International Journal of Agriculture and Food Science 2026; 8(8): 30-34

ISSN Print: 2664-844X
ISSN Online: 2664-8458
NAAS Rating (2026): 4.97
IJAFS 2026; 8(8): 30-34
www.agriculturaljournals.com
Received: 11-04-2026
Accepted: 14-05-2026

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Nutritional Quality and Health Benefits of Extruded Snack

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DOI: https://www.doi.org/10.33545/2664844X.2026.v8.i8a.1754

Abstract
The increasing demand for convenient yet nutritious foods has accelerated the development of healthier snack products using extrusion technology. Hot extrusion is a high-temperature, short-time process that transforms cereal and pulse-based ingredients into ready-to-eat snacks with desirable texture, extended shelf life and enhanced nutritional quality. During processing, structural changes such as starch gelatinization, protein denaturation and dietary fibre modification improve digestibility and reduce antinutritional compounds, thereby enhancing nutrient availability. At the same time, careful optimization of processing conditions is essential to minimize losses of heat-sensitive vitamins and bioactive compounds. The incorporation of functional ingredients, including whole grains, legumes, millets, resistant starch, dietary fibre, oilseeds and fruit or vegetable by-products, further improves the nutritional profile and health-promoting properties of extruded snacks. Evidence suggests that these products may support healthy body weight, glycemic regulation, cardiovascular function, gut health and antioxidant defense. Therefore, extrusion technology represents an effective and sustainable strategy for developing innovative functional snacks that align with current consumer preferences and public health objectives.

Keywords: Hot extrusion, nutritional quality, functional snacks, bioactive compounds, sustainable food systems

Introduction

Snack foods have become an integral component of modern dietary patterns due to increasing urbanization, changing lifestyles and growing demand for convenience foods. Consumers highly prefer foods that require minimal preparation while offering good sensory characteristics and can be stored for long. Traditionally, snack products such as potato chips, fried namkeens and corn puffs were prepared by deep-fat frying, resulting in products that are high in calories, saturated fat, sodium and digestible carbohydrates but relatively poor in essential nutrients and bioactive phytochemicals. The excessive consumption of energy-dense snack foods has been associated with an increased risk of obesity, type 2 diabetes mellitus, cardiovascular diseases, hypertension and metabolic syndrome. These health concerns have encouraged consumers to look towards healthier options that combine convenience with improved nutritional quality. Keeping this in mind, extrusion cooking has emerged as one of the most promising food processing technologies for producing nutritious, shelf-stable and sensory acceptable snack products (Singh *et al.* 2007). Modern extrusion systems integrate several unit operations including conveying, mixing, cooking, kneading, shearing, shaping and partial dehydration within a single continuous operation. Two types of extrusion cooking methods prevail *viz.* cold extrusion and hot extrusion. Hot extrusion is generally classified as a high-temperature short-time (HTST) process in which food materials are subjected to temperatures ranging from approximately 100 to 200°C under elevated pressure for a relatively short residence time, usually less than one minute. During extrusion, the combined effects of heat, pressure, moisture and mechanical shear induce extensive structural modifications in food macromolecules. Starch granules undergo gelatinization and partial dextrinization, proteins become denatured and reorganized, dietary fibre is modified and several antinutritional compounds are inactivated. These physicochemical changes contribute to improved digestibility, enhanced expansion and desirable texture.

Extrusion also improves the nutritional quality of the ingredients by decreasing antinutritional compounds such as phytates, tannins, lectins and protease inhibitors. Reduction of these compounds enhances mineral bioavailability and protein digestibility. Extruded snacks fortified with whole grains, legumes, dietary fibre, prebiotics, antioxidants and plant proteins increasingly fit within this definition (Singh *et al.* 2007) Furthermore, extrusion processing offers opportunities to improve food sustainability by utilizing underexploited crops such as millets, sorghum, pulses and agricultural by-products including fruit pomace and vegetable residues. These ingredients not only enhance nutritional quality but also support circular economy approaches by reducing food processing waste and promoting sustainable food systems (Grasso, 2020) [5].

Physicochemical and nutritional transformations during extrusion

The nutritional value and functional properties of extruded snacks are largely determined by the physicochemical changes occurring during extrusion. These transformations result from the combined effects of heat, pressure, moisture and mechanical shear. Depending on processing conditions, extrusion may simultaneously enhance digestibility and reduce antinutritional compounds while also causing partial losses of heat-sensitive nutrients. Consequently, optimizing extrusion conditions has become essential to maximize nutritional quality without compromising product expansion or sensory characteristics (Ali *et al.* 2024) [1].

Starch gelatinization and dextrinization

Starch is the primary structural component responsible for expansion in the extruded snacks. During extrusion, water penetrates starch granules while increasing temperature disrupts crystalline regions, resulting in gelatinization. Gelatinized starch forms a continuous viscoelastic matrix capable of trapping steam bubbles during die expansion, thereby producing the characteristic porous structure of expanded snacks (Li *et al.* 2014) [7].

Increased starch digestibility generally improves energy availability. Although increased digestibility is advantageous in terms of nutrient utilization, excessive gelatinization may accelerate glucose release during digestion and increase the glycemic index (GI) of starch-rich products. This limitation has encouraged researchers to incorporate resistant starch, whole grains, legumes and dietary fibre into extrusion formulations to moderate postprandial glucose responses (Sadaat *et al.* 2020).

The nutritional implications of starch transformation therefore depend on the balance between gelatinization and resistant starch formation. Functional extruded snacks formulated with oats, barley, sorghum, millets and legumes often exhibit lower predicted glycemic indices than conventional corn-based snacks while maintaining desirable expansion characteristics (Qui *et al.* 2024).

Protein denaturation

Proteins undergo unfolding, aggregation and partial cross-linking during extrusion. Moderate denaturation improves enzyme accessibility, resulting in enhanced protein digestibility. Plant proteins derived from legumes and oilseeds frequently contain antinutritional compounds such as trypsin inhibitors, lectins and protease inhibitors that interfere with digestive enzyme activity. Extrusion inactivates these compounds and enhance the protein digestion and amino acids availability. This improvement is necessary for cereal-legume blends, where complementary amino acid profiles can improve overall protein quality (Singh *et al.* 2007).

Nevertheless, excessive thermal exposure may reduce lysine availability through Maillard reactions with reducing sugars, particularly under low-moisture processing conditions. Consequently, optimization of barrel temperature and moisture content is essential for balancing digestibility and amino acid retention (Ali *et al.* 2024) [1].

Protein denaturation also influences functional properties such as water absorption, emulsification, foaming and gel formation. These characteristics contribute to the structural stability of expanded products and affect texture, mouthfeel and consumer acceptability (Ruihan *et al.* 2017) [12].

Protein digestibility is also influenced by ingredient selection. Extruded snacks containing soybean, pea protein isolate, lentil flour, chickpea flour, whey protein concentrate or milk proteins generally exhibit higher protein digestibility than cereal-only formulations. Furthermore, blending cereals with legumes improves amino acid balance by complementing lysine-deficient cereal proteins with lysine-rich pulse proteins (Sucapuka *et al.* 2021)

Dietary fibre modification

Extrusion significantly alters the physicochemical properties of dietary fibre. It modifies the fibre structure through depolymerization of complex polysaccharides. Mechanical shear and thermal treatment partially convert insoluble fibre into soluble fibre, increasing water-holding capacity, swelling behaviour and fermentability. Soluble dietary fibre delays gastric emptying, slows glucose absorption, reduces serum cholesterol concentrations and supports beneficial intestinal microorganisms through production of short-chain fatty acids (Singh *et al.* 2007).

Consequently, fibre-rich extruded snacks often exhibit greater density and reduced expansion ratios. Advances in twin-screw extrusion and ingredient optimization have substantially improved the manufacture of highly expanded fibre-enriched snacks while preserving their nutritional advantages (Grasso, 2020) [5].

Lipid transformations

Lipids play a relatively minor structural role during extrusion but strongly influence expansion behaviour and oxidative stability. Lipid oxidation generates volatile aldehydes, ketones and peroxides that impair flavour quality while reducing nutritional value (Singh *et al.* 2007).

The incorporation of omega-3-rich ingredients such as flaxseed, chia seed or fish oil presents additional formulation challenges because polyunsaturated fatty acids are highly oxidation-prone. Recent investigations have therefore explored encapsulation technologies and antioxidant-rich ingredients to improve oxidative stability during extrusion and storage. Natural antioxidants present in whole grains, legumes, spices and vegetable powders may contribute to improved lipid stability by scavenging free radicals generated during processing (Brennan *et al.* 2011) [3].

Table 1: Influence of process variables on extruded product quality

Processing variable	Low level	High level	Nutritional impact	Physical impact
Barrel temperature	Incomplete cooking	Greater cooking	Increase digestibility, decrease heat-sensitive vitamins	Increase expansion
Feed moisture	High viscosity	Low viscosity	Better vitamin retention at moderate moisture	Reduced expansion at excessive moisture
Screw speed	Lower shear	Higher shear	Improved digestibility; excessive shear may degrade nutrients	Better mixing and expansion
Feed composition	High starch	High protein/fibre	Improved nutritional quality	Lower expansion if not optimized
Die diameter	Larger	Smaller	Minimal direct effect	Greater expansion pressure
Residence time	Short	Long	Longer exposure increases nutrient loss	More complete cooking

Source: Singh *et al.* (2007); Brennan *et al.* (2011); Ali *et al.* (2024) [1, 3].

Table 2: Effect of extrusion on vitamin content of extruded products

Vitamin	Stability during extrusion	Major cause of loss	Nutritional implication
Vitamin C	Low	Thermal oxidation	Reduced antioxidant capacity
Thiamine (B_1)	Moderate	Heat degradation	Lower vitamin retention
Riboflavin (B_2)	Good	Minor thermal degradation	Generally retained
Niacin (B_3)	High	Minimal degradation	Good retention
Folate	Moderate	Heat sensitivity	Reduced folate availability
Vitamin A	Moderate	Oxidation	Carotenoid degradation possible
Vitamin E	Moderate–High	Oxidation	Depends on processing severity

Source: Brennan *et al.* (2011); Singh *et al.* (2007) [3].

Table 3: Effect of hot extrusion on bioactive compounds and antinutritional factors of extruded products

Component	Effect of extrusion	Nutritional significance
Phenolic compounds	Variable (release or degradation)	May increase bio accessibility
Flavonoids	Moderate reduction at high temperatures	Antioxidant protection depends on formulation
Carotenoids	Partial degradation	Better retained under moderate processing
Betalains	Heat sensitive	Require optimized temperature
Phytic acid	Significant reduction	Improved Fe, Zn and Ca bioavailability
Trypsin inhibitors	Strong reduction	Improved protein digestibility
Lectins	Strong reduction	Improved intestinal tolerance
Tannins	Moderate reduction	Increased protein utilization
Oxalates	Slight to moderate reduction	Improved calcium absorption

Source: Singh *et al.* (2007); Brennan *et al.* (2011); Grasso (2020) [5, 3].

Health benefits of functional hot extruded snacks

The nutritional quality of modern extruded snacks has improved considerably with the incorporation of whole grains, legumes, dietary fibre, resistant starch, fruit and vegetable powders, oilseeds, probiotics and plant proteins. The health-promoting properties of extruded snacks are determined not only by ingredient composition but also by extrusion-induced changes. Recent studies indicate that functional extruded snacks may support weight management, glycemic regulation, cardiovascular health, gastrointestinal function, immune responses and antioxidant defense. However, these benefits are highly dependent on product formulation and optimized processing conditions.

Role in Weight Management and Obesity Prevention

Extruded snacks enriched with protein and dietary fibre have demonstrated considerable potential in weight management. Protein exerts a greater thermogenic effect than carbohydrates or lipids and stimulates the secretion of satiety hormones such as peptide YY (PYY), glucagon-like peptide-1 (GLP-1) and cholecystokinin (CCK). Increased secretion of these hormones delays gastric emptying and prolongs feelings of fullness, thereby reducing subsequent energy intake (Blundell *et al.* 2015). Dietary fibre further enhances satiety by increasing gastric distension, slowing nutrient absorption and prolonging digestion. Soluble fibres, including β-glucan, pectin, inulin and resistant starch, form viscous gels within the gastrointestinal tract that reduce gastric emptying rates and decrease postprandial hunger (Dhillon *et al.* 2016) [4]. The combined effects of reduced caloric density, increased protein content and enhanced dietary fibre suggest that functional extruded snacks may represent valuable dietary tools for obesity prevention and weight management (Sucapuca *et al.* 2021) [15].

Glycaemic Control and Diabetes Management

Legume-enriched extruded snacks possess lower glycemic responses because proteins and fibres reduce enzymatic access to starch granules while delaying gastric emptying. Resistant starch formed during extrusion and subsequent cooling escapes digestion in the small intestine and undergoes fermentation within the colon, producing short-chain fatty acids that improve insulin sensitivity and glucose homeostasis (Bayomy *et al.* 2024) [14]. Millets, barley, oats, sorghum and pulse flours have attracted considerable attention due to their naturally low glycemic characteristics. Their incorporation into extruded snacks reduces rapidly digestible starch while increasing slowly digestible starch fractions. In addition, soluble fibres such as β-glucan reduce glucose absorption by increasing intestinal viscosity (Qiu *et al.* 2024; Singh *et al.* 2024).

Cardiovascular Health

Plant proteins derived from legumes improve lipid metabolism by replacing saturated fat-rich animal protein sources. Soluble dietary fibre, particularly β-glucan, binds bile acids within the intestine, increasing their excretion and stimulating hepatic conversion of cholesterol into bile salts (Reynolds *et al.* 2019) [11]. Polyphenols, tocopherols, carotenoids and flavonoids contribute antioxidant protection by reducing oxidative modification of LDL particles and attenuating endothelial dysfunction. This mechanism contributes to reductions in circulating low-density lipoprotein (LDL) cholesterol concentrations (Brennan *et al.* 2011) [3].

Gastrointestinal Health and Gut Microbiota

Extrusion modifies dietary fibre through partial depolymerization, increasing the proportion of soluble fibre available for microbial fermentation. Resistant starch and soluble non-starch polysaccharides escape digestion in the upper gastrointestinal tract and are metabolized by beneficial bacteria in the colon (Singh *et al.* 2007).

Fermentation produces short-chain fatty acids (SCFAs), primarily acetate, propionate and butyrate, which provide numerous physiological benefits. Butyrate serves as the primary energy source for colonocytes and contributes to maintenance of intestinal barrier integrity, whereas propionate and acetate influence hepatic glucose metabolism, lipid metabolism and immune regulation (Makki *et al.* 2018), Grasso (2020) [5, 8] noted that incorporation of pulse flours and fibre-rich ingredients into extruded snacks enhances their prebiotic potential and may promote the growth of beneficial bacterial populations, thereby supporting gut health.

Antioxidant and Anti-inflammatory Potential

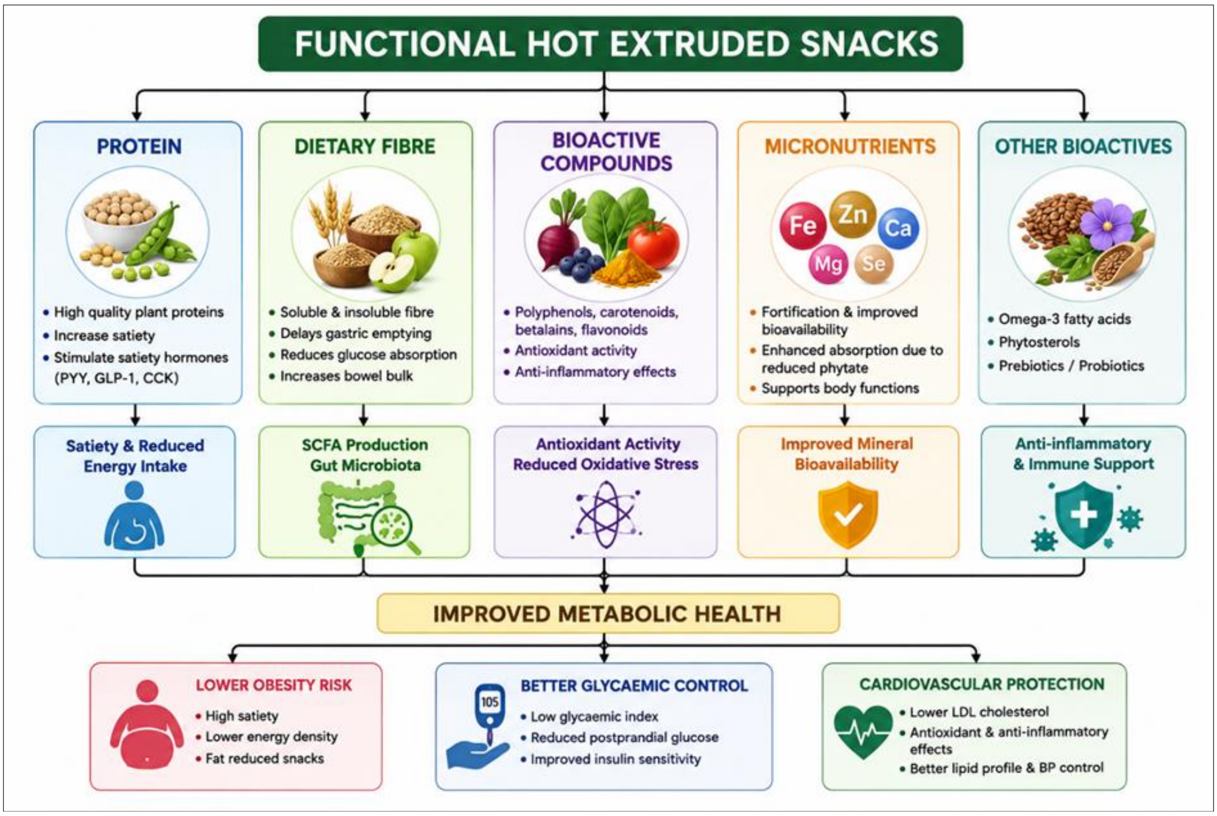
Modern extruded snacks increasingly incorporate antioxidant-rich ingredients such as coloured cereals, beetroot, spinach, carrot, tomato, moringa, turmeric, berries, herbs and fruit pomace. These ingredients supply phenolic acids, flavonoids, carotenoids, betalains, tocopherols and vitamin C (Grasso, 2020) [5]. Although certain antioxidants may undergo partial degradation during extrusion, mechanical disruption of plant tissues simultaneously increases the bio accessibility of previously bound phytochemicals (Brennan *et al.* 2011) [3].

Therefore, functional extruded snacks enriched with antioxidant-rich ingredients may contribute to long-term reduction of oxidative damage and chronic inflammation.

Table 4: Functional ingredients of extruded products and its association with metabolic health

Functional ingredient	Principle bioactive component	Physiological effect	Potential health benefit
Oats	β-Glucan	Delays glucose absorption	Diabetes management
Barley	Soluble fibre	Cholesterol reduction	Cardiovascular protection
Chickpea	Protein + fibre	Increased satiety	Weight management
Lentil	Resistant starch	Lower glycemic response	Diabetes prevention
Flaxseed	Alpha-linolenic acid	Anti-inflammatory activity	Heart health
Chia seed	Dietary fibre	Improved bowel function	Gut health
Millets	Polyphenols + fibre	Reduced postprandial glucose	Metabolic health
Fruit pomace	Polyphenols	Antioxidant activity	Chronic disease prevention

Source: Grasso (2020); Reynolds *et al.* (2019); Makki *et al.* (2018) [5, 11, 8].



Conclusion

Hot extrusion technology has become an effective approach for producing nutritionally enhanced snack foods with significant health benefits. The extrusion process improves starch and protein digestibility, increases soluble dietary fibre and mineral bioavailability reducing major antinutritional factors, thereby enhancing the overall nutritional quality of food. When formulated with whole grains, millets, legumes, pseudocereals, fruits, vegetables and oilseeds, extruded snacks become rich sources of dietary fibre, high-quality proteins, essential minerals, vitamins and bioactive compounds.

Regular consumption of these functional extruded products may support improved glycemic control, enhanced gut health, greater satiety, better cardiovascular health and stronger antioxidant defense, thereby contributing to the prevention of obesity, diabetes, cardiovascular diseases and other lifestyle-related disorders. Although some heat-sensitive nutrients may be affected during processing, careful optimization of extrusion conditions can minimize these losses while preserving nutritional value.

Overall, hot extrusion represents one of the most promising technologies for producing the next generation of functional snack foods by simultaneously improving nutritional quality, promoting sustainability and meeting the increasing consumer demand for healthier, convenient and environmentally responsible food products.

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