Influence of infrared heating processing technology on the cooking characteristics and functionality of African legumes: a review

Opeolu M. Ogundele¹ · Eugenie Kayitesi¹

Revised: 10 January 2019 / Accepted: 17 February 2019 / Published online: 8 March 2019
© Association of Food Scientists & Technologists (India) 2019

Abstract African legumes are an important protein source in the human diet. However, a long and often extended cooking process has been identified as a major challenge in the consumption and utilisation of these legumes. The application of infrared heating as a method of shortening the cooking-time of African legume seeds and flour, by increasing their water absorption rates and pasting viscosity is emphasised in literature. Structural changes caused by infrared heating of moisture-conditioned African legumes include microstructural, molecular and interaction of the biomolecules in the seeds. However, to the best of the authors' knowledge, no overview on elucidated mechanisms surrounding the microstructural and molecular changes of infrared heated African legumes has been done. The authors therefore, present current knowledge of these mechanisms including certain highlighted factors such as seed sizes, moisture, surface temperature and time, affecting the efficacy of the application of infrared heating to African legumes. In conclusion, infrared heating is a promising technology that provides a potential solution to the consumption and utilisation challenges of African legumes and flour from these legumes, to enhance their consumption in the food industry.

Keywords Infrared heating · African legumes · Starch gelatinisation · Protein denaturation · Pectin solubilisation · Starch–protein interaction

Introduction

Legumes are members of the Fabaceae family of flowering plants, which are important grains, grown and consumed in many developing countries, especially Sub Saharan African areas. Africa has an array of different types of legumes, such as cowpeas (*Vigna unguiculata*), soybeans (*Glycine max*) and lentils (*Lens culinaris*), which are known to be in common use. Bambara groundnuts (*Vigna subterranean*), maramba beans (*Tylosema esculentum*) and African yam beans (*Sphenostylis stenocarpa*) are other examples of African legumes which are largely under-utilised due to limitations in their use (Obboh 2006). Legumes are nutritious and inexpensive meals, which are useful in combating malnutrition in developing countries (Vadivel and Janardhanan 2005). One of the major limitations in the consumption and utilisation of legumes in Africa is their long cooking time that requires the use of high amounts of energy during meal preparation (Wang et al. 2003). In some cases, the hard-to-cook (HTC) phenomenon caused by storage conditions, particularly high temperature and high relative humidity, may be responsible for the long cooking time (Ndungu et al. 2012).

Infrared heating is an emerging technology which involves short-time exposure of a food material to electromagnetic radiation in the wavelength region of about 1.8–3.4 μm (Fasina et al. 2001). This infrared heating is highly efficient in achieving temperatures of 750–930 °C in a very short time. Its application in different heat processing areas particularly food processing include dehydration (Sharma et al. 2005; Hebbar et al. 2004), dry blanching (Jeevitha et al. 2013) of food products such as onion, vegetables and red pepper as well as inactivation of enzymes (Jeevitha et al. 2013) and pathogenic fungi (Jun and Irudayaraj 2003). The infrared radiation heating

✉ Opeolu M. Ogundele
doyinoluwa@yahoo.com

¹ Department of Biotechnology and Food Technology,
University of Johannesburg, P. O. Box 17011, Doornfontein,
Johannesburg 2028, South Africa

involves the transfer of thermal energy in form of electromagnetic (EM) waves. It encompasses portions of the electromagnetic spectrum between visible light and microwaves. It can be classified into 3 regions based on their corresponding spectral ranges, namely, near-infrared (0.75–1.4 μm), mid-infrared (1.4–3 μm), and far-infrared (3–1000 μm). Infrared radiation heating involves simultaneous heat and mass transfer, permitting complex chemical changes during processing of food (Cenkowski et al. 2003). The energy is absorbed by the moisture conditioned food materials and this causes vibration and intermolecular frictions among the water molecules and other constituents, resulting in heat generation and a rise in water vapour pressure in the food (Sharma 2009).

The application of infrared heating of moisture-conditioned African legumes such as cowpeas (*Vigna unguiculata*), kidney beans (*Phaseolus vulgaris*), lentils (*Lens culinaris*) and split peas revealed an improvement in the cooking characteristics of various seeds. These include an increase in the water uptake of the legume seeds during soaking and cooking, reduction in the long cooking time and improvement in the sensory qualities of the legume seeds such as appearance, flavour and texture. Infrared heating also influenced the functional properties of flour from moisture-conditioned infrared heated African legumes such as their water absorption, water solubility and pasting properties (Deepa and Hebbar 2016). The microstructural and molecular changes in biomolecules due to infrared heating of the moisture-conditioned seeds are responsible for the improvement in the cooking characteristics of the legumes. These include rupture of the seeds and cotyledons and protein denaturation, starch gelatinisation and pectin solubilisation. However, the underlying mechanisms behind these changes in the physicochemical, cooking and functional properties of moisture-conditioned infrared heated African legumes have not yet been discussed.

Different factors have been highlighted in the use of infrared radiation on food materials that influence the time, rate and efficiency of these food processing technique (Krishnamoorthy et al. 2008). These factors include, plate distance, power level, surface temperature, peak and bandwidth of wavelength of the infrared heating source. Others include air velocity, moisture content and size or thickness of the food samples. The efficacy of the application of infrared heating which improved the cooking characteristics of African legumes, depends on the infrared heating processing parameters such as surface temperature and time, moisture content and the seed characteristics such as seed size. This review therefore presents the underlying mechanisms surrounding the physicochemical properties, microstructure, cooking characteristic and flour functionality of moisture-conditioned infrared heated

African legumes. This review also draws attention to some of the important factors influencing the application of infrared heating with moisture-conditioned African legumes and the prospects in their application in improving the consumption and utilisation of African legumes.

African legumes

The botanical family of African legumes is known as Fabaceae, which is also referred to as Leguminosae. African legumes are primarily cultivated for their seeds, harvested at maturity, and the matured dry seeds are useful as animal feed ingredient or for human consumption (Singh et al. 2007). Generally, legumes are characterised by high drought tolerance and their ability to adapt well in semi-arid regions. They have the ability to use atmospheric nitrogen as a nutrient and are therefore useful in crop rotation systems because they reduce the need for nitrogen fertiliser in subsequent crops (Sanginga 2003).

Africa is the second largest continent that produces legumes, Asia being the first, followed by Europe. Countries that produce the least amount of legumes are North, Central and South America (Ofuya and Akhidue 2005). In 2014, Africa produced legumes such as lentils (*Lens culinaris*), chickpeas (*Cicer arietinum* L.), pigeon peas (*Cajanus cajan*), cowpeas (*Vigna unguiculata*) and bambara groundnuts, with an estimated value of 136×10^3 – 1911×10^3 Mt per year (FAO 2004). In Europe, amongst other continents the major grain legumes cultivated are peas (*Pisum sativum*), faba beans (*Vicia faba*) and lupine (*Lupinus albus* L.), whereas in Argentina, Brazil, China, India, and in the United States, soybeans (*Glycine max*) is the major legume produced (Karr-Lilienthal et al. 2004).

Importance and utilisation of African legumes

In Africa, legume seeds are commonly eaten as fresh, semi-ripe and fully matured seeds by cooking or roasting. They are also used for the production of different relishes eaten in different parts of Africa such as soups, fried bean cakes and steam porridges. African legumes have dietary protein of about 14–40% making them a cheap protein source, carbohydrate of about 20–60%, dietary fiber of about 4.3–25%, fats of about 1–49%, high energy of about 300–540 kcal/100 g, minerals and some key vitamins (Boye et al. 2010; Ofuya and Akhidue 2005; Iqbal et al. 2006).

In addition, African legumes are a good source of bioactive compounds with good health promoting properties. They contain different dietary phenolic compounds such as phenolic acids, flavonoids and tannins (Singh et al. 2017). The consumption of African legumes has therefore

been associated with a reduction in the risk of chronic diseases such as heart disease, obesity and cancer (Han and Baik 2008).

Limitations and challenges associated with African legumes utilisation

Despite the nutritional and health promoting benefits associated with the consumption of most African legumes, their consumption as meals and their use in products' development is still limited particularly in developing countries due to existing challenges. Extended cooking preparation time is one of the challenges that limit the use of African legumes in many African countries (Adebowale et al. 2011). Table 1 presents the cooking time of different African legumes determined with different methods. Results obtained show that the cooking time for African legumes vary, ranging from 30 min to 3 h of cooking. These prolonged cooking times required in the preparation of African legume seeds to convert them into meals, takes up a lot of fuel energy (Wang et al. 2003). Thus, consumers, especially those in rural areas, who cannot afford high energy costs and urban consumers, whose busy lifestyle makes convenience an important factor in food choices, avoid the consumption of African legumes (Kayitesi et al. 2012).

Hard-to-cook (HTC) is a defect developed by African legumes under storage conditions of high temperature and high relative humidity leading to lengthened cooking times

(Ndungu et al. 2012). This defect follows two main proposed hypotheses namely the 'phytase-phytate-pectin' mechanism and the lignification mechanism (Galiotou-Panayotou et al. 2008). In the phytase-phytate-pectin theory, the degradation of phytate is caused by an increase in phytase activity followed by an interaction of the released divalent cations with pectin (Ndungu et al. 2012; Galiotou-Panayotou et al. 2008). This interaction leads to the crosslinking of pectin with cation bridges and the insolubilisation of the pectin to form pectates, e.g. calcium pectate. In lignification theory, the hypothesis proposes the deposition of lignin in the cell wall from the polymerisation of lignin precursors in the presence of peroxide (Ndungu et al. 2012; Hohlberg and Stanley 1987).

In addition, African legumes contain antinutritional factors (ANFs) such as enzyme inhibitors, phytic acid, flatulence factors, tannins and glucosides. Many of these substances have been identified by their adverse effects because they can interfere with nutrient assimilation and reduce digestibility when consumed in high quantities (Parmar et al. 2017; Betancur-Ancona et al. 2012). ANFs also inhibit the bioaccessibility of minerals and protein, examples includes phytates, lectins, tannins and trypsin inhibitors (Murevanhema and Jideani 2013). On the contrary, recent research has shown that some ANFs, in controlled low doses, can have beneficial effects and can be classified as bioactive compounds (Betancur-Ancona et al. 2012). Examples include tannins, lectins and phytic acid with beneficial advantages such as anticancerous and

Table 1 Cooking time of African legume seeds using different methods

Legume	Effect of treatment	Cooking time	Measuring method	References
Bambara groundnut	Soaking (0.1–0.5% natural lye) at 28 °C for 3 h	2–3 h Reduced to about 40–50 min	Tactile and hardness tester, texture analyser	Annan et al. (2002)
Cowpea	Soaking (25–75 °C) between 12 min and 24 h	30–120 min Reduced by 12–40%	Tactile, texture analyser and mattson bean cooker, sensory panel	Taiwo et al. (1997)
Bambara groundnut, black beans	Soaking and dehulling	60–90 min Reduced by 50–60%	Mattson bean cooker	Ogundele (2017) and Jackson and Varriano-Marston (1981)
Yellow field peas		15–24 min	Tactile, texture analyser and mattson bean cooker	Wang et al. (2003)
Common beans	Soaking (18 h)	30 min–2 h	Mattson bean cooker	Bernal-lugo et al. (1997)
White gram, chickpea, kidney beans and lentil	Soaking (2–6 h)	13–110 min Reduced by 18–50%	Tactile	Huma et al. (2008)
Black beans	Soaking at 22 °C (12 h)	60 min	Texture analyser Sensory panel	Silva et al. (1981)

antioxidant effects, reduction of the glycemic index and reduced formation of renal calculi and cavities (Murevanhema and Jideani 2013; Betancur-Ancona et al. 2012).

Application of pre-treatments process with African legumes

The use of certain pre-treatment processes were part of different methods adopted to reduce the cooking times (12–60%) of African legumes (Table 1). Common domestic processes are among the pre-treatments of African legumes seeds. These include soaking the legumes alone in water or the use of natural rock salts (Kawe) and dehulling, which involves the removal of seed coats of pre-soaked legume seeds. These domestic methods help in facilitating water uptake into the cotyledon of legume seeds, therefore, reducing the cooking time and enhancing a soft texture during cooking (Table 1).

Apart from the domestic methods, several processing technologies have been used as pre-treatments to produce legumes with reduced cooking times, thus, producing opportunities to make pre-cooked African legume seeds available. The processing technologies include gamma irradiation (Tresina and Mohan 2011), microwave (Ashraf et al. 2012) and infrared heating (Mwangwela et al. 2006). The application of these technologies to African legumes have additionally, increased their starch and protein digestibility and enabled lower levels of certain AAFIs such as α -galactosides, protease 21 inhibitors, tannins and/or lectins (Nti 2009).

The mechanisms of some of the processing technologies such as microwave heating and roasting are well understood while some others are still unknown. Microwave (300 MHz to 300 GHz), through molecular interaction with the electromagnetic field, absorbs energy directly and internally and converts it to heat (Chandrasekaran et al. 2013). Microwave heating of legumes has been focused on eliminating unpleasant flavour and reducing trypsin inhibitor (Hernandez-Infante et al. 1998). Microwave heating has also been used to gelatinise starch and denature protein of red beans to produce instantised flour with increased water absorption, oil binding, foaming and viscosity (Ashraf et al. 2012).

Hot-air roasting (about 150 °C), another method of processing legumes, transfers heat through conduction to food materials since it is a particle-to-particle (solid-to-solid) heat transfer method focused on reducing phytase activity, controlling hard-to-cook defect and reducing the cooking time of legumes such as cowpeas (Ndungu et al. 2012). Gamma-irradiation, through the penetration of ionising radiation of about 2.0–25 kGy, through plant cells, causes changes in the structural features of legumes and splits chemical bonds, enabling the control of HTC defect

development, thus, resulting in reduced cooking time of beans (Tresina and Mohan 2011). Infrared heating amongst other technologies is discussed in detail below as it is the focus of this review.

Infrared heating technology

Infrared heating technology is the use of infrared radiation to process moisture-conditioned foods. The infrared radiation involves the transfer of thermal energy in form of electromagnetic (EM) waves. It encompasses the portion of the electromagnetic spectrum between visible light and microwaves (Fig. 1). It can be classified into 3 regions based on their corresponding spectral ranges, namely, near-infrared (0.75–1.4 μm), mid-infrared (1.4–3 μm), and far-infrared (3–1000 μm) (Sakai and Hanzawa 1994).

Mode of operation and classification

Figure 2a shows the diagram of a laboratory-scale infrared emitter. It consists of two basic components: a vibrating trough, and a set of infrared radiation emitters. The vibrating trough transfers the granular product to infrared heat. The infrared radiation emitters generate the infrared radiation energy transferred to the granular products. They are classified based on the wavelength of maximum radiation (Zhao 2000). Short wave radiation generates temperature above 1500 °C with maximum radiation at about 1.3 μm (Ginzburg, 1969). Long wave generates temperature ranges between 350 and 400 °C at wavelength of about 3.0 μm (Van Zuilichem et al. 1986).

There are two conventional types of infrared radiators used for process heating namely; electric and gas-fired heaters with temperature range of about 330–2200 °C. The processing efficiency of infrared radiators depends on the intensity of the radiant energy from the source of radiation. The infrared heating process depends on the distance between the heat source and the product, the presence of water vapor in the air, and the length of the processing time (Cenkowski et al. 2003). An example of electric infrared radiator is a tabletop infrared heater with three (2 kW/lamp) Phillips IR lamps which has been used to generate surface temperature between 130 and 170 °C (Mwangwela 2006).

Mechanism of infrared heating technology

Infrared heating involves simultaneous heat and mass transfer, permitting complex chemical changes during processing (Cenkowski et al. 2003). Figure 2b presents a schematic diagram which illustrates the mechanism of the infrared technology with moisture conditioned food (Sakai

Fig. 1 Electromagnetic wave spectrum **Fig. 2** Schematic diagram of laboratory-scale infrared emitter, CS-1 type 400 W (a) and mechanism of infrared heating technology (b). a 1-Frame, 2-infrared radiator, 3-feeding tank, 4-electric motor, 5-control unit, 6-conveyor belt, 7-rollers, 8-heating zone, 9-adjustment of head position. (Adapted from Andrejko et al. 2008; Sakai and Hanzawa 1994)

and Hanzawa 1994). When moisture conditioned food is exposed to electromagnetic radiation with a wave length range of 1.8–3.4 μm (Fasina et al. 1999), efficiently high enough to generate high temperatures (750–930 $^{\circ}\text{C}$) in food materials in a very short time (Sharma 2009). The infrared energy generated is passed into the moisture conditioned food materials (Krishnamurthy et al. 2008). The energy produced is absorbed by the moisture conditioned food materials which cause water molecules to vibrate at a frequency of 8.8×10^7 – 1.7×10^8 MHz (Fasina et al. 2001). During the vibration, intermolecular frictions among the water molecules and other constituents such as starch and protein occurs, resulting in heat generation and a rise in water vapour pressure in the food (Sharma 2009). According to Mwangwela et al. (2006), the rapid temperature increase in pre-conditioned grains, most likely causes liquid water to turn into steam (gas). If the grain is able to hold the expanding gas, then pressure builds up and the cotyledon collapses under this pressure or explodes to release the pressure, resulting in changes in the biomolecules such as starch, protein and pectin and

changes in their microstructure, which modifies the food materials.

Application of infrared heating technology with African legumes

Infrared heating has changed the cooking characteristics of African legumes, producing shortened cooking times of these legumes. In addition, the flour obtained from the infrared heated African legumes shows potential to produce instantised products (Ogundele et al. 2017; Kayitesi et al. 2012). Moisture or water pre-conditioning is important in these hydrothermal heating processes to cause changes in the biomolecules of the food materials. Infrared heating differs from extrusion cooking. Extrusion combines high temperature, pressure and shear force to obtain instantised food products (De Mesa et al. 2009). Food materials absorb IR energy directly and internally in infrared heating which is similar to microwave heating, vibrating biomolecules at frequencies between 8.8×10^7 –

1.7×10^8 MHz (Sadeghi et al. 2010) and 300 MHz–300 GHz (Chandrasekaran et al. 2013) respectively, and converting the energy to heat as a result of molecular interactions (Chandrasekaran et al. 2013).

Factors affecting the efficacy of infrared heating with African legume

Seed sizes

Seed size is one of the factors influencing the efficacy of infrared heating of pre-moisture African legume seeds. Cenkowski et al. (2007) reported that the thickness of a material could influence the depth of penetration of infrared radiation energy through the material. Fasina et al. (2001) reported that small African legume sized seeds (lentils and green peas) had more reduction in their physicochemical properties such as protein solubility than large sized legumes (kidney and pinto beans). This implies that smaller legume seeds with high surface areas to volume are more uniformly infrared heated compared to large legumes where the treatment would be more effective on the outer surfaces of the seeds than inside (Ogundele and Emmambux 2018).

Moisture

Moisture-conditioning results ranging from 1% (low moisture) to 50% (high moisture) prior to infrared heating have been reported by different researchers (Table 2). High moisture conditioned infrared heated legumes of about 50% (Mwangwela et al. 2006; Kayitesi et al. 2012) had more reduction in their cooking time and hardness than low moisture conditioned infrared heated legumes of between 10 and 40% (Kayitesi et al. 2012; Andrejko et al. 2008). The higher level of seed moisture (50% moisture) prior to the infrared heating of Bambara groundnut increased the starch gelatinisation and pectin solubilisation of the seeds, which is responsible for the reduction in cooking time (Ogundele and Emmambux 2018). Infrared heating of moisture conditioned legumes such as cowpeas (small seed size) and Bambara groundnut (big seeds size) at 130–153 °C and further oven drying (50 °C), reduced the moisture content (41–50%) to about 8–13%, ensuring shelf stability during storage of grains or products because of low water activity (Ogundele and Emmambux 2018; Mwangwela et al. 2006). The temperature at which the seeds were dried (50 °C), reduced moisture in the seeds from 20 to 12% and was high enough to evaporate the moisture without causing further molecular changes (Ogundele and Emmambux, 2018).

Surface temperature and time

Infrared heating of pre-conditioned seeds at about 130 and 153 °C (5–15 min) has been reported to be effective in reducing the cooking time of African legumes such as bambara groundnut and cowpea seeds (Ogundele and Emmambux 2018; Mwangwela et al. 2006). However, a high infrared heating temperature of 170 °C for 15 min was reported to be less effective in reducing the cooking time, despite the high moisture pre-conditioning of cowpeas. This was reported to be due to protein–protein, protein–carbohydrate cross-linking and amylose associations in the cotyledon (Mwangwela et al. 2006).

Other factors

Among other factors that have not been reported in literature is the dehulling of legume seeds (Ogundele and Emmambux 2018). The seed coat of legume seeds contains components such as non-starch polysaccharides (dietary fiber) which are high in quantity compared to the cotyledon (Wang et al. 2003). The penetration of IR energy into dehulled Bambara groundnut seeds enables a reduction in the thickness of the seeds and an increase in the penetration of energy (Ogundele and Emmambux 2018). With the presence of the seed coat, the infrared radiation energy can only go a little bit inside the Bambara groundnut seeds, being almost completely absorbed at the seed's surface because of the thick layer (Ogundele and Emmambux 2018). Whereas, when the seed coat is removed, the thickness of the seeds is reduced and the infrared radiation energy can go further into the cotyledon of dehulled seeds.

Cooking characteristics of infrared heated African legume seeds

Table 2 presents the summary of reports on infrared heating of some of the African legumes and their quality attributes reported by different authors. The changes in the cooking characteristics of moisture-conditioned infrared heated African legume seeds have been associated partly with the molecular and microstructural changes occurring in the seeds during infrared heating.

Water hydration

Infrared heating has been reported to improve the water uptake of moisture pre-conditioned seeds during soaking. A higher water uptake was reported in infrared heated pre-conditioned (41%) cowpeas (Mwangwela et al. 2006) and Bambara groundnut pre-soaked seeds (50%) (Ogundele and Emmambux 2018). Higher water uptake was reported in other infrared heated legumes such as green pea, kidney,

Table 2 Summary of reports on the infrared heating of African legumes and its quality attributes

Sample	Infrared heating conditions	Major observations	References
Bambara groundnut, cowpea, lentil and other legumes	10–50% moisture in seeds	Solubilises pectin	Arntfield et al. (2001), Ndungu et al. (2012) and Ogundele (2017)
	Infrared heating time 3–15 min	Gelatinised starch: loss of birefringence, Increased enzyme digestion and reduction in enthalpies	Mwangwela et al. (2007a) and Ogundele et al. (2017)
	Surface temperatures 115–170 °C	Reduced nitrogen solubility	Mwangwela et al. (2007b) and Ogundele et al. (2017)
		IR processing conditions of 10–50% moisture level for legumes minimises the protein denaturation	
Cowpea varieties, bambara groundnut	40–50% moisture in seeds	Increased water absorption. Reduced cooking time by 36–60% compared to untreated	Mwangwela et al. (2006) and Ogundele and Emmambux 2018
	Infrared heating time 6–15 min		
	Surface temperature 130 and 153 °C.		
	41% moisture in seeds	Reduced cooking time by 50%	Kayitesi et al. (2012)
	Infrared heating time 3–15 min		
	Surface temperature 153 °C		
	40–50% moisture in seeds	Infrared heating reduced the pasting viscosities of the resulting flours from pre-conditioned infrared heated legume	Mwangwela et al. (2007a) and Ogundele et al. (2017)
	Infrared heating time 3–15 min	Flours and starch from cowpea seeds processed at high temperature (170 °C, 30 min) exhibited decline in most of the functional properties	Mwangwela et al. (2007b)
Lentils	Surface temperature 130, 153 and 170 °C.		
	33% moisture in seeds	Lentils processed to internal temperature of about 138 °C exhibited better quality attributes	Arntfield et al. (2001)
	Infrared heating time 170 s		
Navy beans, black beans	Internal temperature 138 and 170 °C		
	26–28% moisture in seeds with water and salt solutions	Tempering with water prior to infrared heating is effective in reducing hardness of beans compared to salts, acid mixtures and EDTA	Bellido et al. (2006)
Peas	10% moisture in seeds	Significant shortening of the boiling time of peas, IR-treated seeds had lower compressive strength	Andrejko et al. (2008)
	Infrared heating time 90 s		
	Surface temperature; 170 °C		

black and pinto beans and lentil seeds (pre-conditioned at about 7–10%) during 6 h soaking (22 °C) (Fasina et al. 2001). This is because in untreated legumes, the seed coat is the first barrier to water transfer into the cotyledon and water can only have access through the micropyle (Penicela 2011). However, in infrared heated legumes, the seed coats are no longer intact. Therefore, water access increases into the cotyledon through the fissures and cavities created in the seed coats (Ogundele and Emmambux 2018).

In addition, Mwangwela et al. (2006) found that the hydration capacity of pre-conditioned and infrared heated

cowpea seeds after 18 h of soaking (22 °C) reduced by 20–25% compared to untreated cowpeas. Infrared heating has also been reported to improve the water uptake of pre-conditioned legume seeds during cooking. Andrejko et al. (2008) reported the water hydration of pre-conditioned (10% moisture) infrared heated (180 °C) pea seeds increased by 1.8 times than untreated pea seeds during cooking for a period of 30 min. This is possibly due to a reduction in bulk density and the development of fissures. The increase in hydration of infrared heated lentils (17–45%) was reported to be due to the hydrophilic nature

of the gelatinised starch permitting faster absorption of moisture (Scanlon et al. 2005). Infrared heating altered the granular structure of cowpea starch, thereby requiring less time to hydrate and disrupt the remaining starch structure during subsequent cooking processes of the infrared heated seeds (Mwangwela et al. 2006). Water absorption increased during the cooking of the infrared heated cowpea seeds (Mwangwela et al. 2006) and infrared heated Bambara groundnut seeds (Ogundele and Emmambux 2018). Water uptake had a significant negative correlation with the texture of the cowpea seeds (Arntfield et al. 2001).

Cooking time

Infrared heating has been reported to reduce the cooking time of different African legume seeds under various conditions (Table 2). It was clear that African legume seeds such as cowpeas, lentils, split peas and Bambara groundnut, pre-conditioned at about 40–50% moisture led to a percentage reduction of 30–60% in their cooking time. The reduction in compression force of cooked infrared heated seeds was reported as an indication of a soft texture compared to untreated seeds (Mwangwela et al. 2006). The reduction in the cooking time was associated with the rapid improvement in hydration during cooking (Ogundele and Emmambux 2018). In relation to structural changes in cowpea seeds to cooking time, Mwangwela et al. (2006) reported similarities in the cooking time of fully cooked untreated cowpeas at 60 min and infrared heated cowpeas at 30 min.

On the other hand, with limited initial moisture, the increase in the cooking time of some infrared heated legumes was due to possible hardening (Andrejko et al. 2008). This is because high moisture in a seed is critical since moisture is necessary for the removal of amylose and to enable the swelling of the granules during gelatinisation. The underlying mechanisms responsible for the molecular changes in the biomolecules of infrared heated pre-conditioned African legumes are further discussed.

Molecular changes

Importantly, water is necessary in the infrared radiation heating process of food materials. This is because water absorbs the infrared energy more than other food components responsible for molecular interactions, due to its dielectric property (Michael et al. 1991). Water and food components absorb infrared energy most efficiently at different wavelengths of about 2.5–1000 μm (FIR) and generate heat through molecular vibration and inter-molecular friction of water molecules (Krishnamurthy et al. 2008).

Water shows a strong absorption band at 2.7–3.3 μm whereas amino acids, polypeptides and proteins show two strong bands at 3–4 and 6–9 μm . Carbohydrates also reveal two strong absorption bands at 3 and 7–9 μm and lipids show three absorption bands at 3–4, 6 and 9–10 μm (Sandu 1986). The absorption spectral of food component overlap with one another, while the water effect on absorption of incident radiation is predominant over all the wavelengths because of its dielectric property.

As a result of the heat generated during infrared heating of moisture-conditioned legume seeds, a rapid temperature increase in seeds most likely causes liquid water to turn into steam (gas) (Mwangwela et al. 2006). If the seed is able to hold the expanding gas, then pressure builds up and the cotyledon collapses under this pressure or explodes to release the pressure, resulting in changes in the biomolecules such as starch, protein and pectin. This also results in changes in their molecular structure which modifies food materials. The underlying mechanisms responsible for these changes in the biomolecules of infrared heated pre-conditioned African legumes have been put forward by some authors (Ogundele 2017; Mwangwela 2006). Figure 1 is a schematic representation demonstrating the effect of infrared heating on molecular components of pre-soaked (28% moisture, 130 $^{\circ}\text{C}$) Bambara groundnut seeds.

Starch

Starch pre-gelatinisation has been reported in pre-conditioned (7–50% moisture) lentils (Arntfield et al. 2001) and cowpeas, bambara groundnut and other legumes seeds (Ogundele et al. 2017; Mwangwela et al. 2007a; Fasina et al. 2001) infrared heated between 138 and 170 $^{\circ}\text{C}$. Infrared heating of moisture conditioned African legume facilitates the pre-gelatinisation of starch; the availability of water in starch increases swelling and facilitates heat transfer. This causes a change in the crystalline order and nature of the starch granules.

Infrared heating caused partial starch gelatinisation in tempered Navy (*Phaseolus vulgaris*) (28%) and black beans (*Phaseolus vulgaris*) seeds (26%) for 32 h with water alone and also in different reagents such as mixture of salts of bicarbonate, carbonates and phosphates, mixture of citric and ascorbic acids, or ethylenediaminetetra-acetic acid (EDTA). The use of different reagents however, did not increase the degree of gelatinised starch in either navy or black beans. The starch pre-gelatinisation reported in pre-conditioned (41% moisture) and infrared heated (130, 153 and 170 $^{\circ}\text{C}$) cowpea seeds was responsible for the increased water hydration, softening and increased susceptibility of the cowpea starch to α -amylase digestion (68.2–85.8%) (Mwangwela et al. 2007a).

Fig. 3 Mechanism of effects of infrared heating of moisture-conditioned (53% moisture, 130 °C) bambara groundnut on the molecular components and microstructure. (Adapted from Ogunlele 2017)

Protein

Protein denaturation has also been reported to occur during the infrared heating process of pre-conditioned African legume seeds. The denaturation of protein tends to make protein less soluble. The denaturation of protein in infrared heated moisture conditioned legume seeds is therefore, responsible for the loss of its solubility (Mwangwela et al. 2007b; Ogunlele et al. 2017). The protein becomes more susceptible to denaturation and aggregation, thereby lowering its solubility.

Fasin et al. (2001) reported similar lower solubility in different pre-conditioned infrared heated legume seeds than the control sample at different pH levels (pH 2–10). The reduction in the hydrophilicity of legume proteins was as a result of the unfolding of protein molecules, thereby exposing hydrophobic sites. The protein solubility of untreated cowpeas within the range of 85–88% was reduced to 33–34% (Mwangwela et al. 2007b). Bellido et al. (2006) reported lower soluble protein levels in infrared heated navy (28%) and black beans (26%)

tempered for 32 h using water, mixture of salts of bicarbonate, carbonates and phosphates, mixture of citric and ascorbic acids, or EDTA. An increase in the moisture content between 26 and 28% (Bellido et al. 2006) and infrared heating surface temperature (138 and 170 °C) of pre-conditioned lentil seeds progressively increased the reduction in the nitrogen solubility of legumes such as lentils, navy and black beans (Arntfield et al. 2001).

Pectin

Infrared heating has also been reported to cause solubilisation of pectin in moisture conditioned legume seeds. This is due to the reduction of pectin in the middle lamella to a lower molecular weight product through beta elimination reaction (Ndungu et al. 2012; Arntfield et al. 2001). Soluble pectin of pre-conditioned infrared heated legumes at different temperatures increased when compared to the untreated samples (Ogunlele 2017; Ndungu et al. 2012; Arntfield et al. 2001). Pectin solubility initiates the disintegration of the middle lamella and cell separation during

the cooking of infrared heated legume seeds (Ogundele 2017; Mwangwela et al. 2006). Solubilisation of the pectin substances in the middle lamella into water soluble fractions (Ndungu et al. 2012) contributes to shortened cooking time of legumes (Mwangwela et al. 2006). However, Arntfield et al. (2001) reported that the non-significant increase observed in soluble pectin in infrared heated lentils between 138 and 170 °C, may not be responsible for the reduction in cooking time and changes in texture.

Microstructural changes

The rapid pressure build up and evaporation of water during infrared heating has been reported to cause the cotyledon to rupture, thus, leading to the occurrence of fissures on the surface structure of the seed coat and the creation of cavities in the cotyledon of pre-conditioned infrared heated cowpea seeds (Fig. 4a, b). The cell walls of pre-conditioned infrared heated lentils were reported to be more susceptible to fractures, exposing the starch granules and opening up the microstructure of the cotyledon of lentil seeds (Arntfield et al. 2001). Structural changes in the biomolecules such as starch, protein and pectin at molecular levels, were relatively important to cause the microstructural change in the seed structure of pre-conditioned legume seeds (Fig. 4). For example, the

solubilisation of pectin may be responsible for the separation of parenchyma cells and starch pre-gelatinisation responsible for the deformation of starch granules in the cotyledon of pre-conditioned infrared heated cowpea seeds (Mwangwela et al. 2006).

Infrared heating has been shown to alter the molecular order of starch of pre-conditioned cowpeas evidenced by loss of birefringence (Mwangwela et al. 2007b). Mwangwela et al. (2006) reported that infrared heating caused disruptions in the middle lamella, loosening of the parenchyma cells, increased intercellular space of the cells and possible cell separation in pre-conditioned infrared heated cowpea seeds (Fig. 4c–e) and soaked infrared heated cowpea seeds (Fig. 4f). In addition, infrared heating caused interactions between biomolecules such as possible aggregation of denatured protein matrix surrounding embedded pre-gelatinised starch granules in treated cowpeas (Fig. 5a–c) compared to the untreated cowpeas (Fig. 5d–f).

Functional properties of resulting flours

Various studies reported the effect of infrared heating of moisture conditioned seeds on the functional properties of resulting flours of African legumes (Ogundele et al. 2017;

Fig. 4 Microstructure of seed coat and cotyledon of moisture-conditioned infrared heated cowpea seeds. Fissures on the seed coat (a) and formation of cavities on the cotyledon (b). Cotyledon cross-sections of c raw d infrared heated and soaked e fully cooked

untreated at 60 min f fully cooked infrared heated at 30 min. Is intercellular space, S starch granule. (Adapted from Mwangwela et al. 2006)

Fig. 5 Microstructure of resulting flour and paste of moisture-conditioned infrared heated bambara groundnut seeds. Light microscopy of resulting flour under plane light: **a** iodine stained untreated **b** iodine stained infrared heated. Light microscopy of resulting flour under polarised light: **c** untreated **d** infrared heated. Confocal scanning electron microscopy showing the microstructure of resulting paste: **e** untreated **f** infrared heated: Black spots inside the red stained indicates the starch and the red indicates protein matrix (color figure online). (Adapted from Ogundele et al. 2017)

Padmashree et al. 2016; Vilakati et al. 2015; Arce-Arce et al. 2014; Mwangwela et al. 2007a; Fasina et al. 2001; Cenkowski and Sosulski 1998) such as water absorption capacity, swelling power, water solubility, foaming capacity, gelation and pasting viscosity. The impact of infrared heating on the flours was attributed to major molecular changes in starch and protein that occurred during pre-treatment of these seeds.

Water absorption

The infrared heating of pre-conditioned cowpeas (41% moisture, 130 and 170 °C) (Mwangwela et al. 2007b), common beans (without tempering, about 626 °C) (Arce-Arce et al. 2014), mung beans (55% moisture, 650–750 °C) (Padmashree et al. 2016) and other legumes seeds (< 10% moisture, 140 °C) such as green pea, kidney beans, black and pinto beans and lentils (Fasina et al. 2001) was reported to increase the water absorption of their resulting flours. This was due to the modification of starch and protein which are important constituents that determine the water absorption properties of heterogeneous systems such

as flour. Vilakati et al. (2015) found that infrared heating increased the water absorption index of resulting flours of cowpeas 1.7–2.4 times compared to the untreated cowpeas, due to changes in cellular structure and starch gelatinisation.

Swelling and water solubility index

Infrared heating of pre-conditioned cowpeas (41% moisture, 130 and 170 °C) (Mwangwela et al. 2007b) and mung beans (55% moisture, 650–750 °C) (Padmashree et al. 2016) reduced the swelling index of the resulting flour. This was attributed to starch gelatinization and protein denaturation. Infrared heating of pre-conditioned cowpeas at 130 and 170 °C reduced the swelling index of the resulting flour by 17.8% and 18.2% respectively and the swelling index had a negative correlation with the water absorption of the flour (Mwangwela et al. 2007b). Infrared heating (130 and 170 °C) also reduced the water solubility index (WSI) of resulting flours by 42% and 55% respectively and this was positively correlated with the nitrogen solubility index NSI of the flour (Mwangwela et al. 2007b).

Pasting properties

Infrared heating impacts on the pasting properties of flour from infrared heated African legume seeds. Cenkowski and Sosulski (1998) reported rapid increases in the pasting viscosity of flour from infrared heated split peas than the untreated peas. It was hypothesised that an increase in starch swelling, during pasting, may be responsible for this outcome. On the contrary, the resulting reduction in the pasting viscosity of flour, from infrared heated cowpeas (Mwangwela et al. 2007a), common beans (without tempering, about 626 °C) (Arce-Arce et al. 2014), mung beans (55% moisture, 650–750 °C) (Padmashree et al. 2016) and bambara groundnut (Ogundele et al. 2017), was hypothesised to be a result of either starch being depolymerised or due to the reduced swelling potential of physically induced cross linked starch during subsequent gelatinisation, which reduced water access (Padmashree et al. 2016; Arce-Arce et al. 2014; Mwangwela et al. 2007a). The mechanism behind the reduction in the pasting viscosity of the flour was partially explained by Ogundele et al. (2017). It was hypothesized that the denatured protein matrix, due to infrared heating, partly prevents the embedded starch hydration, dispersibility and molecular entanglement during pasting of the resulting flour, causing a reduction in pasting viscosity.

In addition, an increase in pasting temperatures (onset T_o , peak T_p and endset T_e) was reported in the flour of pre-soaked (50% moisture) or pre-conditioned (41% moisture) and infrared heated (surface temperature 130 and 170 °C) bambara groundnut and cowpea seeds, or their isolated starch compared to the untreated seeds (Ogundele et al. 2017; Mwangwela et al. 2007a). This was attributed to the starch granule modification in infrared heated legume samples, which reduced water access, the presence of other competing hydrophilic molecules such as proteins and amylose–amylose interaction, increased starch granule crystallinity, requiring higher temperatures for melting (Arce-Arce et al. 2014; Mwangwela et al. 2007a).

Other functional properties

Other protein related functional properties such as bulk density, oil absorption capacity (OAC) and foaming capacity of resulting flours from infrared heated cowpeas, common beans and mung beans were altered (Padmashree et al. 2016; Arce-Arce et al. 2014; Mwangwela et al. 2007b). Oil absorption capacity (OAC) slightly increased because of the protein denaturation, the exposure of the hydrophobic side chains led to an increase in OAC because of the bonding between the hydrocarbons and hydrophobic side chains (Mwangwela et al. 2007b). The foaming capacity of flour from infrared heated cowpeas reduced; the

proteins slightly unfolded enabled them to align around the air bubble thus, reducing surface tension (Mwangwela et al. 2007b).

Conclusion

Infrared heating produces African legume seeds with shortened cooking times and instant resulting flour with modified functionality. The modification and interplay of aggregates of starch granules in the protein matrix partly contribute to the prevention of starch molecules dispersion and entanglement, thus reducing pasting viscosity. Infrared heating produces African legumes that can be stocked on shop shelves as pre-soaked dry grains and instant flour products for rural and urban consumers.

Additional research is required to understand the mechanism of the effect of infrared heating on the nutritional and health promoting properties of African legumes. In addition, based on the functionality of the flour obtained from infrared heated African legumes, they can be combined with other food systems such as cereals and tubers. This highlights the need for further research on the nutritional components and functionality of cereal/tuber legumes as complementary foods for infants.

Acknowledgements The work was supported through the Global Excellence and Stature Funding (GES) of the University of Johannesburg granted to the main author (Ogundele O. M).

References

- Adebowale YA, Schwarzenbolz U, Henle T (2011) Protein isolates from bambara groundnut (*Voandzeia Subterranean L.*): chemical characterisation and functional properties. *Int J Food Prop* 14:758–775
- Andrejko D, Rydzak L, Slaska-Grzywna B, Gojdziewska M, Kobus Z (2008) Influence of preliminary thermal processing applying infra-red radiation on pea seeds cooking process. *Int Agrophys* 22:17–20
- Annan N, Plahar W, Swetman T (2002) Effect of kawe treatment on the water absorption and cooking characteristics of bambara groundnut varieties. *FRI, Accra*, p 15
- Arce-Arce EE, Gallegos-Infante JA, Rocha-Guzmán NE, González-Laredo RF, Moreno-Jiménez R, Figueroa-Cárdenas JDD, Montelongo-Montelongo AN (2014) Effect of infrared heating on the physicochemical properties of common bean (*Phaseolus vulgaris L.*) flour. *CyTA-J Food* 12:242–248
- Arntfield SD, Scanlon MG, Malcolmson LJ, Watts BM, Cenkowski S, Ryland D, Savoie V (2001) Reduction in lentil cooking time using micronisation: comparison of two micronisation temperatures. *J Food Sci* 66:500–505
- Ashraf S, Saeed SMG, Sayeed SA, Ali R (2012) Impact of microwave treatment on the functionality of cereals and legumes. *Int J Agric Biol* 14:356–370
- Bellido G, Arntfield SD, Cenkowski S, Scanlon M (2006) Effects of micronisation pretreatments on the physicochemical properties

- of navy and black beans (*Phaseolus vulgaris* L.). LWT Food Sci Technol 39:779–787
- Bernal-Lugo I, Parra C, Portilla M, Peña-Valdivia CB, Moreno E (1997) Cotyledon thermal behavior and pectic solubility as related to cooking quality in common beans. Plant Foods Hum Nutr 50:141–150
- Betancur-Ancona D, Segura-Campos M, Rosado-Rubio JG, Franco LS, Chel-Guerrero L (2012) Chemical composition and antinutritional factors in five tropical legume seeds. Nutr Consum Health, Beans, pp 117–141
- Boye J, Zare F, Pletch A (2010) Pulse proteins: processing, characterisation, functional properties and applications in food and feed. Food Res Int 43:414–431
- Cenkowski S, Sosulski F (1998) Cooking characteristics of split peas treated with infrared heat. Trans ASAE 41:715–720
- Cenkowski S, Hong JT, Scanlon M, Arntfield S (2003) Development of a mathematical model for high-intensity infrared processing (micronisation) of peas. Trans ASAE 46:705–713
- Cenkowski S, Arntfield S, Scanlon M (2007) Far infrared dehydration and processing. In: Hui YH, Clary C, Farid MM, Fasina OO, Noomhorm A, Welte-Chanes J (eds) Food drying science and technology: microbiology, chemistry, application. DESTech Publications, Lancaster, pp 157–201
- Chandrasekaran S, Ramanathan S, Basak T (2013) Microwave food processing—a review. Food Res Int 52:243–261
- De Mesa RY, Alavi S, Singh N, Shi NY, Dogan H, Sang Y (2009) Soy protein-fortified expanded extrudates: baseline study using corn starch. J Food Eng 90:262–270
- Deepa C, Hebbar HU (2016) Effect of high-temperature short-time ‘Micronisation’ of grains on product quality and cooking characteristics. Food Eng Rev 8:1–13
- Fasina O, Tyler RT, Pickard MD, Zheng GH (1999) Infrared heating of hull-less and pearled barley. J Food Process Preserv 23:135–151
- Fasina O, Tyler B, Pickard M, Zheng GH, Wang N (2005) Effect of infrared heating on the properties of legume seeds. Int J Food Sci Technol 36:79–90
- Food and Agriculture Organisation of United Nations (2014) Value of production: Bambara groundnut. <http://data2.un.org/crop/bambaragroundnut.htm>. Accessed Oct 2016
- Galiotou-Panayotou M, Kyriakidis NB, Magiatis I (2008) Phytase–phytate–pectin hypothesis and quality of legumes cooked in calcium solutions. J Sci Food Agric 88:355–361
- Ginzburg AS (1969) Application of infrared radiation in food processing. Chemical and process engineering series. Leonard Hill Books, London
- Han H, Baik BK (2008) Antioxidant activity and phenolic content of lentils (*Lens culinaris*), chickpeas (*Cicer arietinum* L.), peas (*Pisum sativum* L.) and soybeans (*Glycine max*), and their quantitative changes during processing. Int J Food Sci Technol 43:1771–1780
- Hebbar U, Vishvanathan KH, Ramesh MN (2004) Development of a combined infrared and hot air dryer for vegetables. J Food Eng 65:557–563
- Hernandez-Infante M, Sousa V, Montalvo I, Tena E (1998) Impact of microwave heating on haemagglutinin, trypsin inhibitors and protein quality of selected legume seeds. Plant Foods Hum Nutr 52:199–208
- Hohlberg AI, Stanley DW (1987) Hard-to-cook defect in black beans. Protein and starch considerations. J Agric Food Chem 35:571–576
- Huma N, Anjum M, Sehar S, Khan MI, Hussain S (2008) Effect of soaking and cooking on nutritional quality and safety of legumes. Nutr Food Sci 38:570–577
- Iqbal A, Khalil IA, Ateeq N, Sayyar-Khan M (2006) Nutritional quality of important food legumes. Food Chem 97:331–335
- Jackson GM, Varriano-Marston E (1981) Hard-to-cook phenomenon in beans: effects of accelerated storage on water absorption and cooking time. J Food Sci 46:799–803
- Jeevitha GC, Hebbar HU, Raghavarao KSMS (2013) Electromagnetic radiation-based dry blanching of red bell peppers: a comparative study. J Food Process Eng 36:663–674
- Jun S, Irudayaraj J (2003) A dynamic fungal inactivation approach using selective infrared heating. Trans ASAE 46(5):1407–1412
- Karr-Lilienthal LK, Grieshop CM, Merchen NR, Mallin DC, Fahey GC (2004) Chemical composition and protein quality comparisons of soybeans and soybean meals from five leading soybean-producing countries. J Agric Food Chem 52:6193–6199
- Kayitesi E, Duodu KG, Minnaar A, De Vries H (2012) Effect of micronisation of pre-conditioned cowpeas on cooking time and sensory properties of cooked cowpeas. J Sci Food Agric 93:838–845
- Krishnamurthy K, Khurana HK, Saini J, Irudayaraj J, Demirci A (2008) Infrared heating in food processing: an overview. Compr Rev Food Sci Food Saf 7:2–13
- Michael P, Ámingos D, Baghurst R (1991) Tilden lecture. Applications of microwave dielectric heating effects to synthetic problems in chemistry. Chem Soc Rev 20:1–47
- Murevanhema YY, Ajeani VA (2013) Potential of bambara groundnut (*Vigna subterranea* L.) Verdc milk as a probiotic beverage—review. Crit Rev Food Sci 53:954–967
- Mwangwela AM (2006) Physicochemical characteristics of conditioned and micronised cowpeas and functional properties of the resultant flours. University of Pretoria, Pretoria
- Mwangwela AM, Waniska RD, Minnaar A (2006) Hydrothermal treatments of two cowpea (*Vigna unguiculata* L. Walp) varieties: effect of micronisation on physicochemical and structural characteristics. J Sci Food Agric 86:35–45
- Mwangwela AM, Waniska RD, Minnaar A (2007a) Effect of micronisation temperature (130 and 170 °C) on functional properties of cowpea flour. Food Chem 104:650–657
- Mwangwela AM, Waniska RD, McDonough C, Minnaar A (2007b) Cowpea cooking characteristics as affected by micronisation temperature: a study of the physicochemical and functional properties of starch. J Sci Food Agric 87:399–410
- Ndungu KE, Emmambux MN, Minnaar A (2012) Micronisation and hot air roasting of cowpeas as pretreatments to control the development of hard-to-cook phenomenon. J Sci Food Agric 92:1194–1200
- Nti CA (2009) Effects of bambara groundnut (*Vigna subterranea*) variety and processing on the quality and consumer appeal for its products. Int J Food Sci Technol 44:2234–2242
- Oboh G (2006) Antioxidant properties of some commonly consumed and underutilised tropical legumes. Eur Food Res Technol 224:61–65
- Ofuya Z, Akhidue V (2005) The role of pulses in human nutrition: a review. J Appl Sci Environ Manag 9:99–104
- Ogundele OM (2017) Nutritional and functional properties of soaked and micronised Bambara groundnut seeds and their flours. PhD Thesis (Food Science). University of Pretoria, Pretoria
- Ogundele OM, Emmambux MN (2018) Effect of infrared heating of pre-soaked whole and dehulled bambara groundnut (*Vigna subterranea*) seeds on their cooking characteristics and microstructure. LWT Food Sci Technol 97:581–587
- Ogundele OM, Minnaar A, Emmambux MN (2017) Effects of micronisation and dehulling of pre-soaked bambara groundnut seeds on microstructure and functionality of the resulting flours. Food Chem 214:655–663
- Padmashree A, Semwal A, Khan M, Govindaraj T, Sharma G (2016) Effect of infrared processing on functional, nutritional, antinutritional and rheological properties of mung bean (*Phaseolus aereus*) seeds. Int J Adv Res 4:606–613

- Parmar N, Singh N, Kaur A, Thakur S (2017) Comparison of color, anti-nutritional factors, minerals, phenolic profile and protein digestibility between hard-to-cook and easy-to-cook grains from different kidney bean (*Phaseolus vulgaris*) accessions. *J Food Sci Technol* 54:1023–1034
- Penicela L (2011) The Influence of seed coat and cotyledon structure on cooking characteristics of cowpea. M.Sc. dissertation. (Food Science). University of Pretoria, Pretoria, SA
- Sadeghi AA, Fattah ANA, Chamani M (2010) The effects of micronisation on ruminal starch degradation of corn grain. *World Appl Sci J* 16:240–243
- Sakai N, Hanzawa T (1994) Applications and advances in far-infrared heating in Japan. *Trends Food Sci Technol* 5:357–362
- Sandu C (1986) Infrared radiative drying in food engineering: a process analysis. *Biotechnol Prog* 3:109–119
- Sanginga N (2003) Role of biological nitrogen fixation in legume based cropping systems; a case study of West Africa farming systems. *Plant Soil* 252:25–39
- Scanlon MG, Cenkowski S, Segall KI, Arntfield SD (2005) The physical properties of micronised lentils as a function of tempering moisture. *Biosyst Eng* 92:247–254
- Sharma G (2009) Micronisation. Defence research and development organization, ministry of defence, government of India. *Sci Spectrum* 169–171
- Sharma GP, Verma RC, Pathare PB (2005) Thin layer infrared radiation drying of onion slices. *J Food Eng* 67:361–366
- Silva C, Bates R, Deng J (1981) Influence of soaking and cooking upon the softening and eating quality of black beans (*Phaseolus vulgaris*). *J Food Sci* 46:1716–1720
- Singh R, Chung G, Nelson R (2007) Landmark research in legumes. *Genome* 50:525–537
- Singh B, Singh JP, Shevkani K, Singh N, Kaur A (2017) Bioactive constituents in pulses and their health benefits. *J Food Sci Technol* 54:858–870
- Taiwo KA, Akanbi C, Ajibola OO (1997) The effects of soaking and cooking time on the cooking properties of two cowpea varieties. *J Food Eng* 33:337–346
- Tresina PS, Mohan VR (2011) Effect of gamma irradiation on physicochemical properties, proximate composition, vitamins and antinutritional factors of the tribal pulse *Vigna unguiculata* subsp. *unguiculata*. *Int J Food Sci Technol* 46:1739–1746
- Vadivel V, Janardhanan K (2005) Nutritional and antinutritional characteristics of seven South Indian wild legumes. *Plant Foods Hum Nutr* 60:69–75
- Van Zuilichem DJ, Van't Riet K, Stolp W (1986) An overview of new infrared radiation processes for various agricultural products. In: Le Maguer M, Jelen P (eds) *Food engineering and process applications, transport phenomena*, vol 1. Elsevier, New York, pp 595–610
- Vilakati N, Macintyre U, Oelofse A, Taylor JP (2015) Influence of micronisation (infrared treatment) on the protein and functional quality of a ready-to-eat sorghum-cowpea African porridge for young child-feeding. *Int J Food Sci Technol* 63:1191–1198
- Wang N, Daun JK, Malcolm LJ (2003) Relationship between physicochemical and cooking properties, and effects of cooking on antinutrients, of yellow field peas (*Pisum sativum*). *J Sci Food Agric* 83:1228–1237
- Zhao Y (2000) The effects of treatment and micronization on the quality and cookability of lentils. Unpublished M.Sc. thesis. University of Manitoba, Department of Food Science, Winnipeg, Manitoba

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.