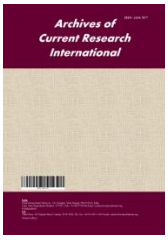

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Extrusion Technology: A Tool for Value Addition to Food By-Products and Wastes

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The food processing industry generates an immense amount of waste and by-products, which leads to major concerns about the environment. However, most of these wastes, such as plant-derived by-products, are still nutritionally adequate for use in food manufacturing processes. Extrusion technology has brought rapid transformation, new research ideas, opportunities and innovations in the food processing industries. Owing to its versatile nature and many advantages it has over other types of processing methods, a wide range of food raw materials could be processed conveniently which are microbiologically safe and also retain nutrients under carefully selected conditions. It is effluents free during processing; therefore, has no negative impact on the environment and fewer worries about waste or effluent disposal. It has been shown by many authors how extrusion technology is applied to process safe and convenient food products from industrial by-products and waste generated during processing. By-products such as bran, grits, hulls, grape pomace, carrot pomace, apple pomace, were combined or formulated with other food such as corn amongst others to make products like biscuits, pasta amongst using extrusion technology. This is carried out under a controlled process and system parameters to ensure the

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best product quality. Additionally, anti-nutritional factors present in some of these by-products can be minimized by the extrusion process for use as a food additive or in the formulation of balanced foods. This review features the past research on the value addition process by extrusion to food processing by-products and wastes from fruits and vegetables, cereals and pulses and oilseed (cakes) processing amongst others.

Keywords: Extrusion; wastes utilization; value addition by- products.

1. INTRODUCTION

Extrusion cooking is a high-temperature short-time or thermo-mechanical process in which heat transfer, mass transfer, pressure changes and shear are combined to produce effects such as, Cooking, Melting, Texturizing, Conveying, Puffing, Mixing, Kneading, Forming, reduction in microbial contamination, enzymes inactivation amongst others [1]. As the world population grows to an estimation of over seven (7) billion by 2017 and still counting, the demand for food products or food commodities, or rather safer and healthier foods is on the increase. The food industries are always innovating by creating solutions and also, new processing methodologies to address emerging challenges. There are various unit operations in the food industry that ensure food safety. Amongst the most common unit operations used in the low-moisture food processing industry is extrusion technology [2].

Extrusion provides a platform for processing a good number of food products, by simply altering a major or minor raw material and processing conditions. However, most Raw materials for extruded foods tend to be cereal flours and starch. Other ingredients from different food sources such as fruits and vegetable by-products amongst others could be incorporated, provided they meet the recommended raw material characteristics for extrusion processes [3].

The main reason for exploring several ingredients solely originates from the health-conscious consumers who want to have a product(s) that are rich in protein, lipids, vitamins, minerals and several other health benefits. Food industrial wastes/by-products imbibes all food residues that are left as a result of several unit operations that occur during production [4]. The Agricultural and food processing sector generates a lot of waste annually [5]. The accumulation of these products from the industries gives a negative impact on the environment owing to the issues regarding waste treatment and disposal. The wastes produced by the food industries are collected over different phases throughout the supply chain. For example, during harvesting, grading, sorting and processing stages [6]. There is a need to ascribe value or process these agricultural wastes and by-products into food products since they serve as cheap sources of dietary fiber, protein and bioactive compounds such as phenolic compounds, antioxidants, minerals and vitamins [6].

The processing of by-products and wastes could reduce its negative impacts on the environment and also improve the nutritional profile of products for human consumption [7,8]. Often, Agricultural by-products are seen as low-value assets and in the post-harvest stage, about 14% of food loss and waste have occurred worldwide [9]. Various By-products arise from different products and processes. For example, a good amount of pomace is generated during juice processing; bran, hull, husk, or pods are obtained during grain milling; and several oil cakes are produced in the oil industry [6]. These by-products or wastes also vary greatly in composition and functional properties; therefore, play an important role(s) in the determination of the characteristics of fortified products [10,6,11]. Agricultural wastes can be incorporated into value-added products which are manufactured using extrusion processing; since extrusion is a versatile technique that can handle a variety of raw materials with its energy-efficient process [10,12]. This is so because extrusion combines the simultaneous application of various unit operations, such as mixing, kneading, cooking and forming under high temperature, high shear and short-time processing technique [10,6] and also that, it is been an effective tool in the food process industry for the production of convenience foods of many attributes due to its very high energy efficiency, no effluents generation and productivity rate [1]. Extrusion technology could be used to salvage this waste or by-products by reintegrating them into processed food for human and animal (pets) consumption. Several reviews papers have been published on different aspects of food extrusion technology, which includes; vitamin stability during extrusion [13], changes in foods [14] and effects of process parameters on quality attributes [15]. Therefore, this review presents pertinent literature on food extrusion technology with regards to the processing, modifications and value addition to food by-products and wastes from fruits and vegetables, cereals, pulses and oilseeds. Tables 1 and 2 show the different food processing industries and main by-products or wastes generated and the composition of main components of some agro-food by-products (g/100gdm) respectively. While Fig. 1 presents the categories and number of articles published on extruded snacks with by-products in 2014-18.

1.1 Extrusion Technology

Extrusion is a combined act of mixing, shearing, kneading, cooking, compressing, and forcing a molten material, under high pressure, through a narrow opening (die) [16]. As the material left the opening, a sudden decrease in pressure translates water into steam, thus expanding the material. The extruded product is often called the extrudate. The shape of the extrudates generally reflects the shape of the die. Aside from the physical alteration, the process denatures protein, solubilizes fiber, gelatinizes starch, and induces crosslinking of biopolymers. This explains the significant changes in the functional and chemical properties of the material. As compared to other heat-involving food processing methods, extrusion results in a relatively small loss of nutritional value. Hence, since its introduction in the 20th century, it has been widely utilized in the manufacture of cereal-based products, snacks, frankfurters, pasta products, and meat analogs [16]. An extruder consists of one or two screw(s) rotating in a tightly fitting cylindrical barrel, which is equipped with a feeder at its inlet end and a die at its discharge end. Based on screw type, extruders can be grouped into the single-screw extruder (SSE) and twin-screw extruder (TSE) [16]. Selection for the right extruder depends on the interests of the manufacturer and the requirements of the process. SSE is relatively cheaper and simpler to operate compared to TSE. However, only a narrow range of materials with specific moisture and fat content are appropriate for SSE processing. A TSE provides greater flexibility over the range of products manufactured and the control over process parameters, such as pressure and temperature. Unlike SSE, TSE can process wet, viscous, and powdery ingredients. It is suitable to manufacture products with very low (<10%) and high moisture content, smaller particle size, and higher fat content. Nevertheless, TSE has a more complex design and higher capital cost compared to SSE [16].

1.2 Role of Extrusion in Product Development

Extrusion has also enabled the production of new processed food products and "revolutionized many conventional snack manufacturing processes". The extrusion process results in chemical reactions that occur within the extruder barrel and at the die. Extrusion has the following effects:

Table 1. Different food processing industries and main by-products or wastes generated

Food Industries	By- Products or Waste Generated
Fruits and vegetable industries	Peeling, stems, seed, bran, shell, trimming, residue after extraction of oil, starch, juice and sugar
Grain Processing Industries	Husk, hull, bran
Brewery and winery Industries	Brewery: spent grain, hot trub, residual yeast
	Grape growing and wine making process: vine pruning, grape stalk, grape pomace, grape seed, yeast lees, tartrate, carbon dioxide, wastewater
Marine industries	Viscera, heads, offal, backbone, bool, shels
Meat Industries	Carcasses, hides, hoofs, heads, feathers, offal, bone, manure, viscera, fat, meat trimings, blood
Dairy Industries	Whey, curd, Milk sludge

Adapted from Helkar et al., [23]

- Destruction of certain naturally occurring toxins
- Reduction of microorganisms in the final product
- Slight increase of iron-bioavailability
- Creation of insulin-desensitizing starches (a potential risk-factor for developing diabetes)
- Loss of lysine, an essential amino acid necessary for developmental growth and nitrogen management
- Simplification of complex starches, increasing rates of tooth decay
- Increase of glycemic index of the processed food, as the "extrusion process significantly increased the availability of carbohydrates for digestion"
- Destruction of Vitamin A (beta-carotene)
- Denaturation of proteins.

High-temperature extrusion for a short duration "minimizes losses in vitamins and amino acids". Extrusion enables mass production of some food, and will "denature anti nutritional factors", such as destroying toxins or killing microorganisms. It may also improve "protein quality and digestibility", and affects the product's shape, texture, colour, and flavor [16].

Also, the nutritional value in vegetable protein is usually enhanced by mild extrusion cooking conditions such that it increases the digestibility due to protein denaturation and inactivation of enzyme inhibitors present in raw foods. The process variables such as temperature, feed ratio, screw speed and length to diameter ratio plays a significant role in protein digestibility. The anti-nutritional factors such as trypsin inhibitors and tannis are destructed during extrusion cooking. The destruction of trypsin inhibitors increases with increase in extrusion temperature and moisture content. It was reported that for protein such as casein, the temperature at 153ºC, 20% moisture and 2 min residence time resulted with 89% reduction in trypsin inhibitors. Higher extrusion temperatures, lower feed moisture, longer residence time are key variables for the destruction of trypsin inhibitors [16]. In addition, the Maillard reaction plays a vital role during the processing of foods. The reaction involving an amino group of protein and carbonyl group of reducing sugars results in browning and flavor production. This reaction significantly decreases the availability of amino acids involved in protein digestibility [16].

Lysine appears to the most reactive amino acid as it has two amino groups and it was reported that the availability of this amino acid are in range of 32 to 40% at 170ºC, 10-14% feed moisture and 60 rpm screw speed. The availability of lysine is maintained by avoiding the extrusion temperature above 180ºC at water content below 15%. The amount of reducing sugars is also reduced during the extrusion process as they influence on the loss of lysine. As the extrusion process involves higher temperature, toxic compound known as acrylamide a probable carcinogenic agent is formed. The compounds are formed when the food substance is exposed to higher temperature <180ºC [16].The extrusion cooking also influences the total dietary fiber as changes in dietary profile is primarily due to the shift from insoluble dietary fiber to soluble dietary fiber. The mild extrusion temperature solubilizes some fiber components and in severe condition, the content increases owing to its increases in soluble dietary fiber and enzyme resistant starch fractions. The presence of vitamins is also influenced by the extrusion process where minimizing temperature and shear within the extruders tends to protect the nature of vitamins present in the food ingredients. Various precaution are done for controlling the loss of vitamins during extrusion such that post extrusion application are carried out [16]. The three main parameters, which influences on the consumption of food are product, nutritional and microbial quality. The products are subjected to high temperature that confers the crunchy nature of the product such that the texture and color are significant in terms of product quality. It is essential for the specialized nutritional foods such as infant and weaning foods to possess high starch digestibility as it has reduced calorie during the process of extrusion. The mild extrusion conditions tend to form nutritive foods as they provide high digestibility product. One of the most important criteria in terms of consumers' requirement is the microbial quality of the food. This process was found to be efficient as it involves higher temperature where the vegetative organisms are destroyed during the extrusion process [17].

1.3 Value Addition to Fruits and Vegetable by-products (Wastes)

Recently, studies on the evaluation of food by-products and wastes are rapidly expanding globally. Food-processing by-products and wastes are promising sources of compounds, which could be used due to their favorable technological or nutritional properties. Food-processing by-products and wastes cause the loss of several valuable constituents, which are vital for nutrition such as dietary fiber, antioxidants, essential fatty acids, antimicrobials, minerals. These constituents have many health benefits and many functional properties [18,19]. Grape skin and seeds are rich sources of monomeric phenolic compounds, such as catechin and epicatechin and acts as anti-mutagenic and antiviral agents. Grape seed extracts could be exploitable for the preservation of food products and also for health supplements and nutraceuticals [19]. Tomato seeds from tomato cannery waste have been reported to have appreciable amounts of digestible amino acids, methionine, cysteine and lysine [3]. Many fruit and vegetable residues such as apple pomace and orange peel, are rich in dietary fiber, which prevents and treats many diseases such as intestinal problems, cancer and diet-related health problems [19,20]. Several authors had investigated the use of apple pomace [21,22] and orange pulp including Strategies for efficient utilization of these agricultural industry residues and by-products have been the focus of several publications [20,9,23,24] as a source of dietary fiber and potential ingredient in bakery products [17]. By-products and wastes from fruits and vegetables alone could account for an estimated 30% of the processed material [24,25]. Some fruit and vegetable residues and by-products which have been used to develop extruded foods include but are not limited to those lists in Table 3.

Table 2. Composition of main components of some agro-food by-products (g/100gd.m.)

Food by-product	Water (fresh product)	Carbohydrates	Protein	Fat
Apple pomace[a]	65.90	84	6.3	6.6
Artichoke waste[a]	83.1	76.2	11.6	2.6
Broad bean pods[b]	86.5	78.4	13.6	1.3
molasses[c]	23	65.1	6.7	
Okara (soymilk by-product)[b]	80	58.7	33.4	8.5
Orange waste[a]	83.6	41	6	
Pea pod[b]	77.4	85	10.8	1.3
Paer pulp[c]		62.8	5.1	1
Potato peels[c]	85	69.7	8	2.6
Tomato pomace[d]	79	70.5	19.3	5.9
Whetat bran[c]	11	64.5	15.5	4.2
whey[c]	92.7	4.9	0.9	0.9
Protein rich by-product				
Linseed meal	8	38	36	0.5
Meat and bone meal	8		50	8
Peanut meal + hulls	9.5	23	45	5
Soybean meal	10	29.9	42	4
Yeast from breweries	5	39.5	43	1.5

Source: Mateos-Aparicio and Matias, (2019)

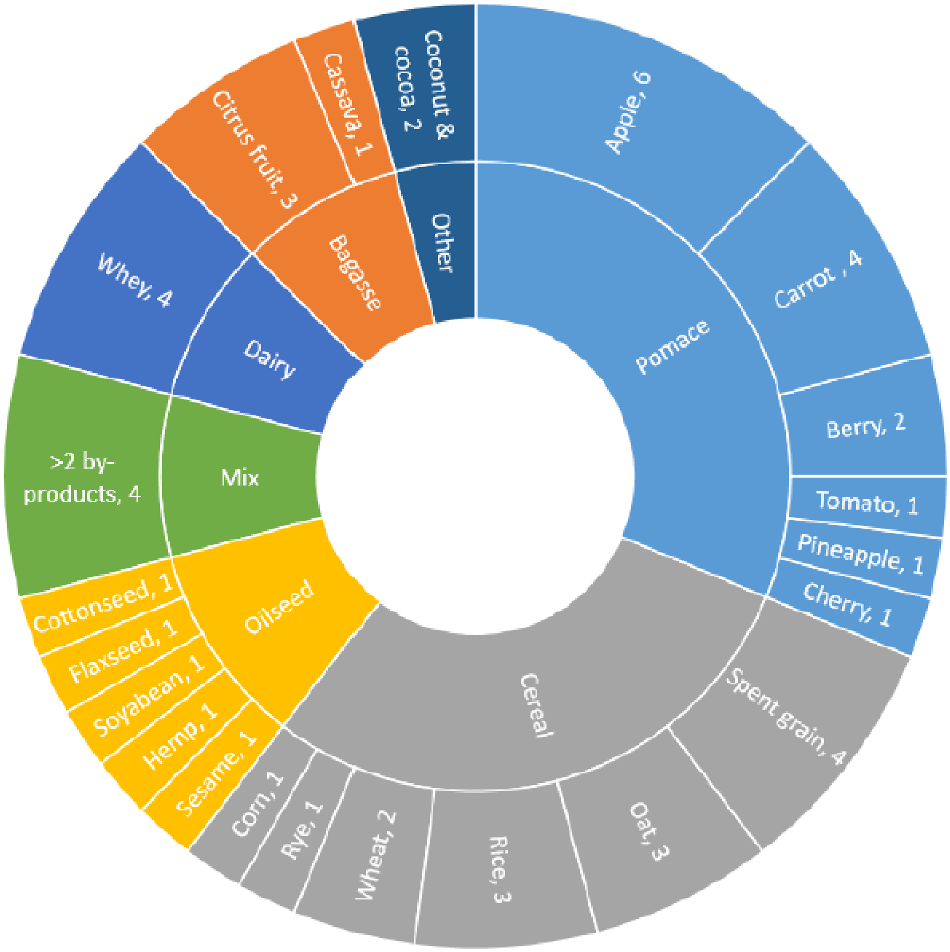

Fig. 1. Categories and number of articles published on extruded snacks with by-products in 2014-18

Source: Grasso, (2020)

1.4 Value Addition to Cereal by-products (Bran and Hulls)

Milling industries (Grain mills) are involved in milling cereals grain into flour or meal. Besides these, some industries use grains as a major source of their raw materials. These industries include the sugar (glucose and high fructose corn syrups) and starch, rice mills, breweries and distilleries amongst others. By-products from grains include rice polishing, dry milling and wet milling of grains for human food, animal feedstuff and industrial products. Dry milling is done for products like meal and flour, while the production of starch, syrups and oil is by wet milling. A large number of by-products of the processing of cereals are mainly used as animal feedstuffs. Although some brewing and distillation processes use starchy cereals, roots crops mostly sweet potatoes and cassava to produce alcoholic beverages as well as starch and sweeteners like glucose and high fructose syrups [26,27]. The by-product (wastes) terms like hulls, bran, germ, are often applied for multiple grains like rice, wheat, sorghum however, some terms may be exclusively used to describe a by-product of a specific grain. To meet consumer preferences, cereal grains for food are milled to separate the germ and bran, thereby removing important nutrients like vitamins and minerals [28]. Durum clear flour is a by-product obtained during semolina production; by collecting the line fractions of certain streams of the flour, which is extracted during grinding and composed of approximately 13–16% of the milled durum wheat. Durum clear flour is high in bran, high in protein (14–16%), ash (1.5–2%) and starch (about 65%) and slightly gray [19]. Durum clear flour is generally used as additives for improving gluten strength of low gluten grains such as rye and some bakery products such as bread. Co-products from the milling of wheat into flour include wheat husk, germ, bran and middling [29]. Wheat gluten is also obtained as a by-product from the manufacture of wheat starch. Dry gluten contains approximately 75% protein, 8% moisture and a little number of lipids, fiber and starch. Extrusion technology has been used to texturize wheat gluten and simulate the fibrous structure of meat [30]. Among the nut species, the hazelnut has great importance because of its special nutritional composition of proteins (15–19%), carbohydrates (15–17%), fat (60%) and vitamins [19]. Defatted hazelnut flour is residual of the hazelnut after the extraction of the oil parts from the main fruit, is high in protein (35–41%), fiber (10%) and other nutritional constituents [19]. Rice paddy milling to produce polished grains tends to yield broken rice in the process in addition to rice hull and bran. Cereal brans like those from rice are high in lipids making them very susceptible to rancidity. An ideal process may yield approximately 68–72% milled rice, 8–12% rice bran and 20% husk, depending on the rice variety used [31,32]. Example of the most common feed brans includes corn, rice and wheat bran amongst others. Table 4 show some by-products from cereals that are used to produce foodstuff by extrusion.

1.5 Value Addition to Oilseeds (Defatted Seed or Seed Cake) by-products

The major by-product of oilseed extraction is the cake. They are useful depending on the oilseed and methodology applied in extracting the oil. Methods of oil extraction, especially those involving heat, may eliminate or reduce anti-nutritional factors to some extent. This process may tend to denature some proteins, reduce the availability of certain amino acids and adversely affecting protein digestibility. Pressed cakes derived from water extraction are typically low in nutrients and other extraction methods may yield by-products better suited for human consumption. Screw-press or hydraulic press meals are higher in oil than residues from solvent extraction and may subsequently have to be extracted with solvent to obtain more oil. Decortication before oil extraction reduces the fiber content but improves protein levels in the residual meal. Examples of some common oilseed meals include soybean meal, peanut meal, canola meal, cottonseed meal and sunflower meal [33]. Soybean (Glycine max L) is the most preferred source of good quality protein residue from oil processing, with crude protein content ranging from 44 to 50% and good amino acid composition [34,32]. Residues from oil extraction could be processed into flour or meal, the extent to which residues or by-products can be usefully applied in food products development depends on its quality which is influenced by toxic factors and the processing required to reduce these factors. Moure et al. (2006) reported that the thermal and Physico-chemical treatments during the processing of vegetable proteins affect the functional properties and nutritional quality of the products. Some oilseed by-products and residues which have been used in extruded products include defatted sunflower meal [35], glandless cottonseed meal [36,37], partially defatted soybean flour [38], defatted flaxseed meal [35], partially defatted peanut flour [32], soybean meal [39], soybean meal and vital wheat gluten [40] and defatted groundnut cake flour [41]. Table 5 shows the manufacturing of extruded plant by-products from Oilseeds (Defatted seed or seed cake).

1.6 Future Prospects

Food extrusion is a technology that will continue to receive research and application attention in developed and developing countries. It is practically impossible to discuss in detail every aspect of food extrusion technology in a single article. However, this article focuses on research efforts, and the application of the technology with regards to food by-products processing. The potentials and benefits of the technology are immense and yet to be tapped fully. In particular, food industries in developing countries have a lot of benefits from the research and application of this technology. Serious research efforts are needed in under-developed and developing countries to increase awareness of the application potentials of this technology. New food products can be produced from the abundantly available food by-products and waste generated cereals etc. Since contemporary food extruders have advanced beyond tools for handling predominantly cereal- or starch-based materials. With the increasing innovations and advances in food extrusion technology, areas relating to value addition and bioprocessing could be explored and rapidly expands to accommodate new ideas and consumer demand for healthier products. Extrusion cooking offers a great potential for converting or re-structuring high protein sources into edible forms. The possibilities for developing novel products by extrusion and creating even newer markets for these products in future is seemingly limitless, and consumers have a continually expanding range of products to choose from.

Table 3. Selected studies in manufacturing extruded plant byproduct from fruits and Vegetables

Plant by-product	Final production	Feed moisture	Screw speed	Temperature ºC	Note	References
Jabuticaba (Myrciaria cauliflora) fruit peel	Corn flour, whole grain, wheat flour,JPP: jabuticaba peel powder (up to 10%) extrudate	16	325	75 – 100	JPP at 10% does not considerably affect the hardness and crispiness of corn flour-wheat flour blends. ▪ Presence of JPP significantly improved appearance, color, aroma and overall impression scores	Oliviera, Alencar, and Steel (2018)
Mango peel	Corn-mango peel (8.34% to 33.33%) Extrudate	15 to 21	76 - 100	75 – 175	.Formulations with higher content of mango peel and moisture, lower temperature and screw speed produced extrudates with lower expansion and increased hardness. ▪ Post drying applied to the extrudate at 105 ◦C for 2 hr compensate the mango peel's lower expansion effect, by giving a well texture (crispy and no grittiness)	Mazlan et al. (2019)
Blueberry pomace	White sorghum flour-Blueberry pomace (30%) blend	45	150- 200	160 – 180	Significantly higher procyanidin monomer (highest at 180 ◦C and 150 rpm screw speed), dimer and trimer content at both temperatures and screw speeds, Due to reduction in polymer contents. • Extrusion lowers anthocyanin content by 33% to 42%.	Khanal, Howard, Brownmiller et al. (2009)
Apple Pomace	Corn flour-apple pomace (5 to 10%) blend	10.5	60 - 100	150 – 200	Maximum screw speeds resulted in higher bulk density, lower expansion ratio, decreased porosity, small specific volume, lower moisture and higher starch degradation (high final viscosity). • Higher temperature led to less expanded and lower quality extruded	O'Shea et al. (2014)

Plant by-product	Final production	Feed moisture	Screw speed	Temperature ºC	Note	References
					products. • Apple pomace, due to its fiber content, significantly affected radical expansion ratio, texture, acoustic properties, starch properties and moisture.`	
Banana and Carambola (Averrhoa carambola L.) pomace	Cereal made from low-amylose rice, seeded banana and carambola pomace at ratio 60:30:10 to 80:10:10	9 – 21	200 -300	90 – 130	• Decrease in expansion with higher pomace levels, due to high fiber content and starch dilution.	Borah, Lata Mahanta and Kalita (2016)
Pumpkin peel water rate:	Corn grit – pumpkin powder (10% to 50% peel) extrudate	0.29 L/h	315	40 – 180	Incorporation of pumpkin flour at 10% resulted in extrudates with similar properties (bulk density, expansion ratio) as control. ▪ Hardness and color of extruded snacks were significantly different from control.	Norfezah, Hardacre & Brennan (2011)
Grape Pomace	Barley-grape pomace (2% to 10%) blends	21.66	150 to 200	140 -160	• Blends of 2% grape pomace extruded at 160 ◦C, 200 rpm and 10% grape pomace extruded at 160 ◦C, 150 rpm had higher preference levels for parameters of appearance, taste, texture and overall acceptability.	Altan et al. (2008a)
Cherry Pomace	Corn starch-cherry pomace blend (5% to 15%)	15.5	150 to 250	140	• The radial expansion ratio increased with 5% pomace addition compared with control, but decreased significantly at 15% addition • Reduction in WAI and WSI (smaller particle size) with higher pomace level • No effect on phenolic content after extrusion	Wang, Kowalski, et al. (2017)

Plant by-product	Final production	Feed moisture	Screw speed	Temperature ºC	Note	References
Carrot Pomace	Corn starch-carrot pomace (5% to 15%) blend	15 to 30	100 to 250	50 to 140	• The smallest particle-sized (< 125 μm) pomace at the 5% level of inclusion resulted in extrudates with the largest expansion ratio among all treatments • Slightly higher expansion at low moisture content and carrot pomace at 5%. Decreasing trend with added pomace after that. • Highest beta-carotene retention rate with carrot pomace at 5%.	Kaisangsri et al. (2016)
Cranberry Pomace	Corn starch Cranberry pomace (30% to 50%) blend	30	150 to 200	150 to 190	• Lower temperature and pomace level led to higher anthocyanin retention (Highest retention at 150 ◦C and 30% pomace) • Extrusion improved flavonol content by 30% to 34%, ORAC values increased at 150 ◦C and 190 ◦C • Increased in procyanidin monomer (DP1) and dimer (DP2), but decreased from DP 3 to 9.	White et al. (2010)
Pineapple pomace	Corn flour-pineapple pomace (10.5% and 21%) blend	14 to 16	220	140 to 160	• Extruded products with added pomace have lower expansion and darker color. • No significant differences between control and 10.5% added pomace in terms of bulk density, hardness, WAS and b* values of extruded products. Showing satisfactory results.	Selani et al. (2014)
Orange pulp	Biscuit-type cookies from wheat flour and orange pulp (5% to 25%)	22 to 38	126 to 194	83 to 167	• No significant difference between control and biscuits with 15% added pulp for flavour, texture and general acceptance scores • Significantly increased moisture content and hardness, lower expansion ratio, in	Larrea et al. (2005)

Plant by-product	Final production	Feed moisture	Screw speed	Temperature ºC	Note	References
					pulp-added cookies	
Tomato Pomace	Barley-tomato pomace (2% to 10%) blends	21 to 22	133 to 217	140 to 160	• Extrudates with 2% and 10% tomato pomace levels extruded at 160 ◦C and 200 rpm had higher preference levels for parameters of color, texture, taste and overall acceptability	Altan et al. (2008b)
Peach pomace	Rice flour:peach pomace at ratio	6 to 12:1	13.5 400	25 to 120	• Addition of peach pomace increased porosity, radial and overall expansion ratios. • Reverse trend for apparent and true density and breaking strength of extrudates	Sarkar and Choudhury (2014)

William et al.*, (2019)*

Table 4. Selected studies in manufacturing extruded plant byproduct from Cereals (*Bran and hulls*)

Plant by-product	Final production	Feed moisture	Screw speed	Temperature ºC	Note	References
Pea hull Corn	semolina-pea hull (20% to 80%) extrudates	14 to 26	72	80 to 200	• Higher pea hull proportion led to increased density, reduced radial expansion ratio, poorer texture, lowered WAI and WSI. • Higher temperature (120 to 220 ◦C) increased expansion and lowered density • Higher moisture content lowered expansion and WSI, increased density and WAI	Rzedzicki et al., (2003)
Buckwheat bran	Pasta from semolina and buckwheat bran flour (25%)	30.5	25	45	• No effect after extrusion on mineral composition and content (Ca, Cu, Fe, K, Mg,	Manthey and Hall (2007)

Plant by-product	Final production	Feed moisture	Screw speed	Temperature °C	Note	References
					Mn, Zn), protein content, amino acid profile (except lysine).	
Rye bran	Blend of corn starch, rye endosperm flour and rye bran (28 and 440 µm; 15% and 30% level)	17	500	40 to 110	• Addition of bran resulted in increased hardness and density and lowered crispiness and expansion • Reduction in bran particle size enhanced macrostructural properties, WAI, expansion and crispiness • 30% fine rye bran in barrel-water feed resulted in crispiest extrudates	Alam et al. (2016)
Corn fiber	Corn grit: corn fiber at ratio 70–100:0–30 extrudates	30	150	90 to 120	Increasing melt temperature improved physical characteristics of corn extrudates • Inclusion of corn fiber reduced expansion ratio, bulk density and breaking strength • Higher corn fiber content led to higher phenol retention, increased antioxidant properties, but lowered L, b, ΔE values • Extrusion resulted in higher WAI (especially with added CO_2), b, ΔE values	Wang and Ryu (2013a;2013b)
Wheat bran	Corn meal-wheat bran-milk protein extrudate	Water feed:1.02 L/h	300	100 to 125	• Addition of fiber at 125 g/kg resulted in higher expansion and breaking strength. It also improved specific mechanical	Onwulata et al. (2001)

Plant by-product	Final production	Feed moisture	Screw speed	Temperature ºC	Note	References
					energy and product quality	
Sorghum bran	Corn flour-sorghum bran (5% and 10%) tortilla	30	112	60 to 90	• Integration of sorghum bran led to improved antioxidant activity, higher ferulic, *p*-coumaric, diferulic and triferulic acids. • Extrusion increased the free forms of phenolic acids	Buitimea–Cantua et al. (2018)
Soybean hull	Maize grits-soybean hull (0% to 40%) extrudate	16	100 to 200	100 to 200	• Inclusion of soybean hull lowered specific mechanical energy and sectional expansion • Higher temperature and levels of hull reduced SME • Soybean hull can be added up to 30% without significant difference in sensory evaluation scores	Duarte et al. (2009)

William et al.*, (2019)*

Table 5. Selected studies in manufacturing extruded plant byproduct from Oilseeds (*Defatted seed or seed cake*)

Plant by-product	Final production	Feed moisture	Screw speed	Temperature ºC	Note	References
Almond powder	Corn flour-defatted almond powder (10% to 30%) puffed snack	12 to 16	120 to 220	140	• High moisture feed and screw rate resulted in desirable characteristics (high ER, low BD, low hardness) • Increased almond powder was followed with reduction in ER and air cell diameter, increased BD, hardness and thickness of	Hashemi et al. (2016)

Plant by-product	Final production	Feed moisture	Screw speed	Temperature ºC	Note	References
					cell wall	
Blackcurrant (Ribes nigrum) seed	Cornmeal-Defatted blackcurrant seeds (10% to 50%) cereal extrudate	14	190	150 to 180	• Addition of seeds resulted in higher vitamin C and sugar and lower starch • Higher WAI and WSI in 10% and 30% added seeds compared to control • Higher seed content caused higher density and lower expansion in extrudates	Gumul, Ziobro, Zieba and Roj (2013)
Olive paste	Corn flour-olive paste (4% to 8%) extrudate	14 to 19	150 to 250	140 to 180	• Higher moisture and paste content, lower temperature and screw speed, were associated with higher density, decreased expansion and porosity in extrudates	Bisharat, Eleni, Panagiotou, Krokida, and Maroulis (2014
Flaxseed meal	Cereal bars Containing extruded FM (1.36%) and flour (mainly wheat) mixes	25 to 40 L/h water input	60	129 to 142	• Cereal bar enriched with FM showed improved protein quality and quantity, dietary fiber and $\omega 6:\omega 3$ ratio.	Giacomino et al. (2013)
Hemp seed powder	Energy bar from rice flour and hempseed powder (20% to 40%)	20	200	60 to 130	• Higher inclusion of hemp resulted in reduced expansion of extrudate • Higher phenolic and flavonoid content, DPPH radical scavenging activity and β-carotene bleaching assays with higher hemp %.	Norajit et al. (2011)

Plant by-product	Final production	Feed moisture	Screw speed	Temperature ºC	Note	References
					• Higher moisture absorption in extruded rice/defatted hemp than extruded rice/whole hemp	
Linseed cake Rapeseed Cake Soybean Cake Sunflower cake	Fish Pellets (contains 25% cake for each formulation, fishmeal and wheat)	30	300	70 to 120	• A replacement of 25% of the reference fishmeal formulation with oilseed cakes resulted pellets with similar nutritional profiles to the reference fish feed but with reduced expansion, increased sedimentation velocity, lower water stability and abrasion resistance.	Tyapkova et al. (2016)
Hempseed (Cannabis sativa L.) cake	Corn grit-hemp cake (5% to 10% DM) snack	15 to 25	100	150 to 180	• Higher levels of defatted hempseed cake and moisture reduced expansion ratio and fracturability and increased hardness and bulk density • Temperature has a significant influence on hardness and color change	Jozinovic et al. (2017)
Sesame oil cake	Corn grit, containing semi-defatted sesame cake (10% to 20%)	15	333 to 387	Room Temperature	• Higher SDSC lowered sectional expansion of corn extrudates and enhanced compression force. • Acceptable sensory properties after presentation of nutritional	da Graca Costa, do Nascimento et al. (2012)

Plant by-product	Final production	Feed moisture	Screw speed	Temperature ºC	Note	References
					benefits, especially for snack with 20% SDSC	
Other plant parts or combination						
Defatted Soybean meal, germinated brown rice meal, mango peel fiber	Corn grit-mixture of plant byproduct (20% total) snack	13 to 18.36	126 to 180	146 to 214	• Addition of byproduct mixture at 20% increased protein, dietary fiber, polyphenol content and antioxidant activity • Reduction in expansion ratio with added meal due to protein and fiber content • Extrusion converted insoluble into soluble fiber, decreased phenolic compound and antioxidant activity	Korkerd et al., (2016)
Cauliflower florets, curd, stem and leaves	Snack containing mainly wheat flour, corn starch and cauliflower waste (5% to 20%)	9 to 11	250 to 350	80 to 120	• Higher dietary fiber, protein content and WAI with addition of cauliflower • No significant effect on hardness of extrudates. Lower expansion indices with higher cauliflower content. • Cauliflower can be added up to 10% for acceptable sensory scores	Stojceska et al. (2008)
Brewer's spent grain	Pasta from yam starch and BSG (5% to 15%)	12	100 to 140	100 to 110	• Expansion increased with screw speed and temperature, but decreased with higher BSG content • WAI increased with	Sobukola et al., (2013)

Plant by-product	Final production	Feed moisture	Screw speed	Temperature ºC	Note	References
					screw speed and temperature, particularly at low BSG levels. WSI increased with higher temperature.	
Partially defatted hazelnut flour, durum clear flour, fruit waste blend (orange peel, grape seed, tomato pomace)	Rice grit-mixture of plant byproduct (total 30%) snack	12 to 18	200 to 280	150 to 175	• Higher PDHF led to increased bulk density and WSI, but decreased porosity and WAI of extruded snack. • Snacks with well expansion and sensory properties were obtained at low PDHF content.	Yağcı and Goğuş, (2008)
Sugarbeet pulp–	Corn grit-sugar beet pulp (5% to 15%) extrudates	-	100	135 to 170	• Higher SBP resulted in lower expansion and fracturability, higher hardness and density. But the addition of pectin (0.5% to 1.0%), to some extent, reversed this trend • Extrusion process significantly affected color and resulted in higher WAI and WSI. • 1% pectin must be added to SBP-(all levels)-incorporated extrudates for acceptable sensory scores	Ačkar et al. (2018)

William et al.*, (2019)*

There is no standardized experimental procedure and method of analysis for food extrusion technology as available for other conventional food processing techniques. Studies of mechanical and rheological properties of food dough are urgently needed. There is the need for fundamental studies on the properties of food just as in plastic extrusion where properties of plastics and plastic melt are well known. Understanding the properties of food dough will help in getting information and data for research and development purposes. The focus should also be in the area of co-extrusion of cereal products with other additives. This is a promising area for developing countries that are rich in cereal. At present, these cereals are grossly underutilized in terms of processing. Improvement in processing as being offered by extrusion cooking will enhance the nutritional quality of these foods and provide the populace with value-added foods. This is a potential source of huge economic benefits and research opportunities.

2. CONCLUSION

Extrusion processing has so far been a vital tool for handling versatile raw materials and also, provides a useful avenue by which unconventional, under-used nutrient sources such as food by-products and wastes, food processing residues are added into food systems. Under-utilized cereals and other food materials which have demonstrated low economic or processing value are today been successfully valorized or re-integrated into consumer menu. Extrusion remains a highly popular technique for modifying the properties of both food commodities, food by-products and wastes and producing products that have special attributes. Food composition and extruder operating parameters are important factors in final product quality. The food extrusion process had also gone beyond the traditional process of cereals and starch-based food as raw materials for extrusion. With the advancement in food extrusion, industrialization, population increase and high demand for food, food industries had innovated in other areas with regards to value addition to food by-products/waste which are rapidly been exploited due to consumer demand for healthier and beneficial foods. This process has opened up new research areas (ideas) and also, brought under-utilized (lesser-used) food materials to add value, modify them and create a variety of foods to curb the challenges of food security globally.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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