged. Make sure the material is suitable for direct contact with food and does not present any health risks.
8. Consider the environmental impact of the packaging material, including its recyclability, biodegradability and overall sustainability. Choose materials that minimize environmental impact and align with sustainable packaging goals.
9. Evaluate user convenience and ease of use of the packaging design, including features such as easy opening, resealability, portion control, and ergonomic handling. Consider how packaging design improves the overall user experience.
10. Consider the aesthetic appeal of packaging design in terms of visual appearance, branding elements and shelf presence. Evaluate factors such as colour, design, texture and overall presentation to ensure your packaging attracts consumers' attention and increases product visibility.

By evaluating these key items, the future entrepreneur in this area will be able to ensure that foods processed by extrusion, using packaging that meet high quality standards. Likewise, these packaging can effectively protect and present the food product, complying with regulatory requirements that meet consumer expectations.

QUALITY CONTROL AND ASSURANCE

In this aspect, it is important to identify the quality control measures implemented throughout the entire production line, pre-quality control of raw materials, grinding and post-extrusion, to ensure product consistency, safety and compliance with regulatory standards. Here, reagents, equipment, operators, laboratory technicians, etc., should be considered, who constantly monitor production. Other aspects, such as assessing costs associated with quality testing, inspection and compliance activities.

It is important to consider that the assessment of the quality of products made by extrusion will depend on the area it will serve. For example, in fish feed, pellets may be those that sink, and others that float, consequently, density will be an important quality point. However, when treating for human consumption, quality factors will also be differentiated, depending on the type of product.

When evaluating the quality of products obtained by food extrusion, several key factors must be considered to ensure they meet safety, nutritional, sensory and functional requirements. In general, the main items are considered below.

Evaluate the visual appearance of extruded products, including colour, shape, size and surface texture. Products must have a uniform and consistent appearance, without defects or irregularities. Evaluate the texture and taste of extruded products, considering attributes such as crunchiness, chewiness, softness and general mouthfeel. Texture must be consistent throughout the product and meet consumer preferences. In addition, the density and porosity of extruded products to ensure they have the desired structure and internal characteristics. Products must have the right balance between density and porosity to achieve the desired texture and eating experience. Determine the moisture content of extruded products to ensure they have the appropriate moisture level for storage stability and sensory properties. Products should be neither too dry nor too moist to maintain quality and freshness.

Analyse the nutritional composition of extruded products to ensure they meet nutritional requirements and label claims. Consider factors such as protein content, fat content, carbohydrate content, fibre content, vitamins, minerals and overall nutritional balance. When adding specific micro ingredients, ensure their presence, not only for regulatory reasons, but also for consumer satisfaction.

Evaluate the distribution of ingredients in extruded products to ensure uniformity and consistency. Ingredients must be evenly distributed throughout the product to ensure consistent flavour, texture and nutritional content. Test the cooking performance of extruded products to ensure correct cooking and achieving the desired results. Evaluate factors such as

cooking time, cooking temperature, water absorption, water solubility, and cooking stability in the extrusion system.

Evaluate the flavour and aroma of extruded products to ensure they have a pleasant and desirable flavour profile. Products must have balanced flavours, free from strange flavours or undesirable odours. Conduct shelf life studies to evaluate the stability of extruded products under various storage conditions. Products must maintain quality and safety throughout their intended shelf life without significant deterioration.

Ensure extruded products meet safety standards and regulatory requirements for food safety, hygiene, labelling and allergen labelling. Products must be free of contaminants, pathogens and allergens and must comply with relevant food safety regulations.

Carry out sensory evaluation studies or consumer tests to assess acceptance and/or preference of extruded products by consumers. Evaluate factors such as general taste, purchase intention, willingness to pay and feedback on sensory attributes. By considering these key items, it is possible effectively assess the quality of food extrusion products and ensure they meet high-quality standards, consumer expectations and regulatory requirements.

General expenses, this item includes indirect costs, such as rental of facilities, public services, insurance and administrative expenses.

Transport and distribution must be evaluated, as companies may have their own fleet of vehicles to send products. These transportation costs may be associated with the delivery of raw materials to manufacturing facilities and the distribution of finished products to customers. This involves vehicle maintenance, fuel, legal issues regarding the vehicle fleet such as licenses, etc., in addition to drivers trained in the transport and handling of food products, especially when dealing with perishable products. Analysis of logistics strategies to optimize transport efficiency and minimize costs is desirable to consider.

MARKET RESEARCH AND MARKETING EXPENSES

It is an important aspect in which investment in market research should be considered to identify consumer preferences, market trends and the competitive scenario. Allocation of marketing expenses to promote the food product, build brand recognition and increase sales. Finally, a careful analysis of the profit at the end of all budget positions, such as the calculation of the total production cost per unit of the food product. The comparison of production costs with sales revenue to determine profitability margins. Sensitivity analysis to assess the impact of changes in key cost drivers on overall profitability.

By covering these topics comprehensively, a cost survey of a food product made by food extrusion can provide valuable information about the economic viability and competitiveness of the production process, allowing informed decision-making and strategic planning for success of business.

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