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REVIEW PAPER

PROCESSING, CHARACTERISTICS AND APPLICATIONS OF EXPANDED GRAINS

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Abstract

The popping and puffing are adiabatic expansion process in which the grains are exposed to high temperature for short time. The heat increases vapour pressure inside the grain leading to rupture of outer shell with expansion of starchy endosperm to several folds creating a crispy and aerated puffed snack. Conventional puffing methods use hot air, oil and sand as medium of puffing, whereas non-conventional puffing methods make use of microwave, fluidized air and pressure differential in system. Although it is commonly believed that processing conditions solely influence the quality of expanded grains, many other variables such as physical, chemical and genetic characteristics of grain, post-harvest handling practices, storage conditions and pre-treatments can also largely affect quality indices of expanded grains. As exposed to heat for only short time, expanded grains retain majority of nutrients and even improved digestibility and nutrient bioavailability traits. Flour obtained by milling of expanded grains exhibit desired functional properties expected in bakery products. This paper briefly discussed the factors influencing puffing quality and effects of puffing on physicochemical and morphological characteristics of grain along with its applications.

Keywords: cereals, expansion, flour, millets, puffing, sensory, snack

Introduction

The change in lifestyle pattern had a great effect on food we consume. As a result, convenience food sector has grown by 70% over the past decade creating a huge market (Gurupavithra *et al.*, 2013). The health consciousness among consumers paved the way for food industries to focus on development of functional and dietary foods (Kapoor, 2013; Mir *et al.*, 2016). Though snack foods are generally thought

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negatively in terms of nutrition, certain products from whole grains have a potential to offer better diet quality. Eating whole grain-based snacks have been linked to health benefits including prevention of diabetes, coronary heart disease and hypertension (Zizza and Xu, 2012; Lillioja *et al.*, 2013). Expanded grain also called puffed or popped grain is an aerated, porous, crispy and cellular structured ready-to-eat whole-grain snack produced by exposing the pre-treated grain to intense heat (>200 ºC) for a short time (<60 seconds). The puffing or popping is an old traditional food processing method used for preparation of expanded cereals and legumes. It is the simplest, inexpensive and quickest method that imparts high palatability to snack (Joshi, 2011; Kumar *et al.*, 2017; Rajput *et al.*, 2019). The expanded whole grain based snack foods like popcorn, popped and puffed rice, popped wheat, roasted and puffed soybean are popular worldwide (Jaybhaye *et al.*, 2014). Certain millets like sorghum, foxtail millet and finger millet and pseudocereals like amaranth and quinoa are also known to pop (Johnson, 2000; Paukar-Menacho *et al.*, 2018). The popping involves rapid heating of grains and due to which temperature of kernel exceeds boiling point of water. Moisture trapped in kernel gets converted to steam, causing a sudden expansion in corn volume. However, the hard shell of kernel keeps the steam trapped and acts as a pressure vessel. Once the internal pressure reaches yield or breaking point of shell, the pericarp ruptures, instantaneously making expanding superheated vapour to take the cooked jelly like starch with it. The exposure of air cools the expanded starch network forming a fluffy product to consume (Quinn *et al.*, 2005). Similarly in paddy, the interlocked lemma and palea provides resistance to expansion thus assisting in building up of sufficient internal pressure (Maisont and Narkrugsa, 2010). In puffing, the kernels are heated until internal moisture gets converted into steam and pops through the pericarp of kernel whereas in popping process sudden release of water vapour and rapid expansion of pregelatinized kernel is carried out (Joshi, 2011). As the expansion is very quick, it is considered as an adiabatic process where there is no heat exchange between system and surroundings during the process (Virot and Ponomarenko, 2015).

The global market value of popcorn valued 12723 million USD in 2021 and was estimated to reach 20071 million USD by 2027 with a compound annual growth rate of 7.89% (www.marketwatch.com). Puffed rice and puffed millets have high demand especially in the Asia Pacific and other developing countries for their use as ready-to-eat breakfast cereals, snacks and street food preparations. Increasing disposable income in developing countries and simplicity in preparing the puffed snacks at movie theatres, stadiums, carnivals and street food trucks offer an evergreen market opportunity (www.entrepreneurindia.co). Though a wide range of cereals can be used for puffing, only few of them pop well (Kamble *et al.*, 2017). There is still major concern regarding the quality of various puffed products made from cereal grains (Sharma, 2012). Many of the heated popcorn kernels remain unpopped and are wasted (Vorwald and Nienhuis, 2009; Quinn *et al.*, 2005). A good understanding of mechanisms and factors involved in expansion of food biopolymers is extremely important as it could create a platform for developing new snacks and reducing wastage (Moraru and Kokini, 2003). This paper reviews the previous research works on factors influencing expansion of grains for better popping qualities and effect of puffing and popping on physicochemical and morphological characteristics of expanded product with its versatile applications.

Puffing methods

Conventional puffing methods

The process involved in manufacturing of expanded grains is presented in figure 1.

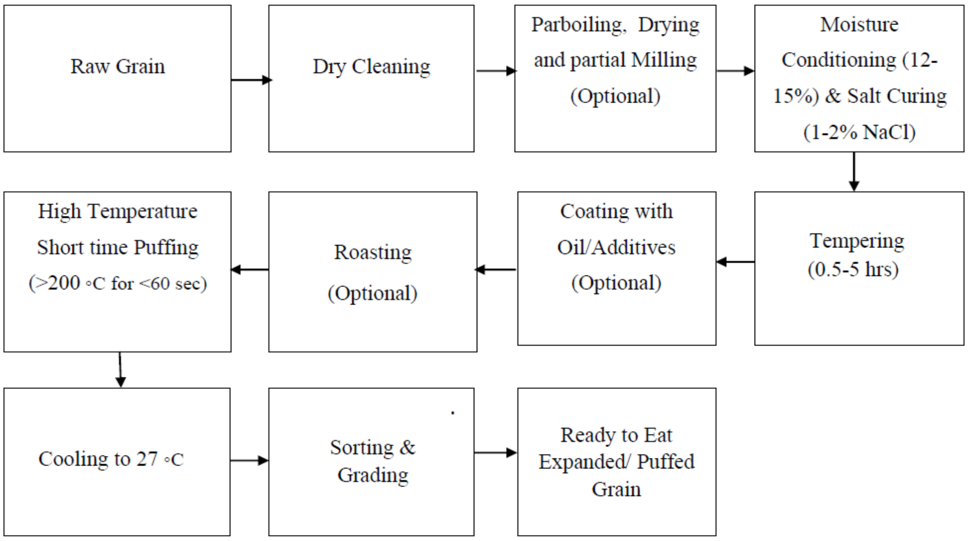

Figure 1. General process flow of puffing.

Conventional puffing is the traditional method of puffing which uses hot air, hot oil or hot sand as medium for puffing or popping. The conduction mode of heat transfer using particulate solids serves as an effective heat transfer method compared to hot air. Popping using particulate medium involves continuous mixing of grains in a bed of hot sand or salt of temperature 200-300ºC for a short contact time of 10-11 seconds until crackling sound just cease (Ali and Bhattacharya, 1976; Kapoor, 2013; Sotocinal *et al*., 1997). The sand to grain ratio is 15:1. Traditionally, the rice will be conditioned to 14-14.5% moisture content and tempered overnight prior to sand puffing (Chinnaswamy and Bhattacharya, 1984). The sand remains on puffed grain are hazardous to health. The sand can be replaced by salt for puffing because the specific heat of salt is higher than sand and so it can give better output and will not contaminate the product (Ashwini *et al*., 2016). The hot air popping of popcorn involves agitation of grains in a wire cage or basket kept over a heat source like camp fire or coal stove and allowing the corn to pop (Ugwu *et al*., 2015). It can be also done in a hot chamber where grains come in contact with hot air at 180ºC for 2 minutes (Paukar-Menacho *et al*., 2018). Using air as a medium can increase popping time because the hot air not only transfers heat to the grain but also takes away the moisture from grain and gets saturated with moisture before all the sensible heat has been utilized (Kapoor, 2013; Sibley and Raghavan, 1985). In oil popping, the grains are deep fried in hot oil having temperature around 200-220ºC for 4-8 Seconds (Villareal and Juliano, 1987; Joshi *et al*., 2014). Oil helps to distribute the heat and cause more even and complete popping. Commercially, coconut oil or other vegetable oils are used for its aroma and lightness (Ugwu *et al*., 2015). The frying oil can be absorbed by the grains which may cause rancidity on exposure to oxygen during storage (Joshi, 2011). These traditional methods are inefficient, tedious, labour intensive and pose serious environmental hazard. This can be overcome by using non-conventional puffing methods (Ashwini *et al*., 2016; Basavaraj *et al*., 2015). The different expanded grains can be seen in figure 2.

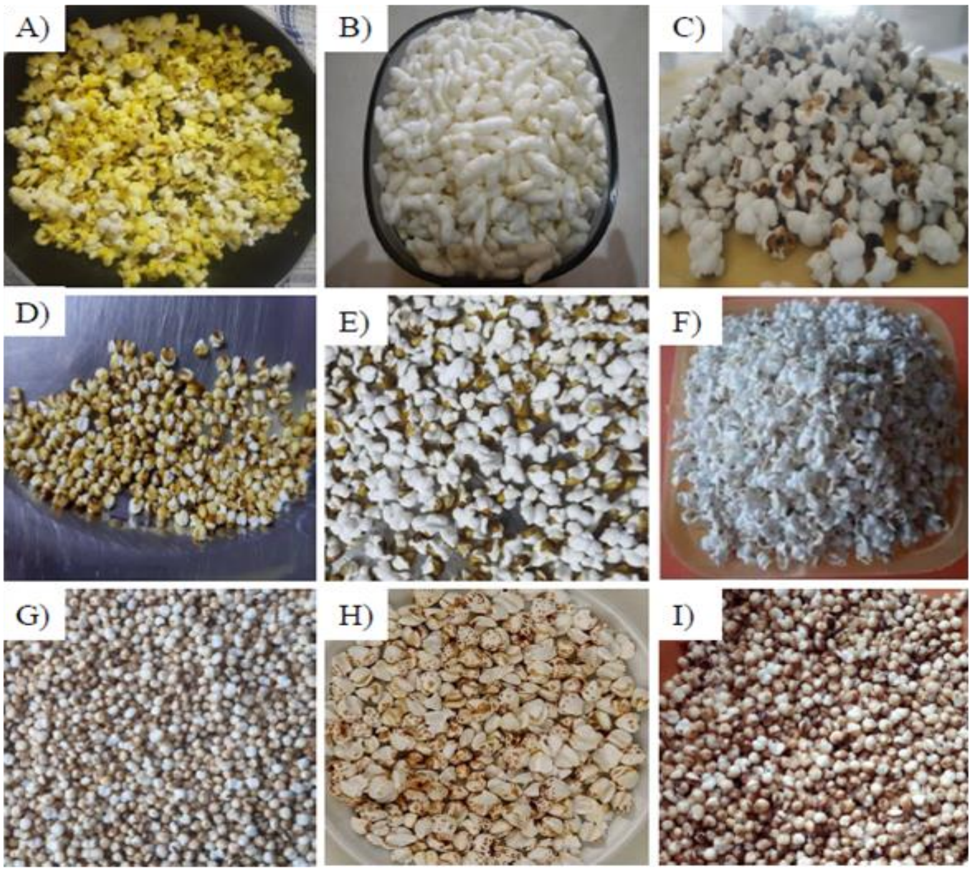

Figure 2. Expanded grains of (A) Corn, (B) Rice, (C) Sorghum, (D) Foxtail Millet, (E) Pearl Millet, (F) Kodo Millet, (G) Amaranth, (H) Buckwheat and (I) Quinoa.

Non-conventional puffing methods

The current technological development makes use of microwave energy to pop grains (Kapoor, 2013). Microwave puffing or popping is highly preferred over conventional puffing method due to its quick startup time, faster heating rate to attain popping temperature, energy efficiency, low space requirement, selective heating and no need for a skilled labour. When microwave energy is applied, the grain gets heated through the vibration of water dipoles and generates superheated steam necessary for expansion. As the cereal matrix undergoes phase transition from glassy to rubbery state, it gets expanded by steam pressure after the rupture of pericarp. Once the moisture is lost from the matrix, it gets cooled down to glassy state and final structure is set (Moraru and Kokini, 2003). Microwave expansion involves both nucleation and cell growth. Nucleation depends on process parameters and volume of polymer, and cell growth depends on rheological properties of bubble walls (Maisont and Narkrugsa, 2010). The grains can be uniformly heated if its thickness is smaller than the penetration depth of microwave (Joshi, 2011). Explosion Puffing or Gun Puffing utilizes the principle of phase change and thermal pressure effect of gas (Huang *et al*., 2018). The preconditioned grains are loaded into a rotating cylindrical gun chamber where the grains are heated under pressure. Once the desired pressure level of 1724 kPa is achieved, the lid will be opened for steam under pressure in interior of grain to equilibrate with the atmospheric pressure which forces the grain to expand quickly (Ferrel *et al*., 1966; Biswal *et al*., 2017). The limitation of gun puffing is that establishing continuous operation is not possible and the vessel should be designed to withstand high pressure involved in the process (Villareal and Juliano, 1987). Fluidized bed puffing is a high temperature short time puffing process which is more efficient than traditional hot air or conduction puffing process. Fluidization increases the heat and mass transfer as the grain surface area is uniformly exposed to heating medium (Joshi, 2011). It consists of a vertical heating chamber in which the fed grains are suspended and heated by the hot air blown from bottom. The grains are puffed in suspended motion by hot air having 180-260ºC and thus, the used air can be recirculated to increase thermal efficiency. As it is a continuous puffing system, it enables continuous feeding of raw material and continuous exit of puffed product, hence frequent adjustment of temperature and air velocity is not necessary (Dahiwale *et al*., 2018).

Quality measures of puffing

Quality factors such as uniform puffing, contamination free, good color, crispiness, tenderness, fluffiness, free from pronounced tough hulls and having good sensory qualities are important for consumer acceptance (Chandrasekhar and Chattopadhyay, 1989; Jele *et al*., 2014; Biswal *et al*., 2017). The three major parameters of interest to industry are expansion volume, flake size and puffing yield (Quinn *et al*., 2005). Puffing yield is very important for processors to maximize the returns. The presence of unpuffed seeds decreases the value and consumer acceptability of final product. The unpuffed seeds are hard to chew, darker in color and its failure to contribute to expansion volume makes them undesirable (Mukhopadhyay *et al*., 2015). The puffing yield can be calculated by the ratio of weight of puffed grains to the total weight of puffed and unpuffed grains (Chauhan *et al*., 2015). Expansion Volume is very important criteria commercially, because popcorn buyers buy by weight and sell the popped corn by volume (Ceylan and Karababa, 2002). Larger volume could save the cost for mass production and gives profit to manufacturers. The larger popcorn size is more aesthetically pleasing to consumer (Quinn *et al.*, 2005). Moreover, crispiness and tenderness of puffed product are positively correlated with expansion volume (Ceylan and Karababa, 2002). The volume expansion ratio can be determined by the ratio of volume of puffed grains after puffing to the volume of raw grains before puffing (Nath and Chattopadhyay, 2007). Flake Size also called as puff size is a measure of final average puffed volume for each successfully puffed grain. A popped grain of larger puff size is assumed to have more air incorporated into their structure leading to desirable sensory properties (Mukhopadhyay *et al.*, 2015). The flake size is given by the ratio of volume of popped grains to the number of popped grains (Sharma, 2014).

Factors affecting puffing quality

Physical factors

The Phenotypic characteristics affecting expansion volume include physical traits such as kernel size, shape, density, hardness, bran content, bran thickness, husk interlocking, initial micropore size and type of endosperm (Jess *et al.*, 2012; Solanki *et al.*, 2018). The smaller, shorter and broader kernels have higher sphericity and gives higher expansion volume and lower unpopped kernels (Ertas *et al.*, 2009). The tenderness and crispiness of popped corn decreases with increase in raw kernel size (Ceylan and Karababa, 2002). The higher the bulk density of grain, the higher will be the expansion volume and flake size due to the presence of densely packed starch molecules in endosperm that can trap the steam internally (Basavaraj *et al.*, 2015; Kumar and Prasad, 2013). The grain hardness is important as harder grains will not get broken during puffing (Joshi, 2011). The tightness of husk interlocking is positively correlated with popping whereas the chalkiness of endosperm has negative correlation (Battacharya, 2011). The chalkiness of grain occurs mainly due to unfavorable environmental conditions and early harvesting resulting in immature kernels (Sharma, 2012). Among all grains, corn pops exceptionally well as it has hard pericarp and less porous structure which ruptures only at a high internal pressure of 931 kPa and high temperature of about 177ºC (Coco and Vinson, 2019; Johnson, 2000).

Compositional and genetic factors

The major component in cereals that play a dominant role in expansion is starch polymer, while other components such as protein, sugar, fat and fibre acts as diluents. The maximum expansion occurs in whole grains next to pure starch (Horn and Bronikowski, 1979). The higher amylose content in grain results in better expansion volume. Amylose forms complex with lipids which offers a significant positive effect on puffing quality (Joshi, 2011; Parkavi *et al.*, 2020). Goodman and Rao (1984) recommended the use of rice having more than 20% amylose for better expansion characteristics of puffing. Similarly, Mahanta and Bhattacharya (2010) observed a positive effect of amylose-lipid complex and a negative influence of amylopectin retrogradation on puffing quality, as well. A contradictory result has been found by Maisont and Narkrugsa (2009) who stated that amylose content was highly negatively correlated with puffing yield, expansion ratio and bulk density. The higher amylopectin content in grain resulted in light, elastic and homogenously expanded texture whereas high amylose grain produced hard and less expanded texture after puffing. Bagchi *et al.* (2016) inferred that higher amylose content would favor inter or intramolecular interactions of starch with other components like lipids and proteins resulting in the harder texture of grain. Similarly, Jiamjariyatam and Atiwittaporn (2016) and Jomduang and Mohamed (1994) suggests the use of rice having low amylose for better expansion. The molecular arrangement of these complex networks needs to be studied to better understand the effect of amylose and amylopectin on puffing. Moreover, multiple factors affecting puffing need to be considered to establish a sound relationship with amylose/amylopectin. The protein surrounding the starch molecules reduces expansion ratio (Baltork *et al.*, 2018). Proteins inhibit the formation of amylose-lipid complex by forming amylose-protein or protein-lipid complex. Proteins reduce the hydration of starch by trapping the water diffusing to starch. Moreover, protein-protein interactions due to its stronger bonding than starch complex network offers resistance to expansion (Suknark *et al.*, 1997; Ilo *et al.*, 2000; Hagenimana *et al.*, 2006; Ibáñez *et al.*, 2007; Jekle *et al.*, 2016). The popping quality is influenced greatly by genetic variations. In popcorn, the expansion volume has high hereditability, estimated around 78% to 83% (Shandu, 2012). The color of popcorn flakes from different hybrids are not the same, the shape also varies from butterfly to mushroom form. The flake volume, popping fold, the number of unpopped kernel and kernel size are significantly different among various hybrids of popcorn (Jele *et al.*, 2014).

Post-harvest factors

The harvesting and handling practices of grains will also affect the popping quality (Farahnaky *et al.*, 2013). The physical damages such as stress cracks are created in grains due to faulty harvesting with rapid drying. It produces higher unpopped kernels with lower flake volume (Swapna, 2017). The expansion ratio is not affected by the adopted drying method, except if the drying air temperature is above 70 ºC. The cracks reduce expansion ratio because the steam generated on heating the grains would escape thus lowering the pressure for expansion (Murugesan and Bhattacharya, 1991). About 6% degree of milling is optimum to promote expansion (Chinnaswamy and Bhattacharya, 1983). The higher degree of hulling and milling reduces the expansion volume, as the outer seed coat that promotes building internal pressure gets removed in these processes (Parkavi *et al.*, 2020). Unlike corn and paddy, milled rice does not have any barrier to build pressure within the kernel. However, the puffing of parboiled and milled rice would even possible without any physical barrier such as husk (Joshi *et al.*, 2014). Parboiling seals the internal cracks and hardens the grain by gelatinization and hence grains having hardened outer layer assist in building pressure on puffing (Joshi, 2011). It reduces glass transition temperature that promotes phase transition during puffing (Gulati and Datta, 2016). The rice having 25.6% amylose puffs best at 1 kg/cm^2 steam pressure. The pressure parboiled rice gives the highest expansion compared to dry heat parboiled and conventional parboiled rice (Mahanta and Bhattacharya, 2010).

Microwave puffing of pressure parboiled brown rice gives the best puffing performance by steaming at 303.6 kPa for 14.25 minutes, whereas sand puffing gives its best at a steam pressure of 260.7 kPa and exposure time of 15 min (Swarnakar *et al*., 2020). Prolonged soaking during parboiling activates and releases internal enzymes i.e. amylase capable of hydrolyzing the starch structure leading to reduced puffing quality (Xavier and Raj, 1995). Similarly, a very high steam pressure in pressure parboiling also affects puffing by collapsing the outer hull and breakdown of starch (Mahanta and Bhattacharya, 2010). Poor gelatinization during parboiling is not encouraged as the ungelatinized starch demands water added during pre-treatment for gelatinization thereby less water left for vapour generation required for puffing (Gulati and Datta, 2016; Van der Sman *et al*., 2011, 2013). The low temperature storage of grains intended for puffing has a slight negative effect on puffing yield due to conformational changes in protein and starch network and so ambient temperature storage is preferred (Mukhopadhyay *et al*., 2015). The storage period or age of paddy has small effect on expansion ratio because of the changes in hydration capacity and viscosity properties of grain upon ageing (Swamy *et al*., 1978; Chinnaswamy and Bhattacharya, 1983).

Pre-treatment factors

Moisture adjustment

The moisture content plays an important role in expansion volume of puffed grain. The moisture present in grain is converted to superheated steam providing the driving force for expansion (Kapoor, 2013). The optimum moisture content would vary based on grain and processing condition. The expansion volume and puffing yield of proso millet increases with the increase in moisture content from 12 to 15%. The higher moisture content above 15% results in insignificant expansion and yield (Lewis *et al*., 1992). At a higher level of moisture, the grain swells and the pericarp becomes soft, cracked and weak enough to hold the internal pressure (Quinn *et al*., 2005; Rahman *et al*., 2019). The pericarp ruptures at a temperature when pressure inside the kernel is too low. As moisture content increases, the melting point of pericarp decreases and due to which the pressure in kernel at popping moment is lower causing less expansion (Farahnaky *et al*., 2013; Shimoni *et al*., 2002). The lower moisture content does not provide enough vapour pressure inside the grain necessary for explosion of pericarp resulting in lower popped volume and the grain getting burned or charred (Hoseney *et al*., 1983; Shukla and Gour, 2014). Oil popping and hot air popping of popcorn gives maximum expansion volume at moisture content of 13.54% and 14.03% respectively. The hot air popping produce larger popcorn flakes than oil popping over the entire moisture content range (Metzger *et al*., 1989). Expansion volume of puffed cowpea is highest with grain soaking and conditioning time of 30:300 minutes (Kamble *et al*., 2017). Expansion ratio of puffed pearl millet increases with increase in tempering time of raw grains (Chauhan *et al*., 2015). Nakade *et al*. (2020) stated that puffing yield, expansion ratio and crispiness of puffed sorghum reduce on excessive soaking time (>2 minutes at 80ºC) and conditioning time (>3 hours).

Ingredients

The brine-soaked grains have increased popping expansion volume (Shukla and Gour, 2014). Potassium chloride, sodium chloride, calcium chloride or sodium bisulfate (also known as sodium hydrogen sulfate) can be used to increase expansion ratio (Chinnaswamy and Bhattacharya, 1983). Salt treatment helps in conducting more heat for its high specific heat. Salt-starch complex reduces glass transition temperature that enhances phase transition during puffing (Gulati and Datta, 2016). On microwave puffing, the paddy soaked in calcium chloride solution gives significantly higher expansion ratio than paddy soaked in water because dielectric property of salt enhances the absorption of microwave energy, transforming it faster into heat and better than water dipoles (Chanlat and Songsermpong, 2015). However, salt treated paddy puffed at low microwave power level has case hardening effect in aleurone layer resulting in a very hard product (Maisont and Narkrugsa, 2010). Water and salt treated foxtail millet grains has higher popping percentage as compared to citric acid and sugar treated grains (Gurupavithra *et al*., 2013). Similar findings have been observed by Anithasri *et al*. (2018) in which water and salt-treated sorghum grains achieved a higher expansion ratio and popping yield than sugar and citric acid treatment. The least puffing quality observed in citric acid treatment might be due to acid hydrolysis of starch and weakening of lignocellulose bonding in outer hull thereby affecting pressure build-up required for expansion (Ohishi *et al*., 2007). The taste of puffed grain would vary based on the type and quantity of ingredient used (Gurupavithra *et al*., 2013; Poornima *et al*., 2017). Minimum 2% of salt increases the expansion volume of paddy by 15% and it gives a good sensory attribute (Murugesan and Bhattacharya, 1991). People making popcorn at home used to pop it in a pan with some oil because the oil coating applied over grain could also enhance the puffing performance. The unique flavor, color and taste characteristics of coating materials increase overall acceptability of product (Quinn *et al*., 2005). The oil pre-treated sorghum with high moisture content gives higher expansion ratio. The oil coated over the surface of grain would act as a barrier for moisture diffusion facilitating more vapour pressure development (Mishra *et al*., 2015). As the oil applied on the surface of grain has low specific heat, it gets heated rapidly in microwave oven resulting in lower unpopped kernel ratio (Lin and Anantheswaran, 1988; Santos *et al*., 2005). The optimum ingredient levels in microwave popping of popcorn are 4.4% salt, 5.9% vegetable oil and 16.4% butter, whereas 3.5% salt, 6% vegetable oil, 0.1% sodium bicarbonate and 12.9% butter are optimum for conventional popping (Ceylan and Karababa, 2002). The optimum conditions for producing expanded grains by various puffing techniques and the corresponding quality achieved are given in table 1.

Table 1. Puffing quality achieved from optimum conditions of different methodologies.

Type of Grain	Puffing Method	Optimum Condition	Response	Reference
Sorghum	Microwave Puffing	Moisture (16.62%) Salt (0.55%) Oil (10%)	Puffing Yield (82.23%) Expansion Ratio (14.56)	Mishra *et al.*, 2015
Parboiled & Milled Rice	Microwave Convective Puffing	Moisture (14%) Pre-heating Temperature (220 °C) Power Level (900 W) Time (60 Sec)	Puffing Yield (93.83%) Expansion Ratio (4.64)	Joshi, 2011
Popcorn	Hot Air Puffing	Moisture (12%) Kernel Size (D) ($m\times10^{-3}$) (5>D>6)	Expansion Volume (28.79 $m^3/kg\times10^{-3}$) Percentage Unpopped Kernels (8.57%)	Ertas *et al.*, 2009
Amaranth	Conduction Puffing	Temperature (140 °C) Time (7 Sec)	Popping Rate (80%)	Solanki *et al.*, 2018
	Fluidized Bed Puffing	Temperature (150 °C) Time (30 Sec)	Popping Rate (65%)	
Little Millet	Hot Air Popping	Moisture (16%) Temperature (260 °C)	Popping Yield (78.44%)	Kapoor, 2013
Proso Millet	Gun Puffing	Moisture (18%) Pressure (965 kPa)	Expansion Volume (14.05ml/g)	Lewis *et al.*, 1992
Brown Rice	Sand Puffing	Moisture (15%) Salt (1.75%) Temperature (225 °C)	Expansion Ratio (6.85)	Mir *et al.*, 2016
Wheat	Gun Puffing	Moisture (19%) Pressure (1241 kPa)	Puff Index (5.50)	Ferrel *et al.*, 1966
Popcorn	Continuous Hot Air Puffing	Temperature (200 °C) Feed Rate (50 g/min) Air Velocity (24 m/sec)	Expansion Ratio (13.36)	Dahiwale *et al.*, 2018

Processing factors

Puffing temperature

The temperature should be high enough to create superheated steam inside the grain (220-270°C) (Kapoor, 2013). The optimum temperature accelerates moisture evaporation and gelatinization of starch and the larger amount of steam generated effectively brings the internal steam pressure above deformation point of cell walls (Vorwald and Nienhuis, 2009; Sharma, 2012). Kernels heated at low temperature gradually make pericarp soften and crack, allowing the moisture to escape out slowly rather than popping out rapidly, resulting in hard unpopped kernels (Quinn *et al*., 2005). At a very high temperature, the grains get burnt which leads to brown color and increased hardness (Dahiwale *et al*., 2018). The rate at which the kernels are heated is also very important as if heated rapidly, the steam in outer layers of kernel can reach high pressure and rupture the hull before the starch in center can fully gelatinize leading to partially popped kernel with hard center (Swapna, 2017). In popcorn, the kernels having low moisture content pop at high temperature (Lucas and Ronney, 2001). On fluidized bed puffing, the differential temperature between surface and center temperatures and between surface and average temperatures of the grains vary linearly with various puffing air temperatures and their ratios remained constant at 2.056 (Chandrasekhar and Chattopadhyay, 1989). The thermal medium used for popping determines the temperature of popping as different mediums have different thermal conductivity (Gökmen, 2004). Oil popping and hot air popping of popcorn gives best popping quality at 190ºC and 230ºC respectively (Metzger *et al*., 1989). The sand puffing of foxtail millet gives maximum popping yield at 230ºC (Choudhury *et al*., 2011). The increase in preheating temperature of convective microwave oven above 200ºC increase the puffing yield (to 93.83%) for same level of residence time and power level because preheating enhance the thermal gradient aided by microwave energy (Joshi, 2011) (Table 1).

Microwave power

Yield and expansion ratio of puffed grains increase with the increase of power density in microwave, but increasing too high has no significant increment due to charring (Mishra *et al*., 2015). At lower microwave power level of 300 W, grains do not get continuous supply of energy required for puffing (Joshi, 2011). The evaporation of water decreases with reduced microwave absorption leading to lower pressure in domain which reduce the expansion volume (Rakesh and Datta, 2011). The paddy soaked in water and salt solution gives higher puffing yield at 600 W and 800 W respectively. The expansion volume of plain rice having 13% moisture is significantly higher at microwave power level of 800 W (Maisont and Narkrugsa, 2010). A similar study conducted by Swarnakar *et al.* (2020) found that pressure parboiled brown rice offers a significant puffing percentage and expansion volume at a microwave power of 900W and 35 seconds exposure time. Optimum popping quality can be obtained for popped sorghum at microwave power density of 18 W/g and residence time of 140 seconds (Mishra *et al*., 2015).

Puffing time

The grains are exposed for only short time under high temperature. The popping percentage of nuna bean (Peruvian popping beans, a subspecies of the common bean (*Phaseolus vulgaris*) increases with the increase in popping time from 60 to 120 seconds on hot air popping. The popping time above 90 seconds with temperature above 244 ºC becomes undesirable due to carbonization (Vorwald and Nienhuis, 2009; Raviteja *et al*., 2015). Gulati and Datta (2016) stated that puffing time should not reduce below 15 seconds on sand roasting of rice at 200 ºC. On microwave convective puffing of paddy, the residence time has significant effect on volume expansion ratio for all preheating temperature and power level because the higher residence time gives sufficient thermal energy required by the grain for its expansion (Joshi, 2011). At low microwave power level, high residence time is needed for pressure development, whereas for high microwave power, less residence time is sufficient (Mishra *et al*., 2015). Mom *et al*. (2020) found that high microwave power level with long time exposure resulted in less expansion of rice snack due to shrinkage. The paddy rice soaked in salt solution takes less time for the start of puffing at all microwave power levels and moisture content due to dielectric property of salt (Maisont and Narkrugsa, 2010). Exposure time of 7-9.7 seconds at 200-270ºC is optimum for fluidized bed puffing of paddy to provide higher expansion ratio of 8.5-10 (Chandrasekhar and Chattopadhyay, 1989).

Pressure

The degree of expansion during gun puffing greatly depends on the differential pressure between heating vessel and atmosphere (Lewis *et al*., 1992). As the firing pressure increases from 690 kPa to 1241 kPa, the puffing index of wheat increases significantly (Ferrel *et al*., 1966) (Table 1). The high pressure increases the degree of gelatinization and the successive sudden depressurization makes the grain explode with an expansion of gelatinized matrix (Xiaoping *et al*., 2018). The gun puffing of proso millet having 15-18% moisture under 965 kPa pressure results in highly expanded structure with lower density (Lewis *et al*., 1992; Mahanta and Bhattacharya, 2010). By lowering the pressure surrounding the kernel, the expansion volume was found to increase on popping. The increased high-pressure vapor inside the heated kernel tries to equilibrate with the outer surrounding. As vacuum condition exists outside the kernel, the force exerted by vapor on kernel hull and starch bodies increases several folds due to high differential pressure causing better expansion (Jha *et al*., 2015). The pressure reduction below 3 kPa increases the expansion volume of popcorn from 10 cm^3/g to 27.5 cm^3/g. The unpopped kernel ratio reduces by a factor of 5 on application of vacuum in pressure cooker (Quinn *et al*., 2005).

Effect of puffing on physicochemical attributes

The physicochemical properties of raw and puffed grains are provided in table 2. The physical, chemical and structural modifications occur during puffing process. The grain undergoes dehydration, starch gelatinization, volume increment, textural changes and production of Maillard reaction induced volatile compounds giving pleasant flavor to puffed product (Paukar-Menacho *et al*., 2018). There is no adverse loss of nutrients even though the grains are subjected to high temperature short time (HTST) treatment (Swapna, 2017). Puffing significantly reduces the moisture content of grains because the higher temperature converts moisture into steam and makes it to escape on expansion (Huang *et al*., 2018). The puffed rice has moisture content of about 1.18% which provides crispiness to product (Khan *et al*., 2017).

Table 2. Effect of puffing on physiochemical properties of grain.

Property	**Variety**	**Raw Grain**	**Puffed Grain**	**Reference**
Moisture (%)	Basmati Rice	11.87±0.53	6.18±0.33	Wafaa *et al*., 2019
	Kiwicha	9.39±0.01	4.38±0.01	Paukar-Menacho *et al*., 2018
	Quinoa	9.54±0.10	5.11±0.01	
	Pearl Millet	7.74	1.84	Chauhan *et al*., 2015
	Kodo Millet	7.35	3.35	Patel *et al*., 2018
	Wheat	10.96±0.14	7.71±0.10	Huang *et al*., 2018
Ash (%)	Foxtail Millet	3.7±0.08	2.3±0.06	Choudhury *et al*., 2011
	Proso Millet	3.23±0.11	1.75±0.11	Lewis *et al*., 1992
	Kodo Millet	3.98	3.92	Patel *et al*., 2018
	Quinoa	2.43±0.04	2.21±0.02	Paukar-Menacho *et al*., 2018
Energy (kcal/100g)	Foxtail Millet	393.40±0.02	408.5±1.67	Choudhury *et al*., 2011
	Kodo Millet	322.56	342.56	Patel *et al*., 2018
Carbohydrate (%)	Finger Millet	72.97±0.10	72.15±0.10	Dharmaraj *et al*., 2012
	Kiwicha	80.13±0.04	77.39±0.01	Paukar-Menacho *et al*., 2018
Starch (%)	Millet	74.36±0.15	43.41±0.19	Huang *et al*., 2018
	Barley	70.48±0.24	38.21±0.50	
	Rice	75.40±0.48	56.84±1.09	
	Wheat	67.24±0.18	49.11±0.32	
Dietary Fibre (%)	Pearl Millet	1.95	3.19	Chauhan *et al*., 2015
	Proso Millet	17±1.20	6.0±0.40	Lewis *et al*., 1992
	Finger Millet	10.1±0.06	11.3±0.07	Dharmaraj *et al*., 2012
	Basmati Rice	1.35±0.23	1.23±0.12	Wafaa *et al*., 2019
Proteins (%)	Foxtail Millet	11.80±1.30	12.9±0.35	Choudhury *et al*., 2011
	Finger Millet	4.70±0.02	4.69±0.02	Dharmaraj *et al*., 2012
	Rice	6.85±0.07	6.82±0.02	Huang *et al*., 2018
Total Fat (%)	Foxtail Millet	8.60±0.17	5.5±0.24	Choudhury *et al*., 2011
	Kodo Millet	1.44	1.41	Patel *et al*., 2018
	Black Rice	2.26±0.04	1.65±0.06	Huang *et al*., 2018
Linoleic acid (g/100g oil)	Finger Millet	20.26±0.20	2.14±0.10	Dharmaraj *et al*., 2012
	Quinoa	50.94±0.05	50.52±0.08	Paukar-Menacho *et al*., 2018
	Kiwicha	40.76±0.01	40.26±0.13	

α-Linolenic acid (g/100g oil)	Quinoa	7.28±0.02	7.19±0.00	
Oleic acid (g/100g oil)	Finger Millet	50.43±0.40	61.68±0.40	Dharmaraj *et al.*, 2012
	Quinoa	23.14±0.03	23.49±0.02	Paukar-Menacho *et al.*, 2018
Phytic acid (mg/100g)	Pearl Millet	516.37	373.82	Chauhan *et al.*, 2015
Phenolics (µg/g)	Quinoa	686.42±5.35	784.63±5.13	Paukar-Menacho *et al.*, 2018
	Amaranth	14.45±0.90	10.76±2.10	
Total Antioxidants (ppm Ascorbic Acid Equivalent/ 100g)	Rice (Kabirajisal)	739.09	1132.14	Bagchi *et al.*, 2016
in vitro starch digestibility (%)	Foxtail Millet	77.9±0.50	107.0±0.64	Choudhury *et al.*, 2011
	Finger Millet	78.0±1.00	99.0±1.00	Dharmaraj *et al.*, 2012
	Rice (Kalabhat)	79.50	104.14	Bagchi *et al.*, 2016
in vitro Protein digestibility (%)	Foxtail Millet	76.7±0.60	86.8±1.18	Choudhury *et al.*, 2011
	Finger Millet	91.0±1.00	97.0±1.00	Dharmaraj *et al.*, 2012

The starch content of puffed amaranth grains is slightly lower than in whole grains. This difference might be from mechanical degradation of starch polymers due to high temperature and pressure involved in puffing (Piłat *et al.*, 2018). The increment in starch solubilization confirms the changes associated with starch on puffing (Ferrel *et al.*, 1966). The above findings are in accordance with the results of Dharmaraj *et al.* (2012), Kapoor (2013), Anithasri *et al.* (2018) and Huang *et al.* (2018). Puffing induced phase transition of the crystalline arrangement of starch to a more amorphous form was confirmed by narrowing of band and change in intensity of Fourier Transform Infrared Spectra. The A-type diffraction found in raw rice changes to V-type upon puffing due to the formation of amylose-lipid complex (Mir *et al.*, 2016; Cornejo-Ramírez *et al.*, 2018).

The puffing results in complete loss of birefringence due to gelatinization of starch (Murali Krishna *et al.*, 1986). The gelatinization degree increases to 80% for puffed grains and it has strong positive correlation with *in-vitro* starch digestibility (Huang *et al.*, 2018). The coarse and porous structure of popped grain enhance the permeation of amylase for digestion and so *in-vitro* starch digestibility is higher than unprocessed grain (Kapoor, 2013). On puffing, some portion of starch undergoes retrogradation and hardens leading to the formation of resistant starch (Kumar and Prasad, 2013; Swapna, 2017). Barua and Srivastav (2017) stated that heat-moisture treatment resulted in increment in resistant starch due to the formation of hydrogen bonds that compacted the starch network and reduced inter-granular distance.

Popping does not have significant effect on protein content of millet. Hence, popped millet would be a source of protein as good as native millet (Kapoor, 2013). Though there is no change in protein content of grain (Table 2), changes occur in protein structure due to denaturation. The denaturation enhances protein digestibility by making protein more susceptible to hydrolysis (Piłat *et al*., 2016). Puffing significantly increases the net protein utilization from 65% to 74% (Kamble *et al*., 2017). Oil Puffing of parboiled milled rice has no degradation of amino acids like lysine, cysteine, methionine and tryptophan. The gun puffing significantly decreases cysteine content (Villareal and Juliano, 1987). The fat content of grains significantly decreases due to its decomposition into fatty acids and monoglycerides under processing pressure (Huang *et al*., 2018). Puffing of finger millet increases oleic acid from 50% to 62% (Table 2), whereas the palmitic acid and linoleic acid decreases from 26% to 19% and from 20% to 2% respectively. It shows that heat treatment reduces unsaturated fatty acids mainly linoleic acid content substantially. The reduction in linoleic acid might be due to the formation of amylose-fatty acid complex with specific preference for linoleic acid (Dharmaraj *et al*., 2012). The seed coat enriched with minerals gets exploded on puffing and only few residues remain attached to popped kernel. Apart, minerals also get leached out on pre-treatment of grains (Kapoor, 2013). Hence, total mineral content of popped foxtail millet is lower than raw grains (Choudhury *et al*., 2011). A similar reduction in total ash, calcium and iron levels was observed by Anithasri et al. (2018). Unlike other puffing methods, mineral content increases in the case of sand puffing due to adherence of sand bed associated minerals in puffed grain surface (Mir *et al*., 2016). Puffing significantly increases the total phenolic content of little millet from 225mg GAE to 661.462mg GAE per 100g of sample. This is because the high temperature popping weakens phenol-polysaccharide and phenol-protein linkages thereby making the phenols highly susceptible to solvent on extraction (Kapoor, 2013). Although puffing significantly increased phenolic content of quinoa, a marginal reduction was noted for amaranth grain due to temperature induced oxidation (Paukar-Menacho *et al*., 2018) (Table 2). The loss or retention of phenols would vary depending on the puffing method and process conditions involved. Popped popcorns have high antioxidant capacity compared to raw popcorns (Coco and Vinson, 2019). The phytic acid is an antinutrient and its reduction would enhance the bioavailability of iron and other minerals. The outer hull of grain is a concentrated source of phytic acid, whose removal during puffing significantly reduces phytic acid (Chauhan *et al*., 2015; Swapna, 2017). The redness and yellowness color values of expanded finger millet are significantly lower than decorticated millet. The steam formed inside the kernel transforms the starch into papery thin layers creating vacuoles in between. This transformation imparts translucent appearance to the product and the removal of darker outer hull is the reasons for the reduction in yellowness and redness values on puffing (Dharmaraj *et al*., 2012). Moreover, longer soaking time during pre-treatment leaches out the reducing sugars and free amino acids thereby influencing Maillard reaction induced color formation during puffing (Lamberts *et al*., 2006).

Effect of puffing on grain morphology

On popping, scanning electron microscopy studies reveal the compact internal structure of raw grains change to porous matrix with cavities of different sizes (Mir *et al*., 2016). The gelatinization plays a key role in disappearance of the honey comb like structure of starch matrix (Dharmaraj *et al*., 2012). The air cell size varies based on processing variables like temperature, time, pretreatments etc. (Sharma, 2012). Paddy rice soaked in water has smaller air cells than paddy rice soaked in salt solution (Maisont and Narkrugsa, 2010). As salt diffused into grain blocks the pores and increases internal steam pressure by offering resistance, largely expanded air cells are obtained (Jomduang and Mohamed, 1994; Gulati and Datta, 2016). When moisture content increases from 10 to 20%, the air bubble diameter also increases from 37µm to 48µm due to higher vapour generation (Farahnaky *et al*., 2013). The air spaces of oil puffed parboiled and cooked milled rice are of variable sizes, irregular and are randomly located. In contrast, the air spaces in gun puffed milled rice has regular matrix of uniform size because the dextrinization of starch on pressurized expansion might have fixed the porous structure (Villareal and Juliano, 1987). Even though the expanded grain appear to be smooth; it has many uneven ridges and furrows. The greater degree of expansion results in larger air cell holes and thinner cell walls (Maisont and Narkrugsa, 2010). The thin walls of puffed grain seems to be responsible for soft and crispy texture of the product (Farahnaky *et al*., 2013). A study compared the morphology of different puffed grains and found that puffed rice had a highly porous structure with a large number of cavities compared to puffed wheat, barley and emmer wheat (Mariotti *et al*., 2006). The high hydration capacity of insoluble glutenin and gliadin proteins in wheat, barley and emmer wheat might have reduced the water uptake of starch leading to less expanded starch bodies and less porous matrix. The strong bonding of insoluble proteins surrounding the starch might have also suppressed large cavity formation (Day and Swanson, 2013; Jekle *et al*., 2016; Schalk *et al*., 2017). This inference substantially supports the findings of Dharmaraj *et al.* (2012) stating the poor expansion and absence of starch deformation in protein-rich embryo and its adjacent endosperm on puffing.

Applications

Popped grain is a precooked ready-to-eat material which can be used in snack foods, speciality foods, cereal drinks, infant foods and a base for development of supplementary foods (Solanki *et al*., 2018). Puffed cereal grains are commonly used as ingredient in a variety of food products especially in street foods like bhelpuri, a popular Indian chaat item (Sharma, 2012; Kumar and Prasad, 2013). The popped rice is very porous and becomes very soft in a few seconds of wetting and hence, itcan be consumed with milk or curd (Bagchi *et al*., 2016). The puffed grains mixed with salt, cumin seeds, red chilli powder and oil seeds are popular snack products (Raya *et al*., 2015; Wafaa *et al*., 2019). Popping adds commercial value to grain (Chauhan *et al*., 2015). The processing of not so popular millets into nutritious popped ready-to-eat food products increases their consumption by mass thus improving their market prospects (Kapoor, 2013). Puffed proso millet, puffed amaranth and other puffed grains can be introduced into diets of people suffering from food allergies associated with gluten intolerance (Piłat *et al*., 2016). Apart from being a conventional and nutritious low cost reach food to mass population, the roasted form of rice as puffed rice may be considered as prebiotic food because the resistant starch formed on puffing escapes digestion and absorption in small intestine and serves as a food for gut microflora in large intestine (Kumar and Prasad, 2013). The butterfly shaped popcorn kernels are tender, light, and fluffy and its non-uniform shape maximizes profit for less product serving size. The mushroom shaped popcorn kernel flakes are compact, ball shaped, dense and its consistent round shape provides larger surface area for coating. It is highly used in confectionery industry where caramel, cheese, chocolate or other coatings are applied (Swapna, 2017). The food industry incorporates the puffed grain into fatty pastes, chocolate or boiled sugar confections. The coating material applied imparts part of nutrition and improves sensory aspects (Villareal and Juliano, 1987). Blending the puffed product with different flavors and marketing them in moisture impermeable plastic film pouches provides enormous opportunity for increasing acceptance and usage of puffed product (Nath and Chattopadhyay, 2007). The sweet puffed rice balls can be prepared by coating the puffed rice with boiled syrup mixture containing sugarcane juice, water and glucose syrup and later molded to ball shape and cooled (Wafaa *et al*., 2019).

Studies have confirmed that the replacement of sodium chloride with potassium chloride and calcium chloride during salt curing resulted in better puffing quality and sensory perception of puffed grains (Chanlat and Songsermpong, 2015; Dash and Das, 2019). It gives a new scope to use puffed grains as a fortification medium for its affordability and wide utility (Paraman *et al*., 2012). Being porous in nature, puffed grains are researched for its potential to act as a matrix to deliver drugs and bio-functional compounds to the body (Soni *et al*., 2018). The puffed grain can also be pulverized and made into flour. Puffed flour has certain advantages over flour from raw grain in terms of both functional and nutritional properties (Kapoor, 2013). As the swelling power and water absorption index of puffed grain flour is twice higher than flour from raw grain, it can be incorporated into bread for absorbing the free water released during staling thereby keeping the bread soft and enhanced storage life (Dharmaraj *et al*., 2012). Moreover, the oil absorption capacity of puffed flour is higher than its raw counterpart and this ability of flour to absorb oil helps in improving sensory properties like mouth feel and flavour retention (Kapoor, 2013). The enhanced functional properties of flour from puffed grain are supported by the findings of Burgos and Armada (2015), Bagchi *et al*. (2016), Huang *et al*. (2018) and Lee and Yang (2020). Puffed flour-based products are mostly used by population at higher altitudes and for school children (Raya *et al*., 2015). The pregelatinized and puffed flour has been utilized as ingredients for cakes, desserts, sweets, formulated baby foods, soups, crackers, noodles, puddings, bread, fermented foods like idli, dosa, dhokla, rice vinegar, wine etc. (Kumar and Prasad, 2013). Besides this, the popped rice powder can be used as substitute of glucose in Oral Rehydration Solution (ORS) formulation (Rumana *et al.*, 2009).

Conclusions

This review gives an idea about the crispy, expanded whole-grain products which not only depend on heat and moisture treatment, but on many other factors, starting from harvest which also plays an indispensable role towards puffing/popping performance. Collectively, it can be said that all the factors influencing puffing quality aims for improving only two responses. One is to build pressure gradient, which is the driving force for expansion. The other is to aid in thermal phase transition of starch. The cause for collapse in such aforementioned mechanisms are (most possibly, but not limited to) moisture/steam induced crack formation in structure, strongly-bounded proteins, biopolymer interactions, less or too high heating rate and other external atmospheric/man-made conditions. Compared to rice and corn, irrespective of puffing method and optimized condition, minor cereals like millets and pseudocereals still experience poor expansion and higher wastage in terms of more unpopped kernels. It is recommended to adopt hybrid technology with harvesting multiple modes of heat transfer and controlled atmospheric conditions for improving puffing performance. Infrared fluidized air-puffing, microwave-assisted sand-puffing, solar light projection-puffing, vacuum atmospheric explosion puffing, microwave-vacuum puffing etc. can hence be recommended. Additionally, in-depth research on interactions of starch polymorphs with proteins, lipids and salts in co-relation with puffing conditions is required to bridge the knowledge gap left after completion of various previous research studies.

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