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REVIEW ARTICLE

Effects of Extrusion Cooking on Food Quality Attributes, Storage Stability, and Inactivation of Bacterial Spores: A Review

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Abstract

The objective of this study was to review the literature on the definition and components of food quality, examine the storage stability of foods and evaluate the effect of extrusion cooking on contaminating microorganisms. Food quality encompasses the attributes that determine consumer acceptability, with consumers serving as the primary arbiters of quality. These attributes may be extrinsic (e.g., colour) or intrinsic (e.g., chemical composition). Food quality is typically monitored through standardized quality control tests assessing multiple parameters and is often enhanced through legislative frameworks that render non-compliance subject to legal sanctions. A major challenge for food processors is ensuring product stability during storage. Storage stability assessments are conducted to evaluate changes in product quality over time and appropriate packaging plays a critical role in enhancing stability and extending shelf life. Microorganisms pose significant challenges by causing food spoilage and foodborne illnesses. Raw materials may be exposed to various sources of contamination prior to extrusion cooking and inadequate hygienic practices may also render the extruder itself a source of contamination. Extrusion cooking contributes to microbial inactivation through the combined effects of high temperature, moisture content and mechanical shear within the screw, which can destroy microbial cells, enzymes, spores and toxins. Since food spoilage is predominantly of microbial origin, food processing primarily aims at preservation to prolong shelf life. Additionally, reduced water activity inhibits the growth of many microorganisms, particularly bacteria, thereby further contributing to product stability.

INTRODUCTION

Over the past 10-15 years, food quality has improved substantially owing to advancements in food legislation and stricter legal requirements imposed on food manufacturers and retailers, thereby enhancing consumer protection against hazardous foods[1]. Food quality may be defined as the set of features and characteristics required of a food product, which distinguish individual units of that product. Within the food industry, food quality is associated with fitness for intended use, product safety and consumer acceptability. Consumers are regarded as the primary arbiters of food quality[2]. In recent years, the food industry has become increasingly competitive due to growing consumer demand for improved food quality, sustainability, traceability, safety and authenticity[3]. Beyond food safety considerations, preferences for food quality attributes are heterogeneous, reflecting the diversity of consumer populations[4]. In many countries, regulatory bodies establish common criteria, such as quality control standards, issue certifications to companies and monitor compliance with these standards. In Nigeria, such bodies include the Standards Organization of Nigeria and the National Agency for Food and Drug Administration and Control, while internationally, the Codex Alimentarius Commission plays a central role[5].

Packaging contributes significantly to the maintenance of food quality by preserving attributes such as crispiness, vitamin content, aroma and flavour, structural integrity and by limiting lipid oxidation, which leads to rancidity[6]. Lipid oxidation is accelerated by free radical formation in foods, resulting in quality deterioration and reduced consumer acceptability[7]. Maintaining food quality throughout shelf-life is highly dependent on appropriate packaging, including effective sealing of packaging materials, particularly at the seal interface. Tiwari and Jha[8] reported several benefits of extrusion cooking on food quality, including the destruction of antinutritional factors, increased nutrient bioavailability, enhanced soluble dietary fibre content, reduced lipid oxidation and decreased levels of contaminating microorganisms.

One of the major challenges faced by food processors is ensuring food stability during storage. The interval between food processing and consumer consumption is critical, as the product must remain wholesome while retaining its desirable quality attributes. Storage stability refers to the ability of food to maintain its quality or shelf-life over time under specified storage conditions. Shelf-life may be defined as the period during which a food product remains safe and suitable for consumption, such that consumers have no reason to consider it unacceptable[9]. Microbiological quality, as well as physical and chemical properties, are commonly monitored to assess food stability during storage. The concept of food quality varies among professionals in the food industry: for chemists, it is often associated with stability; for nutritionists, with nutritional value and for microbiologists, with safety. However, due to the role of consumer perception and acceptability, the consumer, as the end user, is widely recognized as the ultimate arbiter of food quality[10]. Consequently, a strong relationship exists between food quality and storage stability.

In a review, Boukid et al.[11] reported that enzyme inactivation contributes to prolonged storage stability, citing studies in which microwave radiation was used to inactivate lipase in wheat germ. Similarly, Sawhney *et al.*[12] and Correia *et al.*[13] demonstrated that water activity is a key determinant of food deterioration and recommended its modification to enhance storage stability.

Factors influencing storage stability may be classified as inherent (intrinsic) or environmental (extrinsic). Intrinsic factors include water activity, available oxygen, nutrient composition, biochemical products (type and quantity of enzymes present), moisture content, biological structures, natural microflora and surviving microbial populations, pH (total acidity and acid type), preservatives (such as sugar and salt), antimicrobial components, nutrient content and oxidation-reduction potential. Extrinsic factors encompass cultural practices during production, time-temperature profiles during processing, temperature and relative humidity control during storage and distribution, exposure to light (UV and IR) during processing, storage and distribution, microbial environment, packaging atmosphere composition, subsequent heat treatments (e.g. reheating or cooking prior to consumption), mechanical handling during distribution and consumer handling practices[14,15]. Sensory quality of food products is commonly evaluated through taste and aroma. Overall, storage stability can be enhanced through appropriate storage conditions, effective food processing techniques, the use of suitable packaging materials and the application of safe food additives.

Extrusion technology originated in the plastics industry for the processing of polymeric materials and was subsequently adopted by the food industry. Within the food sector, extrusion cooking is predominantly used in the manufacture of pet foods[16]. Food extrusion was initially applied in the late 1930s, while commercial extrusion cooking became established in the mid-1940s for the production of cornmeal snack products[17]. However, Emin[18] reported that the application of food extrusion dates back to the late nineteenth century. Extrusion cooking involves a series of unit operations[19] integrated into a single continuous process, during which diverse food ingredients are uniformly mixed and forcefully conveyed through a die[8]. This technology enables the development of a wide range of food products, including those formulated to meet the needs of specific consumer groups through the incorporation of functional constituents. Extrusion cooking is performed under controlled moisture conditions and is capable of producing food products in various shapes and sizes.

Extrusion technology is widely applied in the production of snacks, breakfast cereals, ready-to-eat foods and more recently, three-dimensional breakfast cereals and snack products. It is also utilized in the manufacture of pet treats, soy-based meat analogues and fish feeds[20]. Extrusion cooking is typically characterized as a High-Temperature, Short-Time (HTST) process and is particularly effective for the production of low-fat snack foods[21]. Mild extrusion conditions, involving high moisture content, very short residence time and relatively low processing temperatures, promote higher amino acid retention, fibre solubilization, enhanced protein and starch digestibility and the inactivation of antinutritional factors, toxins and deleterious enzymes such as peroxidases[22]. Although, extrusion cooking is fundamentally considered an HTST process[23], its application at lower temperatures has also been demonstrated, as in pasta production, where the primary function is shaping and moulding rather than thermal cooking. Additionally, extrusion cooking reduces water activity in food products. Yin et al.[24] reported that food preservation is increasingly challenged by pathogenic microorganisms worldwide, posing significant threats to public health and adversely affecting the global economy.

The high temperatures typically employed during extrusion cooking generally do not favour the survival of contaminating microorganisms[25], with the exception of thermophilic species capable of withstanding processing conditions. These thermophiles may originate from raw materials or persist within various components of the extruder, thereby serving as potential sources of post-processing contamination of the extrudate. In addition to temperature, mechanical shear forces generated within the extruder contribute significantly to the destruction of microbial cells and spores. Conversely, extrudates may become contaminated after processing through handling practices outside the extruder, including contact with personnel, packaging materials and the surrounding environment. The characteristics of packaging materials may further influence microbial growth in extruded products.

Extrudates typically exhibit low water activity, which is unfavourable for microbial proliferation. However, inadequate packaging and storage conditions may result in moisture uptake, leading to increased water activity, product deterioration and the establishment of favourable conditions for microbial growth and subsequent spoilage. Intrinsic factors such as pH and water activity determine the dominant microflora responsible for food spoilage, while storage stability plays a critical role in determining shelf-life. Novel food packaging technologies, including active packaging systems, contribute significantly to shelf-life extension by incorporating substances designed to inhibit undesirable changes in food products, such as oxygen scavengers, antioxidants and antimicrobial agents. Microorganisms are the primary agents of food spoilage and include bacteria, fungi, yeasts, moulds and certain protozoa[26]. Arêas *et al.*[27] reported that extrusion cooking inhibits biological activity while preserving nutritional value, thereby supporting its role as an effective food preservation method through the inactivation of microorganisms.

Collectively, these factors underscore the importance of producing stable food products and justify the need to review existing literature on the definition and components of food quality, to evaluate the storage stability of foods and to assess the effects of extrusion cooking on contaminating microorganisms.

Food quality

Definition of food quality: Some authors have attempted to define food quality (Table 1) but generally, food quality has to do with the acceptability of food products by consumers.

Components of food quality: Food quality encompasses both subjective (sensory) and nonsubjective (objective) attributes. Subjective attributes include texture, flavour and appearance, which are primarily assessed through sensory evaluation, whereas nonsubjective attributes comprise nutritional and microbial qualities, which are evaluated using instrumental and analytical methods. Objective assessments typically involve the use of instrumentation, such as atomic absorption spectrophotometry and physical measurement devices, including pH meters and viscometers, as well as chemical analyses, for example those used to assess rancidity. Objective tests are designed to measure specific properties associated with food quality and must be appropriate for the particular food product under evaluation. However, objective measurements alone do not determine overall food acceptability; therefore, objective and subjective evaluations are complementary approaches[33].

Food quality is dynamic and changes over time as a result of various reactions, including chemical reactions (e.g. oxidation), biochemical reactions (e.g. enzymatic browning catalysed by endogenous enzymes) and physical changes (e.g. particle aggregation and sedimentation). Chemical reactions often manifest as observable physical changes and many physical alterations are underpinned by chemical mechanisms, such as those leading to changes in texture[2]. Food quality is generally defined by three major components: food safety, organoleptic properties and nutrient content[40]. The composition of food strongly influences both its nutritional and sensory quality. Major food constituents include nutrients (proteins, carbohydrates, fats and oils), as well as water and enzymes, all of which contribute to the functional properties of the final product following processing. Each component possesses distinct physical and chemical characteristics that influence product quality.

Enzymes are naturally present in all biological organisms and are produced by living cells. These endogenous enzymes can contribute to food quality deterioration and therefore must be effectively controlled during processing. Extrusion cooking has been shown to inactivate endogenous enzymes, thereby enhancing food quality. Water plays a critical role in

Table 1: Definitions of food quality

Definition	References
Food quality is a combination of attributes or characteristics of a product that have significance in determining the degree of acceptability of the product to a user. These attributes include external factors such as appearance (size, shape, color, gloss and consistency), texture, flavor and internal composition (chemical, physical, microbial) Food quality also deals with product traceability (e.g., of ingredients), should a recall of the product be required. It also deals with labeling issues to ensure there is correct ingredient and nutritional information	Tanner[2]
Food quality is an expectation of consumers. To meet this consumer need, every food business should develop and use an effective quality control program. Failure to meet consumer demand can cause a decline in product sales and profitability. A major product failure can totally destroy a business	Hurst *et al.*[28]
Quality has a vast number of meanings and can encompass parameters as diverse as organoleptic characteristics, physical and functional properties, nutrient content and consumer protection from fraud. Furthermore, it can cover political and social issues such as wages paid to farm workers, geographical issues such as controlled appellations and religious issues such as halal and kosher.	Burlingame and Pineiro[29]
Food quality has two facets i.e. it can be considered as the most well defined or least well-defined concept in the food industry. None of the measures like microbiological, nutritional, or physiochemical characteristics serve adequate indices for food quality as food is a consumer based evaluative/perceptual construct specific to a person, time and place. 'Consumer acceptability' is the measurement that comes closest to an adequate index. Sensory quality is the major factor determining consumer acceptance for food products.	George *et al.*[30]
Food quality and safety are closely related to people's health and living standard and the risk assessment of food quality and safety has great social significance.	Han *et al.*[31]
Food quality could be explained as the totality of features and characteristics of food satisfying customers and the intended and unintended impact on relevant interested parties, according to the definition of quality specified in ISO 9000:2015; whereas food safety refers to the presence of food-borne hazards in food at the point of consumption. Definitions of food quality and food safety indicate that food safety in essence is one of the features and characteristics that compose food quality, despite that food safety is usually referred independent of food quality due to its importance to human health	Yang *et al.*[32]
Food quality can be defined as the degree of excellence of a food and includes factors such as taste, appearance and nutritional quality, as well as its bacteriological or keeping quality. Food quality goes hand in hand with food acceptability and it is important that quality is monitored, both from a food safety standpoint and to ensure that the public likes a particular product and will continue to select it. Quality is difficult to define precisely but it refers to the degree of excellence of a food and includes all the characteristics of a food that are significant and that make the food acceptable.	Vaclavik[33]
Food quality is the extent to which all the established requirements relating to the characteristics of a food are met. Food safety is the extent to which those requirements relating specifically to characteristics or properties that have the potential to be harmful to health or to cause illness or injury are met. Some food quality characteristics (e.g., counts of total bacteria, coliform bacteria) can be used as indicators of food safety, although they are not considered specifically as food safety characteristics.	Alli[34]
Quality definition of food includes several complex factors like physical, compositional and microbial features, modifications induced by technological processes or storage, nutritional value and safety.	Trimigno *et al.*[35]
The quality of a product should be defined according to consumer expectations and, more particularly, to those of target consumers.	Van Biesen *et al.*[36]
Food quality assessment is recognized as a critical component in contemporary food production systems, aimed at ensuring the safety and quality of products.	Zhang *et al.*[37]
Food quality is a multifaceted, evolving concept encompassing various aspects throughout the production chain.	Bagnulo *et al.*[38]
The term "quality" in food refers to a variety of characteristics, including technological, microbiological, sensory parameters and shelf-life. Food quality is critical to the food industry's productivity, driven by contextual and situational aspects that evolve over time	Bisht *et al.*[39]

food stability and instability in food systems has been associated with quality deterioration, as reported by Wijaya *et al.*[40]. Food stability encompasses physical, chemical and microbiological aspects, which are closely interrelated.

Microbial load is a key indicator of food quality, particularly in extruded products, as it directly relates to consumer safety and product shelf-life[41]. Obaroakpo *et al.*[42] reported a reduction in microbial flora following extrusion cooking. However, Eze *et al.*[43] noted that certain microorganisms with sublethal spore injury may recover and pose potential health risks to consumers. Monitoring food quality through analytical assessment is therefore essential for evaluating public health risks[44].

Food safety and quality are of particular importance during thermal processing, as spoilage microorganisms (yeasts, moulds and bacteria) and pathogenic organisms are inactivated; however, excessive heat treatment may also result in deterioration of food quality. To address these challenges, systems such as Hazard Analysis and Critical Control Points (HACCP) have been implemented to ensure food safety and facilitate the production of high-quality food products. During food processing, efforts are made to minimize chemical reactions and nutrient losses while preserving sensory attributes such as texture, colour and flavour, thereby enhancing consumer acceptability.

Storage stability of foods

Effect of packaging materials on storage stability: Packaging materials play a critical role in determining the storage stability of food products. Wani and Kumar[45] reported that packaging type significantly influences shelf-life, noting that extrudates stored in low-density polyethylene pouches may exhibit longer storage stability than those packaged in laminated pouches. The incorporation of antioxidants into packaging materials has been identified as an effective strategy for enhancing storage stability and extending shelf-life. In addition, storage stability may be improved through the removal of oxygen from food products during packaging, thereby limiting oxidative reactions[46,47].

Ogunmuyiwa *et al.*[48] reported that the storage stability of wheat flour can be enhanced by the removal of bran during milling. In the case of table eggs, the thickness of shell membranes has been shown to influence storage stability. Imai *et al.*[49] observed that quail eggs exhibited superior storage stability compared with chicken eggs, attributed to the thicker shell membrane of quail eggs. Ottaway[50] further reported that inadequate processing and storage practices may negatively affect the vitamin content of processed foods. Factors influencing vitamin stability include exposure to oxygen, light, moisture, heat and variations in pH.

Mu *et al.*[51] emphasized that particular care must be taken during the packaging of carotenoid-rich products, such as sweet potato snacks, as carotenoids are highly susceptible to degradation. Degradation may occur due to the presence of oxygen in the package headspace, light transmission through the packaging material, oxygen permeability of the package, dissolved oxygen within the product, defects in the hermetic seal of the packaging material and inappropriate storage conditions, including storage duration and temperature. Collectively, these factors substantially influence the storage stability of packaged sweet potato snacks.

The type and intrinsic properties of a food product largely determine the dominant factors affecting its storage stability. For instance, peanuts are rich in lipids; therefore, lipid oxidation is the primary cause of shelf-life reduction and the development of off-flavours. Gong *et al.*[52] reported that packaging conditions, vitamin E content and storage temperature significantly affect lipid oxidation in roasted peanuts. Furthermore, Gong *et al.*[52] noted that the stability of peanut butter is influenced by fatty acid composition, particularly oleic and linoleic acids and concluded that peanuts with a high oleic acid content are more suitable for peanut butter production.

Ngamwonglumlert and Devahastin[53] reported that the microstructure and composition of dried food products significantly affect their storage stability. Highly porous products possess greater surface area exposure and are therefore more susceptible to oxygen and moisture uptake, as well as light exposure. Products with an amorphous structural arrangement are more prone to moisture and oxygen absorption, whereas those with a crystalline structure generally exhibit greater stability during storage[53]. Consequently, these factors must be carefully considered when selecting appropriate packaging materials to ensure optimal storage stability of food products.

Storage stability of extruded food products: During the storage of extruded food products, several factors, including storage conditions and the initial moisture content of the product, may contribute to quality deterioration, particularly rancidity[54]. Storage conditions such as temperature and relative humidity play a critical role in influencing product stability[55]. Lee and Lee[56] suggested that shelf-life can be extended by maintaining food moisture content at levels unfavourable for microbial growth. They further emphasized that equilibrium relative humidity is a key parameter for enhancing the storage stability of food products[56].

Kocherla *et al.*[54] evaluated the storage stability of extruded snacks by monitoring changes in moisture content during storage in different packaging materials, namely Metallized Polyethylene Terephthalate (MPET) and High-density Polyethylene (HDPE). Their findings indicated that MPET exhibited superior moisture barrier properties, as reflected by lower moisture content of the extrudates after three months of storage, with values ranging from 2.1-3.8% and 2.1-3.3% for HDPE and MPET, respectively.

Effect of moisture content on storage stability of foods: Moisture content is a critical determinant of the storage stability and textural quality of extruded foods. Kocherla *et al.*[54] reported that maintaining a low moisture content (1.8-2.4%) is essential for preserving the crispness of extruded snacks. David *et al.*[57] identified an acceptable upper moisture limit of 10% for flour to ensure improved storage stability, which is consistent with the findings of Awolu[58], who reported that moisture content should be equal to or below 10% to achieve shelf stability. Extrusion cooking is generally characterized as a low-moisture processing method, as moisture content increases, the degree of product expansion typically decreases[59]. However, exceptions have been observed for protein-rich formulations. Singh *et al.*[60] reported that extrusion at low temperature and high moisture content is more favourable for the production of protein-based products. Under conditions of high moisture, very low temperature and short residence time, extrusion cooking results in greater amino acid retention.

Kocherla *et al.*[54] further noted that the use of packaging materials with effective barrier properties, particularly against moisture, or the application of modified atmosphere packaging, is essential for maintaining texture and improving the keeping quality of extruded snacks. Although, oxidation does not typically occur during the extrusion process itself, flavour deterioration during subsequent storage remains a significant quality concern[61].

Effect of water activity on the storage stability of foods: The low water activity of extruded food products, typically ranging from 0.682-0.703, is largely due to their low moisture content[62]. Similarly, other dry food products, such as confectionery items, exhibit water activity values between 0.20 and 0.80, which substantially limits microbial spoilage[63]. The low water activity observed in these products corroborates moisture content data, confirming their dry nature. Very dry food products are generally expected to be microbiologically and chemically stable during handling and storage, as the availability of water for microbial metabolism and chemical reactions is governed by water activity.

In the food industry, microbial growth is commonly controlled through key parameters, including pH, water activity and temperature. However, moulds are more adaptable than bacteria and may survive under conditions that inhibit bacterial growth[64]. Foods with a water activity below 0.85 are classified as low water activity foods[65]. At such low water activity levels, the risk of microbial hazards, including spoilage and foodborne illness, is minimal. This is because the minimum water activity required for the growth of most fungi is approximately 0.85, whereas most bacteria require a higher threshold of about 0.94. Only certain yeasts and moulds are capable of growth at water activity values below 0.85[66].

Nevertheless, if storage abuse occurs and products absorb moisture, fungal growth is more likely to initiate at the product surface, where water uptake begins and oxygen availability is relatively high. In addition to microbial stability, products with low water activity are generally more resistant to physicochemical deterioration. At low water activity levels, solid components become more concentrated and the food matrix more viscous, which restricts the diffusion and mobility of reactants, thereby reducing the rate of physicochemical degradative reactions. Although. most bacteria and fungi are unable to grow at water activity levels below 0.85, xerophilic fungi can proliferate under these conditions and may cause visible spoilage even at water activity values lower than 0.85[63].

Effect of extrusion cooking on contaminating microorganisms

Destruction of bacterial spores during extrusion cooking: Extrusion cooking has been widely reported to reduce levels of contaminating microorganisms in food products[67]. Although mycotoxins produced by moulds are generally considered heat-stable toxic compounds, extrusion cooking has been shown to significantly reduce their concentration. For instance, aflatoxins present in corn and peanuts are markedly reduced during extrusion cooking without compromising the nutritional quality of the food. Cazzaniga *et al.*[68] demonstrated that extrusion cooking effectively reduced mycotoxin levels in corn flour when appropriate processing conditions were applied, with extrusion temperatures of approximately 160°C or higher being required to achieve substantial reductions.

Bullerman and Bianchini[69] reported that the addition of 10% glucose to fumonisin-contaminated corn grits prior to extrusion cooking resulted in a considerable reduction (75-85%) in fumonisin content. Furthermore, feeding trials using the extruded products revealed a significant decrease in expected toxicity in experimental rats. In another study, Quéguiner *et al.*[70] inoculated whey protein isolate powder with viable *Streptococcus thermophilus* (5×10 CFU/g) and subjected it to low-moisture extrusion cooking in a twin-screw extruder under controlled conditions of barrel temperature and length, screw configuration and speed, residence time, feed rate and moisture content. They reported a reduction in *S. thermophilus* populations in the extrudate ranging from $10^{4.2}$ - to $10^{4.9}$-fold.

Likimani *et al.*[71] developed an extrusion cooking protocol using a single-screw extruder that effectively destroyed *Bacillus globigii* spores in a 70% corn and 30% soybean (w/w) mixture at 18% moisture content, with residence times ranging from 1.7 to 6.6 sEC and maximum mass temperatures between 100°C and 115°C. The spores were found to be most sensitive at mass temperatures exceeding 95°C. Using a similar methodology, Likimani and Sofos[72] investigated the extent of injury caused by extrusion cooking to *Bacillus globigii* spores in a 70:30 (w/v) corn–soybean mixture. The isolate studied was *Bacillus subtilis* var. *niger* (ATCC 9372). Extrusion cooking was conducted using two barrel temperature zones (Zone 1: 80°C, constant; Zone 2: 100-140°C). Post-extrusion recovery and enumeration of spores were performed using five culture media ranging from minimal to nutrient-rich compositions. Viable spores, including those present in low numbers, were successfully recovered using all media. The authors concluded that extrusion cooking can effectively inactivate bacterial spores even at relatively low processing temperatures.

Zepeda *et al*.[73] inoculated a beef-based product with *Clostridium sporogenes* PA 3679 spores (4 log CFU/g) prior to extrusion cooking in a twin-screw extruder at 72°C. Their results showed reductions of 3.63 log cycles in aerobic plate counts and 2.02 log cycles in viable cell counts of *C. sporogenes*. Similarly, Zhang *et al*.[74] inoculated concentrated gelatin with the heat-resistant bacterium *Microbacterium lacticum* and processed it using a twin-screw extruder. A 5.3 log reduction was observed at a pressure of 409 kPa, a die-end temperature of 73°C and a residence time of 49-58 sec. Microorganisms were not detected above the minimum detection limit of 2×10 CFU/sample, indicating complete inactivation. The authors further suggested that physical forces generated around the screws and die, in addition to thermal effects, contribute to microbial destruction during extrusion.

Thermophilic bacterial spores are generally more heat-resistant than those of certain heat-stable anaerobic mesophiles. *Bacillus stearothermophilus* is a representative thermophilic bacterium commonly used as a biological indicator in moist heat treatment processes. Fraiha *et al*.[75] reported that *B. stearothermophilus* serves as an effective biological indicator for evaluating the sterilization efficiency of extrusion cooking, emphasizing that factors beyond temperature, such as mechanical shear, also contribute to bacterial inactivation.

Saalia and Phillips[76] extruded naturally and artificially aflatoxin-contaminated peanut meals separately under varying moisture levels, pH values and extruder die diameters. They observed the highest reductions in aflatoxin levels at moisture contents of 35 and 20 g/100 g for naturally (59%) and artificially (91%) contaminated peanut meals, respectively and concluded that extrusion cooking is more effective in reducing aflatoxins in artificially contaminated samples. In a subsequent study, Saalia and Phillips[77] mixed a nucleophile with peanut meal at 2 g/100 g and spiked the samples with aflatoxin standards prior to extrusion cooking in a single-screw extruder. Extrusion processing resulted in an 84% reduction in aflatoxin content, decreasing from 417.72 to 66.87 µg/kg.

Janić Hajnal *et al*.[78] reported that extrusion processing led to optimal reductions in Alternaria toxins in whole wheat flour, with moisture content and screw speed being key determinants of toxin reduction. Scudamore *et al*.[79] investigated the effects of extrusion cooking on *Fusarium* mycotoxins in maize grits and flour and observed significant reductions in fumonisin content following extrusion. Additionally, Castells *et al*.[80] formulated corn-based breakfast cereals to reduce fumonisin B1 by incorporating varying levels of malt, salt and sugar prior to extrusion cooking. Their results indicated that fumonisin B1 reduction was greatest in formulations containing the highest salt concentration.

CONCLUSION

Food quality reflects the degree of acceptability of a food product to consumers and, consequently, consumer preferences play a central role in guiding processing decisions within the food industry. The objective of food production is compromised when products are rejected by consumers, particularly when rejection is attributable to perceived quality deficiencies. Maintaining storage stability is therefore essential for preserving food quality and ensuring product integrity throughout shelf-life, ultimately supporting consumer acceptance. As the end users, consumers are widely regarded as the ultimate arbiters of food quality, as reflected in their purchasing decisions. Extruded food products are generally expected to be microbiologically safe due to the severe processing conditions involved, including high temperatures and intense shear forces generated within the extruder. However, the presence of microorganisms in extruded foods may arise from the survival of resistant microorganisms during extrusion cooking, post-extrusion contamination, or inadequate packaging and storage conditions. Among these factors, post-processing handling and poor packaging practices are likely the primary contributors to microbiological spoilage in extruded food products.

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