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COMPREHENSIVE REVIEWS IN FOOD SCIENCE AND FOOD SAFETY

Comprehensive REVIEWS in Food Science and Food Safety WILEY

Thermal treatment of common beans (*Phaseolus vulgaris* L.): Factors determining cooking time and its consequences for sensory and nutritional quality

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Abstract

Over the past years, the shift toward plant-based foods has largely increased the global awareness of the nutritional importance of legumes (common beans (*Phaseolus vulgaris* L.) in particular) and their potential role in sustainable food systems. Nevertheless, the many benefits of bean consumption may not be realized in large parts of the world, since long cooking time (lack of convenience) limits their utilization. This review focuses on the current insights in the cooking behavior (cookability) of common beans and the variables that have a direct and/or indirect impact on cooking time. The review includes the various methods to evaluate textural changes and the effect of cooking on sensory attributes and nutritional quality of beans. In this review, it is revealed that the factors involved in cooking time of beans are diverse and complex and thus necessitate a careful consideration of the choice of (pre)processing conditions to conveniently achieve palatability while ensuring maximum nutrient retention in beans. In order to harness the full potential of beans, there is a need for a multisectoral collaboration between breeders, processors, and nutritionists.

KEYWORDS

legumes, nutrient, thermal processing

1 | INTRODUCTION

Food and Agricultural Organization (FAO) of the United Nations defines pulses as "leguminous crops that are harvested solely for their dry seeds." Common beans (*Phaseolus vulgaris* L.) are one of the most important pulses for consumption. They belong to the Order Fabales, Family Fabaceae, Genus *Phaseolus* L. and Species *Phaseolus vulgaris* L. (OECD, 2016; Siddiq & Uebersax, 2013). Domestication of beans is predated by the occurrence of two evolutionary lineages based on two eco-geographical gene pools namely Mesoamerica and Andes but are now widely cultivated (Bitocchi et al., 2012). Different common bean cultivars exist showing a range of morphological and agronomical characteristics such as seed size, shape, color, and growth habits (Singh et al., 1991). The main classes/types of common beans include red kidney, black, haricot, yellow, cranberry, pinto, and navy beans (Hayat et al., 2014).

Structurally, common beans are made up of two major parts; seed coat and the cotyledon as depicted in Figure 1. Nutritionally, beans are composed of complex carbohydrates including resistant starch and oligosaccharides such as raffinose that have been reported to have prebiotic properties (Berg et al., 2012). Furthermore, the presence of

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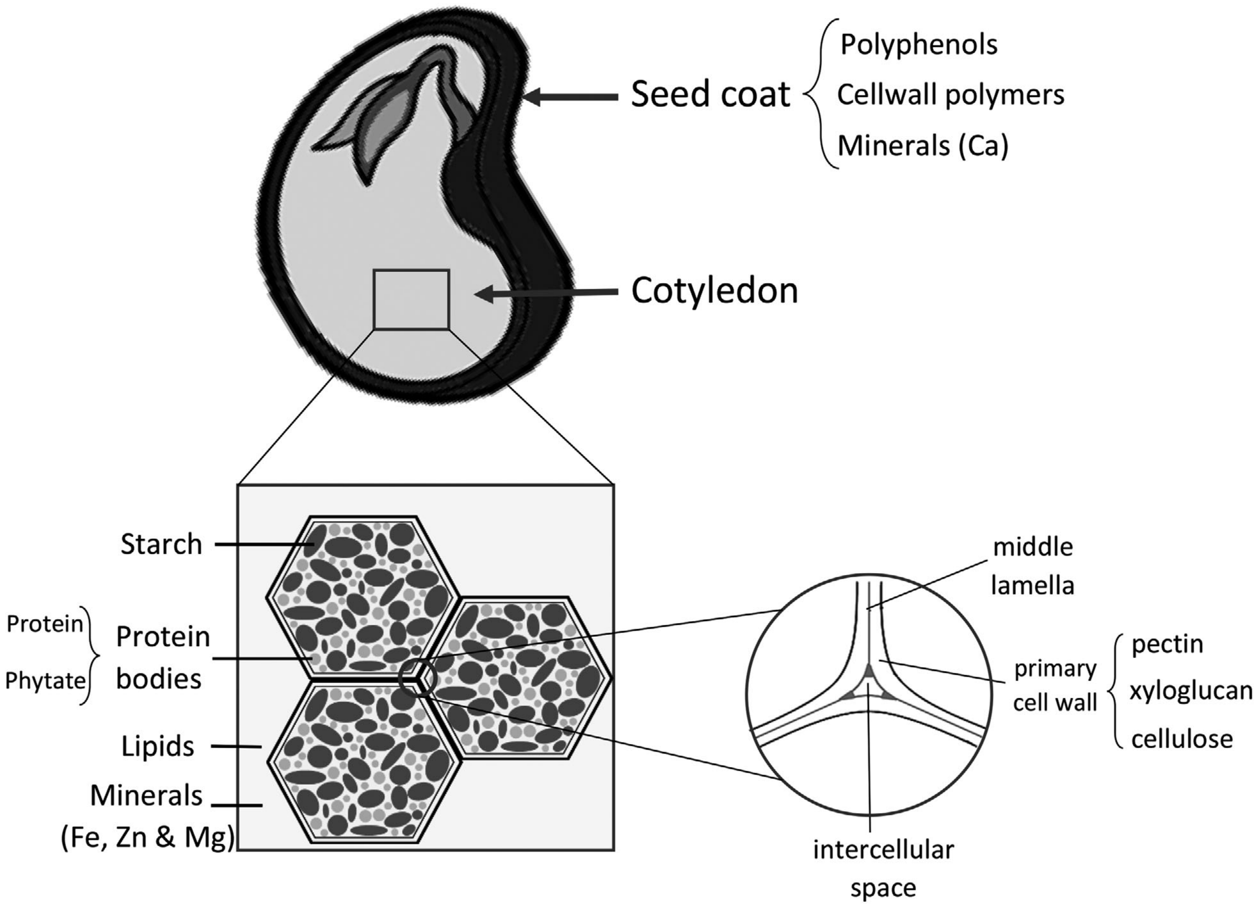

FIGURE 1 Schematic illustration of the structural composition of bean. Adapted from Pallares et al. (2021)

dietary fiber as well as slowly digestible starch (SDS) contributes to the low glycemic index of beans compared to other carbohydrate-rich foods (Los et al., 2018). Beans are also rich in proteins with an amino acid profile complementary to that of cereals (Bressani, 1993; Hayat et al., 2014) and the presence of micronutrients such as minerals and B-vitamins contributes to their high nutritional quality. Common beans are increasingly gaining attention as functional foods due to presence of compounds such as polyphenols that have been reported to show both antioxidative and anticarcinogenic properties (Çalışkantürk et al., 2017; Cardador-Martínez et al., 2002). Next to these nutritional properties, summarized in Table 1, common beans are able to fix nitrogen in the soil (Foyer et al., 2016), they have relatively low carbon footprint (Nijdam et al., 2012) and low water footprint per gram protein (Mekonnen & Hoekstra, 2012) in comparison to animal sources of protein as illustrated in Table 2, which results in a positive environmental impact.

The current annual global production of dry beans according to FAO estimates is 30 million metric tons (FAOSTAT, 2020). Majority of this production takes place in Latin America, Africa, and some parts of Asia, which are also the regions with the highest rates of bean consumption per capita (McDermott & Wyatt, 2017). In parts of these regions, beans are mostly cultivated by small-scale farmers and are mainly grown for subsistence. Common beans may be consumed in their fresh form as green beans or snap beans when harvested before physiological maturity. Alternatively, they are harvested after maturity as dry beans which is the most common form of consumption (Broughton et al., 2003). After harvesting, the dried beans can be stored for a long time until consumption.

Soaking is the most widely applied pre-processing of beans prior to cooking. It is mainly done to soften the beans which reduces the overall cooking time and saves on energy costs. This is due to increased water availability which facilitates reactions such as starch gelatinization during cooking (Bellido et al., 2006). Since soaking is a crucial step during bean processing, in the recent past, several studies have focused on understanding the hydration process and kinetics (Kumar et al., 2018; Li et al., 2020; Mikac et al., 2015). Current insights will be discussed in this review.

TABLE 1 Nutritional and antinutritional composition of common beans (all *Phaseolus vulgaris* L.) (% dry matter unless indicated otherwise) (Reyes-Moreno et al., 1993; Champ, 2002; Hayat et al., 2014)

Nutrients		**Antinutrients**
Macro-components	Micro-components	
Carbohydrates (50% to 60%) of which – Starch (30% to 60%) – Dietary fiber (14% to 19%) – Oligosaccharides (2% to 6%)	Vitamins in mg/100 g (thiamine 0.81 to 1.32, riboflavin 0.112 to 0.411, niacin 0.85 to 3.21, vitamin B6 0.299 to 0.659 and folic acid 0.148 to 0.676)	Tannins (0% to 2%)
Proteins (16% to 33%)	Minerals (calcium 0.09% to 0.2%, iron 3.83 to 7.55 mg/100 g, copper 0.69 to 1.20 mg/100 g, zinc 2.2 to 4.4 mg/100 g, phosphorous 0.46%, potassium 1.54% and magnesium 0.20%)	Phytates (0.6% to 2.7%)
Lipids (1% to 3%) of which – Unsaturated fatty acids (65% to 87%) – Saturated fatty acids (10% to 15%)	Polyphenols (0.0% to 0.4%)	Lectins (8200 HA)

HA, hemagglutinin activity.

TABLE 2 Summary of the water and carbon footprints of some selected protein-rich products (Mekonnen & Hoekstra, 2012; Nijdam et al., 2012)

Food item	**Water footprint (L/g protein)**	**Carbon footprint (GHG kg CO_2-eq /kg protein)**
Beef	112	46 to 640
Pork	57	20 to 55
Poultry	34	10 to 30
Eggs	29	15 to 42
Milk	31	28 to 43
Pulses	19	4 to 10

Thermal processing, henceforth referred to as cooking, is a fundamental preparation step of beans for consumption that is aimed at achieving palatability coupled with increased digestibility of nutrients (Liener & Thompson, 1980), reduction/elimination of antinutrients (Chau & Cheung, 1997; Thompson, 2019) and improved sensorial attributes such as aroma, taste, and texture. Additionally, cooking inactivates hemagglutinin, a protein which has been shown to be able to bind to carbohydrates on the surface of cellular membranes such as red blood cells thus causing toxicity (Gabius et al., 2011). Several methods of cooking beans involving use of dry or wet heat, with (out) application of pressure and (not) preceded by soaking (Bressani, 1993; Wood, 2017) have been exploited. There are no standardized cooking protocols of beans and the few guidelines available vary depending on market class or bean variety. In the absence of a validated cooking procedure, the determinant for use of a particular cooking method often is affordability and convenience in terms of time and energy costs without considering the nutritional consequences.

The cooking time of beans is influenced by various factors. Understanding and controlling the influence of these factors on the cooking time of beans is of importance toward breeding of beans for specific purposes, for example, shorter cooking time in regular cooking or some increased resistance to softening in the context of sterilization processes that otherwise might result in extremely soft end products. At the same time preservation of the nutritional quality of beans during storage and processing should be ensured. Shorter cooking times allow considerable reduction in energy consumption (Ghasemlou et al., 2013). Moreover, with the trend in increased urbanization, a factor such as convenience has become an important driver of food choice (Karlsen et al., 2016).

Although cooking is paramount to achieve the nutritional benefits, prolonged exposure to high temperatures may be detrimental to some nutrients present in beans and may negatively affect the nutrient retention of processed beans (Van Der Poel, 1990). This is attributed to either leaching out of nutrients, the degradation of compounds such as vitamins and amino acids and/or due to heat-induced crosslinking reactions that lead to formation of insoluble complexes that limit the digestibility of the nutrients involved (Vaz Patto et al., 2015). Thermal processing of beans is therefore an intricate balance between enhancing textural attributes and reduction of antinutrients and toxic compounds while ensuring maximum retention of nutrients. Detailed studies into optimization of cooking conditions to deliver safe and nutritious beans to the consumers are required.

This review will provide some insights into the most recent findings on the cooking process of beans. Additionally, the influence of genetics, environment, postharvest storage as well as pre-processing conditions on the cooking times of common beans will be discussed. Common

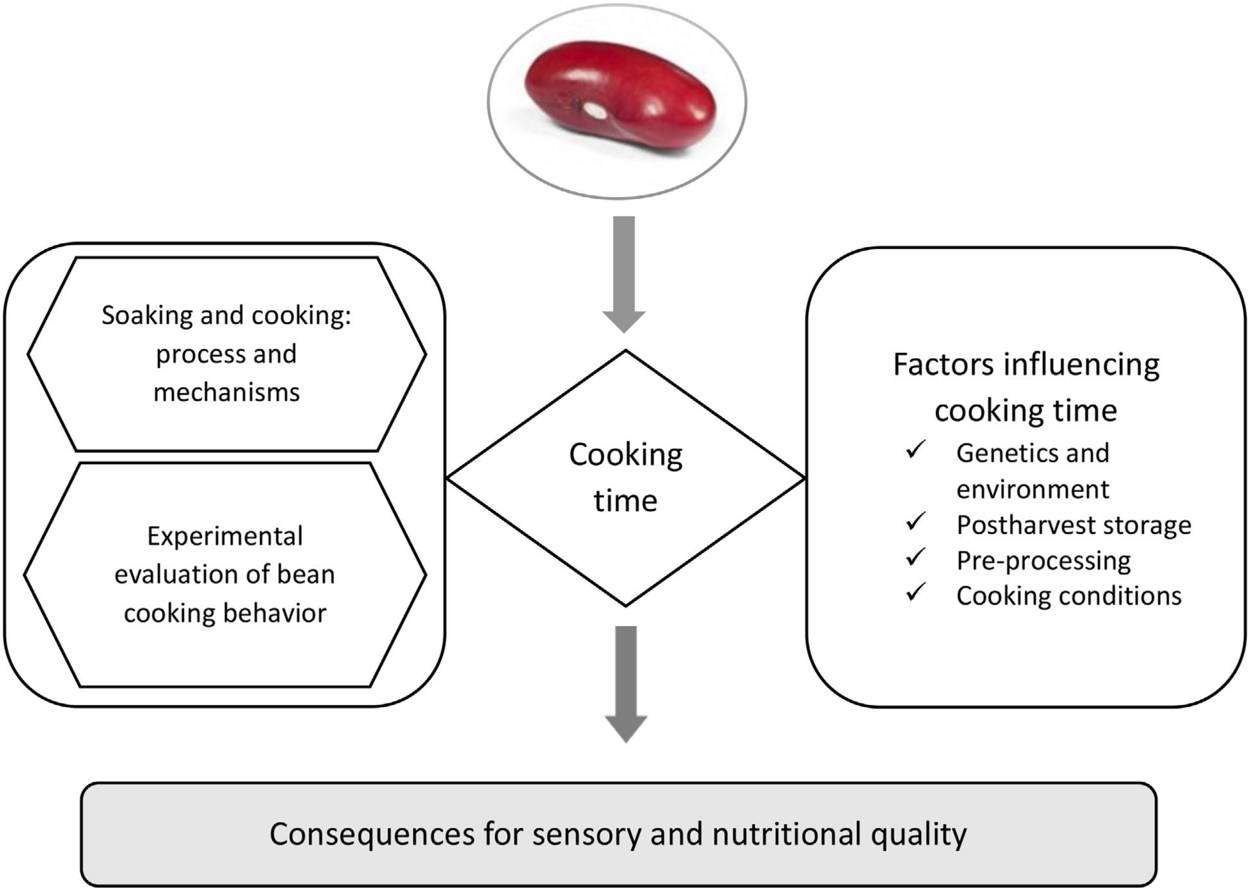

FIGURE 2 Schematic overview linking the topics highlighted in this review

methods used for determining the cooking time of beans will also be highlighted. Furthermore, the sensorial and nutritional impact of cooking time will be evaluated to provide insights into how processing methods can be adapted to ensure optimum nutrient retention. The topics covered in this review are as schematically illustrated in Figure 2. Although this review focuses on common beans, examples from other legumes or even fruit and vegetable cooking will be included when relevant to point out specific principles.

2 | BEAN SOAKING AND HYDRATION: MECHANISM AND KINETICS

Soaking is an integral part of (whole) bean processing as it improves the hydration characteristics of beans ensuring subsequent uniformity of cooking. During soaking, the seeds absorb water leading to an increase in size until an equilibrium is attained. According to American Association of Cereal Chemists (AACC) method 56-35.01, the hydration capacity of pulses is defined as the amount of water that whole seeds absorb after soaking in excess water for 16 hr at room temperature (22 ± 2°C). The result is expressed as the amount of water absorbed per 100 g of seeds. During this process some seeds might remain entirely or partially unswollen, these are defined as hydrated seeds and the number of nonhydrated seeds is expressed as a percentage of the total number of seeds (AACC, 2007; Wood, 2017). Seed hydration comprises of two processes, that is, entry of water in to the seed and the consequent swelling of the seed polymers (Leopold, 1983). The first point of entry of water into the seeds is not well understood and various authors have proposed different paths such as micropyle, hilum, and seed coat (Ma et al., 2004; Mikac et al., 2015).

2.1 | Hydration kinetics during soaking

Hydration kinetics of beans during soaking is a complex phenomenon that has been characterized by a sigmoidal curve with either a short (negligible) or longer lag phase. The sigmoidal curve with short/negligible lag phase has been described by some authors (Abu-Ghannam & McKenna, 1997; Kumar et al., 2018) as a biphasic model

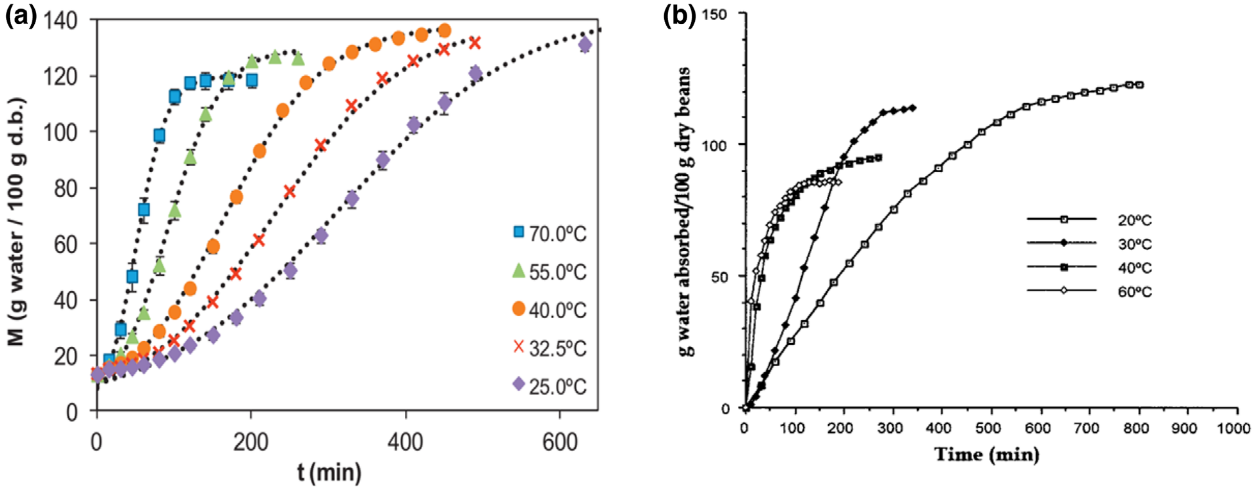

FIGURE 3 Graph showing rate of moisture uptake during soaking of (a) Adzuki bean (*Vigna angularis*) and (b) red kidney bean. Reprinted with permission from Oliveira et al. (2013) and Abu-Ghannam and McKenna (1997). Copyright (2020, 2021)

due to the downward concave shape exhibited by the water absorption behavior. For the longer lag phase, the initial water uptake is slow, subsequently follows an exponential increase and then slows down with time (Miano et al., 2018; Oliveira et al., 2013), as shown in Figure 3. The lag phase is ascribed to the role of the seed coat as a barrier for water absorption. Thus, water enters through the hilum or micropyle followed by the hydration of the seed coat from inside. Once the seed coat is hydrated, the water uptake rate increases now entering the bean through the seed coat (Miano et al., 2018). The absence of a lag phase suggests a more rapid initial water uptake as can be seen in Figure 3, and is attributed to filling up of capillaries located on the surface of the seed coat and the hilum (Kumar et al., 2018). As soaking continues, the rate of hydration slows down owing to the increased extraction of soluble materials as well as filling up of the free capillary and other intercellular spaces (Abu-Ghannam & McKenna, 1997). This suggests that the water uptake mechanism is changing from capillary transport in the early phase to diffusion in the later phase of moisture transport.

The differences in hydration behavior have been reported to be a function of the initial moisture content of the bean which alters the seed coat permeability (Miano et al., 2018). In a study on Adzuki beans (*Vigna angularis*), a change in hydration behavior from a sigmoidal curve with a longer lag phase to one with a shorter lag phase was reported when the initial moisture content of the beans was above 20% dry basis (Miano & Augusto, 2015). Moreover, as shown in Figure 3, this change also happens when the soaking temperature increases. At low initial moisture contents, the lag phase can be attributed to the necessity of the seed coat to be saturated with water in order to transition from a glassy to a rubbery state, while at higher initial moisture content, the plasticizing effect of water facilitates the diffusion of water (Abu-Ghannam & McKenna, 1997; Miano & Augusto, 2015). This moisture-dependent permeability of the seed coat results from physical, chemical, and morphological characteristics of the bean.

2.2 | Mechanistic insight into soaking

Although soaking is a fundamental part of bean cooking, very few studies try to explain the mechanisms involved in the reduction of cooking time due to soaking. Nuclear magnetic resonance (NMR) relaxometry has been used in hydration studies to understand changes in water fractions during soaking. The higher the degree of molecular mobility, the longer the relaxation time (time required for an exponential system to return to equilibrium after disturbance) (Li et al., 2020; Zhang & McCarthy, 2013). Mikac et al. (2015) reported an association of relaxation time of water protons with the amount of water in the cotyledon tissue of the soaked bean. They reported a decrease in relaxation time of unbound water (in cotyledon void) with continued soaking and cooking. They attributed this time dependence to bean tissues being solubilized during soaking and subsequently the pre-soaked beans would take shorter time to cook. Similar results have been reported during hydration of navy beans and black beans (Li et al., 2020; Zhang & McCarthy, 2013). Additionally, Martínez-Manrique et al. (2011) hypothesized that during soaking, cell wall enzymatic activities are enhanced which lead to changes in degree of polymerization of pectin making it more extractable. As a result, these changes lead to loss of cell wall rigidity due to a decrease in intercellular adhesion and consequently leads to shorter bean cooking time. The importance of this mechanism has not been clarified. More important, it can be hypothesized that during cooking of un-soaked beans, moisture transfer becomes the rate limiting factor during initial stages of cooking as the bean tissues need to be hydrated to ensure sufficient moisture for processes such as starch gelatinization and protein denaturation. In the later phases of cooking, pectin solubilization becomes the rate limiting process. Whereas during cooking of soaked beans, there is sufficient moisture during the initial stages to facilitate uniformity during cooking with rapid starch gelatinization and protein denaturation and pectin solubilization being the rate limiting process of cooking (Chigwedere et al., 2018). (for more detailed information see Section 3.2).

2.3 | Factors influencing soaking time

Soaking of pulses is generally done for 12 to 24 h at room temperature (Abu-Ghannam & McKenna, 1997) and is a time consuming step. Toward shortening this soaking time, several techniques have been investigated. An increase in soaking temperature, for instance, results in an increased hydration rate and consequently a decreased soaking time to achieve hydration equilibrium (Kinyanjui et al., 2015; Kumar et al., 2018; Miano et al., 2018; Oliveira et al., 2013) as depicted in Figure 3. The increased hydration rate with increasing temperature is as a result of enlarged seed pores and higher water diffusivity (Li et al., 2020; Mikac et al., 2015). Nevertheless, care should be taken when soaking at temperatures between 50 and 70°C as this has been reported to promote hardening of beans during subsequent cooking (Koriyama et al., 2017). This phenomena is similar to the hardening that occurs during heating of vegetables at temperatures above 50°C due to pectin demethoxylation as a result of the action of pectin methyl esterase (PME) (Kasai et al., 1994; Koriyama et al., 2017).

Ultrasound energy has also been explored as a treatment to enhance fast hydration. It is a form of energy created by mechanical sound waves at frequencies of approximately 20 kHz (Gallo et al., 2018). The acoustic energy is responsible for increasing the mass transfer rate without heating the material which enhances the hydration rate thus decreasing the soaking times required (Ghafoor et al., 2014; Ulloa et al., 2015). Miano et al. (2018) reported that when both ultrasound and increased temperatures are employed in combination, the effect of ultrasound treatment was lowered as the temperature of the soaking water increased. Next to temperature and ultrasound treatments, influence of dehulling on soaking has also been evaluated. Kinyanjui et al. (2015) reported an increase in the rate of hydration coupled with a shorter lag phase while soaking dehulled beans. This suggests that the seed coat plays a significant role during soaking (see mechanistic aspects as described in Section 2.2) and ultimately during cooking to influence the cooking times of beans. Additionally, increasing the ratio of monovalent to divalent ions in the salt solutions has been shown to significantly decrease the cooking times of beans (de León et, al.,1992; Njoroge et al., 2016).

3 | BEAN HYDROTHERMAL PROCESSING METHODS AND MECHANISMS OF SOFTENING

3.1 | Cooking methods

3.1.1 | Hydrothermal processing (wet heating)

Boiling is the simplest and most conventional hydrothermal processing method of beans. Generally, soaked or un-soaked beans are cooked at temperatures between 95 and 100°C (Siegel & Fawcett, 1976). The beans are placed in a pot and water is added to cover the beans before closing the pot with a lid. The pot is then brought to a boil by placing it on a stove (heat source). During the boiling process water is periodically added to compensate for water lost during evaporation (del Castillo et al., 2012). This boiling process continues until the beans are soft. The time required to soften the beans while cooking at the atmospheric pressure conditions is dependent on various factors as discussed later (Section 5).

3.1.2 | Hydrothermal processing under pressure

In order to increase the rate of cooking, beans are cooked under pressure. This is attained through a pressure cooker in domestic cooking or a retort in industrial processing, typically referred to as canning. Whereas a pressure cooker works by trapping the steam produced by the boiling water within the vessel, in a canning factory, depending on the working principle of the retort, the heating medium consists of pressurized saturated steam, a pressurized steam air mixture (or with water cascading/spraying/immersion), leading to entrapped steam and heated water in the closed container (Drulyte & Orlien, 2019). The canning operation is usually preceded by a soaking step where beans are hydrated at room temperature for between 8 and 18 hr (Pedrosa et al., 2015; van der Merwe et al., 2006). In some cases, a subsequent blanching step is done which typically involves immersing beans in hot water (between 80 and 95°C) for a few minutes (Howard et al., 2018). Blanching expels gases in the intercellular spaces thereby improving the hydration uniformity of the seeds. The soaked and/or blanched beans are weighed into cans which are then filled with brine solution (typically containing NaCl or $CaCl_2$ for texture enhancement. EDTA is also sometimes added for color retention) or sauce (tomato) before sealing (Howard et al., 2018; van der Merwe et al., 2006). After sealing, the cans are placed in retorts and heat processing proceeds for a duration of time dependent on the temperature and pressure applied. The temperatures applied range between 110 and 135°C with pressures of about 1.04×10^5 Pa (Posa-Macalincag et al., 2002; Walters et al., 1997). After thermal treatment the cans are cooled to an internal temperature of about 35°C to prevent deformation or straining of the seams (Howard et al., 2018).

3.2 | Softening mechanism

During cooking of pre-soaked beans, the water absorption that occurs is reported as a biphasic model whereby there is an initial rapid influx of water into the bean during cooking followed by a more linear phase (Zhang & McCarthy, 2013). During NMR and magnetic resonance imaging (MRI) relaxometry studies, Zhang and McCarthy (2013) indicated that the initial rapid water uptake was attributed to uptake by intracellular contents such as starch whereas the water absorbed during the latter slow water uptake was mainly distributed in the intercellular space of the bean. Similarly, during a study on water distribution of common beans during cooking, Mikac et al. (2015) reported that the water absorbed by the bean after attaining its maximum expansion is mainly distributed within the cotyledon region and they proposed a molecular structure rearrangement that leads to retention of more water. One such molecular change that would require water and temperature is starch gelatinization (Ratnayake & Jackson, 2008).

The main macrostructural change that occurs during cooking of beans is softening. This textural change takes place as a result of (bio)chemical changes occurring within the cell wall and the middle lamella, particularly those involving pectic polymeric material (Van Buren, 1979). Other molecular changes that have been proposed to alter the textural properties of beans are protein denaturation (Garcia-Vela & Stanley, 1989) and starch gelatinization. It has been shown that in common beans, a heterogeneous matrix containing both pectin and starch, kinetics of thermal softening is mainly controlled by the rate of pectin solubilization with limited influence of starch gelatinization and protein denaturation mostly during the initial phases of cooking (Chigwedere et al., 2018).

A two-step mechanism is proposed for bean softening that firstly involves some enzymatic degradation of pectin during soaking (Martínez-Manrique et al., 2011) followed by pectin thermal solubilization via dissociation of hydrogen bonds during a consequent boiling step (Bernal-Lugo et al., 1997), the latter being by far the most important. Thermal solubilization of bean pectin during cooking is reported to be attributed to pectin interconversions that occur distinctly in the cotyledons. In detail, the high temperatures employed during cooking lead to an increase in the water-soluble (loosely bound) pectin fraction coupled with a decrease in ester bound (alkaline extractable) pectin fraction (Chigwedere, Nkonkola et al., 2019; Njoroge et al., 2016; Yi et al., 2016).

4 | EXPERIMENTAL APPROACHES TO EVALUATE BEAN COOKING TIMES

To evaluate cooking time of beans, methods of texture (i.e., hardness or softness) evaluation are employed, whereby beans are characterized based on the ease with which cotyledons disintegrate upon application of a force.

4.1 | Subjective methods

4.1.1 | Sensory analysis

This involves evaluation of perception acquired through the human senses of touch, smell, taste, sight, and hearing and is usually assessed by trained, semi-trained, or nontrained panellists. Sensory analysis has been widely used to evaluate the cookability of pulses (Yeung et al., 2009). Texture perception is highly dynamic owing to the changing nature of the physical attributes of foods whilst in the mouth. In that regard, the most crucial aspect during hardness evaluation is the first bite which is highly dependent on the magnitude of the applied force and the extent to which food disintegrates in the mouth (Guinard & Mazzucchelli, 1996). Several descriptive factors are used by panellists and include: "skin surface," "stickiness," "flouriness," and "softness." Sensory scales in which attribute intensities are rated on a continuous and unstructured graphical intensity scale are used (Armelim et al., 2006; Castillo et al., 2012). For instance, a scale score of 1 for "undercooked" to 5 for "overcooked" was used to evaluate the cooking quality of carioca beans cooked using different methods (Siqueira et al., 2013). However, the choice of the limits of the scale depend on the researcher. The cooking time of beans can be expressed as the time required for the beans to attain a palatable texture determined through mastication studies (Pallares et al., 2019). Not only is sensory analysis quite costly and time consuming but is also highly subjective. Nevertheless, the complex multimodal nature of sensory tests cannot be completely replaced, despite the several proposed objective methods (Birwal et al., 2015).

4.1.2 | Finger pressing

Finger pressing also known as the tactile method, has been extensively used to evaluate the cooking time of beans. Generally, bean seeds are sampled, cooled, and pressed between the thumb and the fore finger (Kinyanjui et al., 2015). The bean seeds are classified as cooked when the cotyledons disintegrate upon pressing (Jones & Boulter, 1983). The percentage of cooked beans is obtained as a function of cooking time. The time required to cook the batch is expressed as the time taken for a certain fraction of beans to be cooked. For instance, values of 80% and 90% have been reported (Kinyanjui et al., 2015; Sangani et al., 2014) with 95% being the commonly acceptable cooked fraction range. Despite being a simple and less costly method of cooking time evaluation, this method remains subjective and requires training to ensure that repeatability and reproducibility is achieved. Additionally, the expression of cookability and the values of percentage cooked may vary in the literature.

FIGURE 4 Image of a Mattson bean cooker. Reprinted with permission from Wood (2017). Copyright (2021)

4.2 | Objective methods

4.2.1 | Mattson bean cooker method

A common method used to determine the cooking time of pulses is using an apparatus (Figure 4) that was first developed by Mattson (1946). The apparatus essentially uses a set of plungers held in position by racks and a bottom surface that holds the bean seeds while cooking. The pointed end of the plungers touches the surface of (pre-soaked) beans and the entire apparatus is immersed in the boiling water (Wang & Daun, 2005). During cooking the bean seeds soften and consequently the plungers can puncture through the beans. The time required for the plungers to go through is either manually or automatically recorded (Bitjoka et al., 2008; Proctor & Watts, 1987; Wang & Daun, 2005). Cooking time is then defined as the time required for plungers to go through either 50%, 80%, or 92% of the beans (Jackson & Varriano-Marston, 1981; Proctor & Watts, 1987; Wang & Daun, 2005). The time required for plungers to go through 92% of beans was reported by Proctor and Watts (1987) to correspond with the findings of an acceptable sensory texture. In contrast to the subjective methods, the current method objectively determines the cooking time of beans and allows evaluation of bean to bean texture variation/variability through its ability to test a large number of beans individually (Proctor & Watts, 1987). Nevertheless, variabilities pertaining to plunger size (weight and diameter), orientation of the seeds under the plunger, make it difficult to compare results obtained in the literature (Wood, 2017). Besides, the fact that the plunger needs to go through the seed coat first may lead to inaccurate results especially for beans that have higher resistance of the seed coat to plunger penetration.

4.2.2 | Texture analysis

This method uses texture analysis equipment to evaluate the firmness of foods. Seed hardness is related to the quality of the seed and the maximum force parameter obtained in texture analysis (indicated as firmness) has been correlated with several seed quality factors. It is reported that factors such as shape and size of the seed, contact area with the plate, rate of deformation, the way a seed is fixed/mounted on the plate, can influence the accuracy of texture measurements (Arntfield et al., 2000; Stępniewski & Dobrzański, 2013). Additionally, matrix differences brought about by variations in pretreatments applied before cooking such as soaking and dehulling influence texture evaluation. Therefore, careful consideration of all the aforementioned factors will help

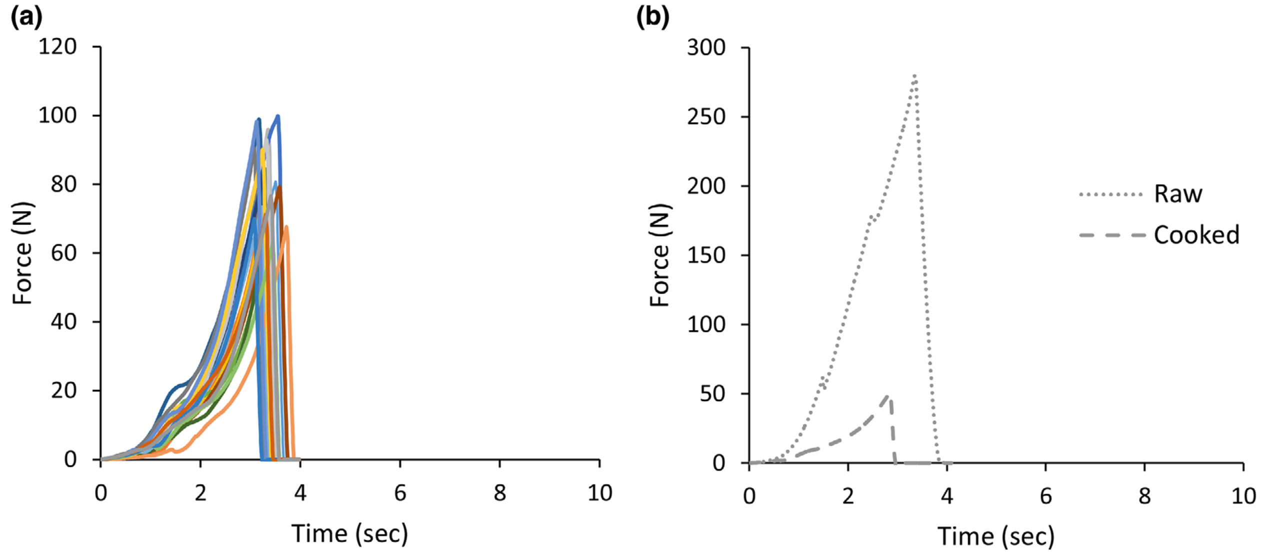

FIGURE 5 Force-deformation graph of red kidney beans obtained after compressing the cotyledons to 75% strain at a speed of 1 mm/s. (a) 20 cotyledons of beans soaked and cooked (at 95°C) for 45 min. (b) single cotyledons of soaked raw and cooked red kidney bean

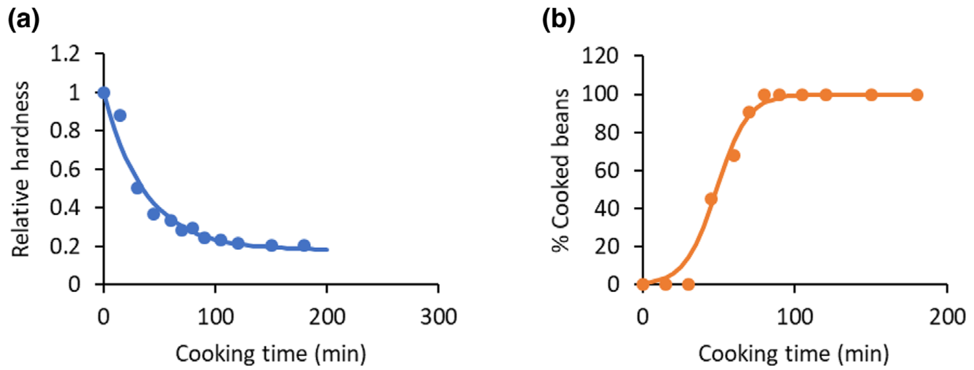

FIGURE 6 Graph showing the cooking profile of red kidney bean at moisture content of 12.8% and cooked at 95°C. (a) Texture evolution curve of cooking modeled using fractional conversion model. (b) Cooking profile after modeling using logistic regression model. The markers are experimental values whereas the continuous lines are predicted data (unpublished results)

guide decision on what methods of texture analysis to use, the operating parameters and how to express cooking time.

Today a wide range of commercial equipment is available. Depending on the type of probes used on the equipment, two types of tests can be conducted, namely, compression and puncture test. The compression test is a test by which the maximum force required to cause a predefined deformation is determined and expressed as degree of hardness. Usually the equipment comprises of a single cylindrical probe with a diameter of about 25 mm, a load cell, and a stage plate on to which the sample is placed. Beans are sampled at set time intervals during cooking. During measurement, a single cotyledon of the bean samples is placed horizontally on the sample holder and the probe is lowered to measure hardness which is expressed as the gram force required to compress the cotyledon to 75% (Chigwedere et al., 2018; Mendes et al., 2011) or 90% (Siqueira et al., 2013) strain. A force-deformation graph such as the one shown in Figure 5 is obtained. The hardness of beans decreases with cooking. Due to the significant variation of individual bean hardness as shown in Figure 5a, the average hardness data and standard deviations of about 25 cotyledons is plotted against the cooking times analyzed to obtain cooking profiles as shown in Figure 6a. Another possible way to express the cooking profiles could be to plot the percentage of cooked beans at a particular hardness/texture value against the cooking times as in the case with the finger pressing method or use of Mattson cooker. For instance, hardness data used to plot Figure 6a is set at 70 N (palatable range) (Pallares et al., 2019) to obtain binary data of cooked or not cooked beans and this data is modeled using logistic regression to obtain Figure 6b. Logistic regression uses a logit function which in this case, is the natural logarithm of the odds that a bean will be cooked after a given time of cooking (Wafula et al., 2020). By doing so, two approaches of expressing texture data of beans can be explored and integrated to provide more insights into texture evolution during cooking. The graphs obtained for either approach can be modeled to determine the cooking time of the batch. For example, cooking time of a bean sample can be expressed as time required to reach a particular relative hardness (palatable range) obtained from Figure 6a, or time required for a certain percentage (usually 95%) of beans to cook obtained from Figure 6b.

Next to the compression test applied to single beans, a bulk compression test that involves the analysis of several beans in a single compression cycle can be used. The main advantage with this test is that it can test many samples with less replications. A disadvantage is the loss of information on the variability in texture values within a cooked batch of beans. Variations on this test are the use of the Kramer shear cell (a multiblade shear cell whereby the sample is sheared, compressed, and extruded through bottom openings) and the Ottawa cell using a compression plate extruding the sample through an extrusion plate at the bottom of the cell. The methods have been applied to measure the tenderness of peas (Voisey & Nonnecke, 1973) as well as the cooking behavior of beans (Richardson & Stanley, 1991; Ziena et al., 1991).

The puncture test is like the single compression test, but the only variation is that the puncture test measures the amount of force required to push a probe into the sample. Thus, the cylindrical probe diameter is much smaller than the sample diameter. Additionally, unlike compression tests where the deformation is similar to the action of the molar teeth on a seed (Wood, 2017), in puncture tests both compression and shear elements exist. Therefore, as in the case for the Mattson bean cooker, the resistance of the seed coat to probe penetration can influence the results of the puncture test.

Although texture is a multimodal sensory attribute, texture instruments can only be used to analyze specific textural parameters which should then be interpreted in terms of sensory perception. It can therefore be inferred that both sensory and objective methods of texture analysis of beans are important and complementary.

4.3 | Nondestructive, predictive methods

The need for a fast, reliable, and nondestructive method for screening cooking time of intact dry bean seeds has led to the development of several predictive methods of evaluating cooking time particularly in industrial processing and in breeding programs. The suitability of visible and near infrared (Vis/NIR) spectroscopy in predicting cooking time has been recently reported (Cichy et al., 2015; Wafula et al., 2020). This optical sensing technique involves identifying the most suitable spectra that can be correlated to quality attributes such as texture and composition. The spectra data obtained is then modeled using multivariate data analysis techniques to obtain calibration equations (Saeys et al., 2019). The obtained calibrations are validated and tested against large data sets before being used for predictive purposes. Development of calibrations and their validations using the objective and/or the subjective methods previously mentioned require expertise and can be time consuming. However, once the calibrations have been performed the analysis is faster and easier. In a study on 206 bean accessions, Cichy et al. (2015) reported that Vis/NIR spectroscopic scanning of whole seeds explained about 68% of phenotypic variation in cooking time. The ability of Vis/NIR spectroscopy to predict hardness of canned black beans from intact dry beans as well as prediction of cooking times of freshly harvested beans and their susceptibility to develop HTC has also been reported (Mendoza, Cichy et al., 2018; Wafula et al., 2021). Similarly, in a recent study by Wafula et al. (2020) it was established that NIR spectroscopy has the potential to predict the cooking times of aged common beans. Prediction of cooking times was found to be better for one- and two-variety models for dehulled bean samples and this was attributed to the reduced interferences from the seed coats as well as intrinsic varietal differences.

Next to Vis/NIR, prediction of cooking time by hyperspectral imaging has also been explored. Hyperspectral imaging which combines imaging and spectroscopy for spectral and spatial data acquisition, has successfully been used to predict cooking time of soaked and nonsoaked beans of a broad set of cultivars and landraces (Mendoza, Wiesinger et al., 2018). To improve the robustness of the prediction models obtained from these methods, periodic updates and maintenance with data obtained from new samples that have high genotypic and phenotypic variability in textural properties are needed.

5 | FACTORS INFLUENCING BEAN COOKING TIMES

5.1 | Genetic factors

Cooking time (of soaked beans) has been shown to vary across genotypes and a variation of up to 5.5-fold has been reported for over 206 freshly harvested bean genotypes of different seed types (Cichy et al., 2015). The genetic variability of cooking time could be caused by physical and chemical factors that differ across the various seed types such as seed coat thickness and composition as well as cotyledon composition. In fact, earlier studies have shown that seed coat thickness influences water uptake rate with more preferential permeability of the light colored seeds compared to the darker ones (Valle et al., 1992). This can be attributed to darker beans having a thicker seed coat due to deposition of polyphenols which have been hypothesized to play a role in the seed coat permeability (Smýkal et al., 2014).

Some studies suggest that genetic variability of cooking time is highly heritable and is mainly regulated by a small number of genes (Cichy et al., 2019; Elia et al., 1997). Despite reporting a low association between the cooking time trait and DNA markers, Jacinto-Hernandez et al. (2003) concluded that two genes control the cooking time trait. In a more recent study, Cichy et al. (2015) using the genome-wide association analysis of cooking time reported several genes of interest in chromosome regions associated with cooking time. These genes are the trichome birefringence-like 13 involved in esterified pectin content, glucosyl transferase genes for flavonoid biosynthesis, and 2 cation/H+ exchanger genes involved in transport of calcium ions in Arabidopsis. Nevertheless, the underlying genetic mechanism for inherent variations in cooking time of freshly harvested beans has not yet been fully elucidated. As a matter of fact, very few studies have attempted to study the relationship between the cooking time and composition of freshly harvested beans (Hooper et al., 2017; Proctor & Watts, 1987) and even so, no clear relation has been put forward. The inherent variability in cooking time of freshly harvested beans therefore necessitates the investigation of the role of compositional factors, particularly those linked to the softening process of beans during cooking such as pectic polysaccharides and phenolic compounds. On the other hand, it has not been shown whether the mechanisms responsible for differences in cooking time of fresh dry beans are similar to those postulated for hard-to-cook (HTC) development during postharvest storage (see Section 5.3).

5.2 | Environmental conditions

Although few studies exist in the literature, environmental conditions during growth have also been reported to influence the cooking times of beans through influencing their textural properties (Proctor & Watts, 1987). The environmental conditions discussed here encompass both the atmospheric conditions during growth such as temperature and rainfall pattern and most importantly the agronomic conditions such as soil mineral content and composition. For instance, Wang et al. (2017) showed that beans grown on a site with warmer temperature (16.9°C) and less precipitation (274.9 mm) during the growing season had significantly longer mean cooking times. Similarly, in a study on dry beans, Cichy et al. (2019) reported that genotypes grown in Morogoro, a tropical region, took about two times longer to cook compared to averages of other environments. It is hypothesized that the high temperature and relative humidity conditions encountered in the tropical regions cause HTC development, a phenomenon that is discussed in the next section (Section 5.3).

In general, the relative contribution of the factors controlling inherent variation in cooking time remain unclear. While in the past some authors reported a higher influence of genotype (Halstead & Feller, 1964) and others reported a higher influence of environment (Proctor & Watts, 1987) on the cooking time, a significant influence of the interaction between both factors (genotype and environment) with cooking time has recently been reported by Cichy et al. (2019). They concluded that there could be multiple genetic mechanisms influencing the cooking time and that these mechanisms are possibly expressed differently in different environments. Moreover, it remains unknown whether the mechanisms responsible for cooking time variations in freshly harvested beans are similarly responsible for influencing the cooking time of beans during postharvest storage (in other words, the sensitivity to develop HTC under adverse storage conditions). Although the storage-induced hardening of beans has been widely studied, as reviewed in the next section, the mechanisms responsible are quite complex and not properly understood to date. Further research into these aspects is needed.

5.3 | Postharvest storage conditions

Biochemical deterioration of seeds and eventual loss of viability during storage is collectively referred to as aging, and the rate at which the deterioration reactions occur is enhanced by storage conditions employed (Walters et al., 2005). Among the changes occurring in beans during storage, the HTC phenomenon and the (bio)chemical mechanisms have been more intensively studied due to their direct influence on cooking quality of beans. This phenomenon develops when legumes are stored under adverse conditions of high temperatures (>25°C) and high relative humidity (>65%) (Kinyanjui et al., 2017; Liu et al., 1992; Reyes-Moreno et al., 1993) and is characterized by prolonged cooking times for cotyledons to soften to a desired texture. In Figure 7, we have integrated the current insights in the mechanisms responsible for HTC development during postharvest storage. HTC development should not be confused with "hard shell development" (HSD), the latter referring to lack of or slow water uptake during soaking and cooking (due to the resistance/defects

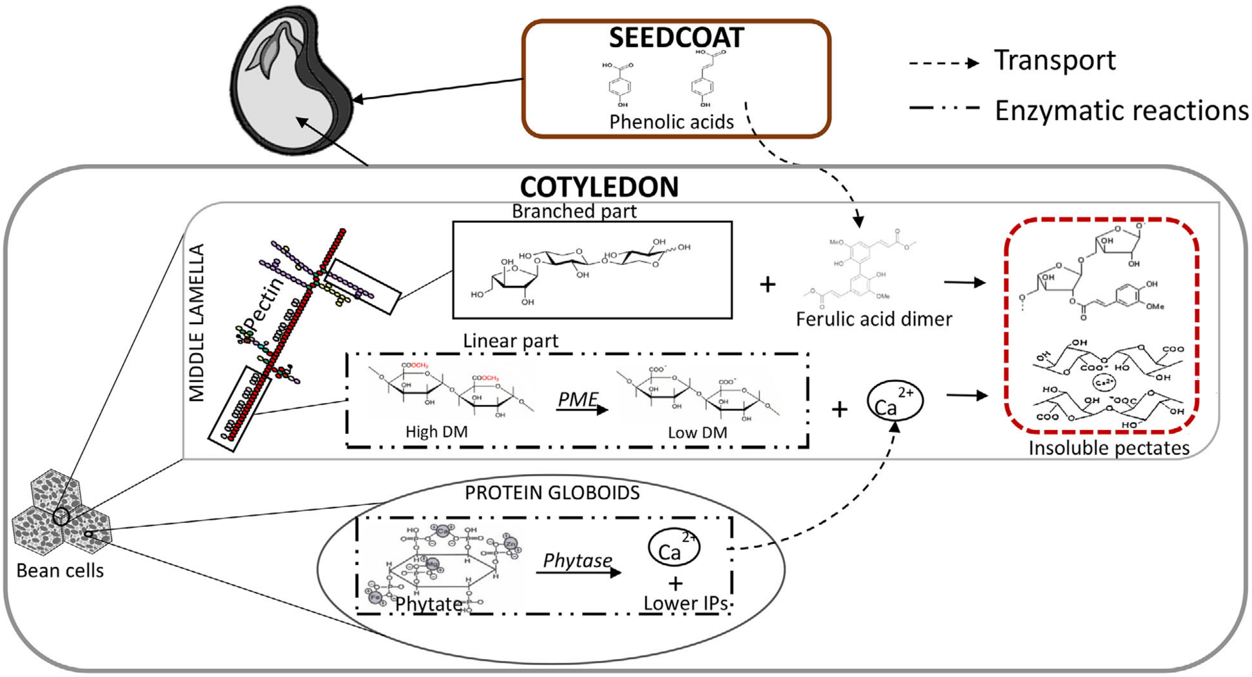

FIGURE 7 Schematic representation of the current insight on the mechanistic reactions taking place during postharvest storage conditions to induce hardening in beans. DM, degree of methylesterification; PME, pectin methylesterase enzyme; IPs, inositol phosphates

of the seed coat). HTC development is an irreversible process while HSD is reversible (Liu & Bourne, 1995). HSD can be easily detected after soaking as the beans with this defect generally have a wrinkled seed coat and/or are hard compared to the rest and therefore can be sorted out before proceeding to the cooking process. On the other hand, when un-soaked beans are cooked it is not possible to detect HSD and this is suggested to be a cause of variability in the cooking times of un-soaked beans (Cichy et al., 2019).

Membrane damage resulting from lipid oxidation during adverse storage conditions is proposed to be a primary event in occurrence of HTC (Moscoso et al., 1984; Richardson & Stanley, 1991). In addition, due to membrane damage coupled with enhanced molecular mobility, cations like calcium, released from phytate by the action of phytase, are hypothesized to migrate from the protein globoids to the middle lamella, as depicted in Figure 7. In the middle lamella, they crosslink demethylesterified pectin, already present and/or resulting from the action of PME, to form insoluble pectates (Jones & Boulter, 1983; Kilmer et al., 1994). Studies involving pectic polysaccharide changes show that in beans that have developed HTC, the extractability of pectin in hot water is lowered whereas it is increased in alkaline (sodium carbonate) solutions (Njoroge et al., 2014; Shiga et al., 2009; Yi et al., 2016). These changes are reported to be as a result of ionic (calcium) and ester bound crosslinking reactions with the pectin polysaccharides (Njoroge et al., 2016) which enhance bean tissue texture and retard pectin solubilization and hence softening during cooking. On the other hand, nonsignificant changes in degree of methylesterification (DM) of pectin during ageing of beans have been reported in the recent literature putting the role of PME in question (Chigwedere, Nkonkola et al., 2019; Njoroge et al., 2016). However, DM determination has so far been carried out on overall cotyledon and thus necessitates additional insight into local DM changes at the cotyledon cell wall level. To this end, we hypothesize the role of the ratio of calcium to carboxylic group of the pectin chain at the cell wall level to be playing a significant role in hardening.

It is proposed that storage under adverse conditions also enhances the migration of tannins and other polyphenolics from the seed coat to the middle lamella and cotyledon where they crosslink with macro-components such as pectin and proteins (Stanley, 1992). A decrease in total free phenolics coupled with an increase in lignin content was reported for HTC beans and these changes were found to correlate with the hardness (Martín-Cabrejas et al., 1997; Nasar-Abbas et al., 2008). Binding of phenolic acids to the cell wall polysaccharides leading to accumulation of insoluble pectates has also been detected in HTC carioca beans through Fourier transform infrared spectroscopy (Garcia et al., 1998). Similarly, a significant correlation between bean hardness and autofluorescence intensity of bean cell wall material has been reported. This fluorescence was attributed to accumulation of phenolic compounds within bean cell walls under adverse temperature-relative humidity storage conditions (Stanley & Plhak, 1989). Supportive evidence of the two hypotheses; pectin-cation-phytate hypothesis and involvement of phenolics is still limited in the literature and the existing studies are either limited in scope, inconclusive, or have discrepancies as to what reactions take precedence in hardening mechanism of beans during storage. In this regard, more research coupled with quantification analysis of the constituents involved such as pectic substances, phenolic substances, and cations is needed. In a recent microscopy study, Chen et al. (2021) concluded that there is a possible contribution of both the pectin-cation-phytate hypothesis and the involvement of pectin crosslinks in HTC development in the cotyledon during storage of red haricot

It is suggested that the cooking quality of beans can be maintained during storage under specific conditions of low temperature (<25°C) and low relative humidity (<65%). In this context, the glass transition (T_g) theory has been described in the literature as a concept to explain food stability in relation to molecular mobility of reacting components in the matrix. According to this theory, foods are most stable below T_g, a state in which molecular motion is greatly suppressed and chemical reactions are (very) limited (Murthy et al., 2003; Rahman, 2009). The relation between T_g and moisture content and temperature of foods can be illustrated using state diagrams which are used to predict the behavior of foods under conditions of storage and/or processing (Roos, 2010; Sablani et al., 2010). The state of a material is dependent on its composition, temperature, and time. It should be noted that the molecular weight of components in a matrix, especially sugars, plays an important role in determining the T_g (Roos, 2010). This is interesting for multicomponent matrices such as common beans that contain sugars and other high molecular weight polymers such as starch and protein.

Applying this concept of glass transition, it can be inferred that the biochemical changes occurring during storage-induced hardening of beans are enhanced by molecular mobility resulting from the high temperatures (>25°C) and relative humidity (>65%) conditions. This molecular mobility then enhance deteriorative enzyme catalyzed reactions involving phytase, PME, and peroxidase, as well as mobility of compounds such as calcium and phenolic acids as a result of membrane damage. In a more recent study, Chigwedere, Flores et al. (2019) showed that the storage stability of common beans in the context of aging and cooking quality is achieved when beans are stored below their overall glass transition. These authors established a glass transition temperature–moisture relation which could form a basis of selecting appropriate storage conditions. However, this research was the first attempt at exploring stability of beans in this context and more insights are needed. In particular, the role of the heterogeneous nature of the bean matrix (leading to local T_g values as recently shown by Kyomugasho et al. (2020) in relation to the local reactions taking place.

It has been shown that the higher the moisture content of beans the lower the T_g values and consequently the beans would need to be stored at very low temperatures to be at or below the T_g (Chigwedere, Flores et al., 2019). This is disadvantageous for people in the tropical regions where temperatures are typically high throughout the year with limited cooled storage facilities. Therefore, after harvest, the moisture content of the beans should be lowered to a level that is biologically and chemically safe for long-term storage (Bradford et al., 2018). Low moisture content is achieved through either sun drying, mostly employed in developing world, or heated-air drying mainly in developed countries. In the case of sun drying, care should be taken since prolonged exposure of beans to high temperatures (>25°C) and relative humidity (>65%) conditions could cause HTC as discussed in Section 5.2.

5.4 | (Pre)processing and processing conditions

Various (pre)processing conditions that have been explored in a quest to study their influence on cooking time of beans include soaking, which has been previously discussed (Section 2), micronization, gamma irradiation, and pressure application. The effect of these (pre)processing conditions on cooking times of beans is summarized in Table 3. It should be noted that while the goal in conventional cooking of beans is to achieve a soft texture, for commercial processing such as canning, in addition to softening, a certain level of bean firmness is desired (Howard et al., 2018). In canning, therefore, calcium salts are often added in the brine solutions to help maintain bean firmness and integrity during sterilization and subsequent storage (Howard et al., 2018; Revilla & Vivar-Quintana, 2008).

Next to soaking, dehulling is considered as a common (pre)processing technique of beans that involves manual or mechanical removal of the beans seed coat (hull). Dehulling not only facilitates reduction of antinutrients such as polyphenols but also reduces the cooking time (Kinyanjui et al., 2015; Singh, 1995). The reduction in cooking time is caused by the removal of the seed coat which has been shown to be a physical barrier for water absorption.

The influence of micronization, a heat treatment of foods after a short exposure to electromagnetic wavelengths in the infrared region, on the cooking time of

TABLE 3 A summary of the effect of (pre)processing conditions on the cooking times of beans

(Pre)process	(Pre)processing conditions	Bean sample	Effect on cooking time	References
Soaking	Temperatures between 50 and 70°C	Red kidney beans	Increase	Koriyama et al. (2017)
	Monovalent salts			
	– 0.5% $NaHCO_3$ and 2.5% K_2CO_3	Black beans	Decrease	de León et al. (1992)
	– 0.1 mol/L (NaCl, $NaHCO_3$, Na_2CO_3)	Zebra beans and Soya fupi	Decrease	Kinyanjui et al. (2015)
	Diva lent salts			
	– 0.1 mol/L $CaCl_2$	Zebra beans and Soya fupi	Increase	Kinyanjui et al. (2015); Njoroge et al. (2016)
Dehulling		Pinto and Rose coco	Decrease	Kinyanjui et al. (2015)
Micronization	Infrared heating to			
	– 99 and 107°C	Pinto beans	Increase	Abdul-Kadir et al. (1990)
	– −112 and 115°C	Navy and black beans	Decrease	Bellido et al. (2006)
Gamma irradiation	Irradiation doses			
	– 1, 2, and 10 kGy	Dry beans (Yalova and Yunus)	Decrease	Celik et al. (2004)
	– 1, 5, and 10 kGy	Carioca beans	Decrease	Lima et al. (2019)
Thermal treatment	Under pressure			
	– Autoclaving at 110°C	Carioca beans	Decrease	Siqueira et al. (2013)

pulses has also been investigated. However, there is a discrepancy in the literature as to whether micronization leads to a decrease or increase in the cooking time of pulses. Abdul-Kadir et al. (1990), for instance, reported a significant increase in the cooking time of pinto beans with micronization whereas it has been shown to lead to reduction in the texture of navy beans and black beans (Bellido et al., 2006).

Gamma irradiation, a technique for food preservation, has also been reported to have a significant influence on the cooking time of pulses. According to Celik et al. (2004), using irradiation doses of 1, 5, and 10 kGy, leads to a significant reduction in the cooking time of dry beans. Similar findings were reported by Lima et al. (2019) for carioca beans irradiated at doses between 1 and 10 kGy. This decrease in cooking time was attributed to the disruption of membrane integrity during irradiation treatments which leads to improved water absorption properties during cooking. This is interesting since as discussed earlier (Section 5.3), membrane damage during storage enhances HTC development.

Pressure application during processing can also have an influence on the cooking time of beans (Marques Corrêa et al., 2010). Whereas cooking through the conventional boiling of pulses in an open pan could take about 1 to 2 hr, cooking under pressure has been shown to take about 10 to 15 min (Chavan et al., 1987). The faster softening achieved during pressure cooking is attributed to the increased cooking temperature (and heat transfer through convection as a result of the additional vapor pressure generated) (Siqueira et al., 2013) which ensures acceleration of the reactions involved in softening, a fast heat transfer and uniform temperature in the cooked material.

Germination, a process by which soaked beans are allowed to sprout, has also been applied as a pre-processing step. Germination is mainly aimed at improving the nutritional quality of beans due to the resulting biochemical reactions (Bressani, 1993; Siddiq & Uebersax, 2013). Nevertheless, a recent study has reported a significant influence of germination on the cooking time of red beans (Haileslassie et al., 2019).

6 | INFLUENCE OF COOKING TIME ON NUTRITIONAL AND ANTINUTRITIONAL QUALITY OF BEANS

Thermal processing is fundamental to ensure palatability of beans. The impact of cooking time on the nutritional quality of beans is summarized in Table 4 and is discussed in detail in this section.

6.1 | Antinutritional factors

Antinutritional factors (ANFs) are plant secondary metabolites that interfere with the absorption of nutrients by reducing their intake, digestion, and utilization by the body (Popova & Mihaylova, 2019). They include phytate and tannins that bind to minerals and proteins, thereby influencing their bio-accessibility and digestibility, respectively (Kumar et al., 2010; Rousseau,

TABLE 4 A summary of the influence of cooking time on the nutritional and antinutritional quality of common beans (all *Phaseolus vulgaris* L.)

Component	Processing conditions	Bean sample	% Change	References
Antinutritional factors (ANFs)				
Phytates		White bean	−(13 to 25)	ElMaki et al. (2007)
	Boiling for 45 min	Kidney beans	−58	Khattab and Arntfield (2009)
	Cooking for 60 min	Sugar beans	−14	Şat and Keleş (2004)
	95°C for 1 hr	Pinto beans	−1.75	Shi et al. (2018)
	95°C for 1 hr	Black beans	−0.29	Shi et al. (2018)
	Autoclaving at 121°C for 25 min	Kidney beans	−69	Khattab and Arntfield (2009)
	121°C for 90 min	White and red kidney beans	−(28 to 51.6)	Rehman and Shah (2005)
	Autoclaving for 30 min	Sugar beans	−10	Şat and Keleş (2004)
Tannins	121°C for 90 min	White and red kidney beans	−(33.1 to 45.7)	Rehman and Shah (2005)
	Cooking for 60 min	Sugar beans	−79	Şat and Keleş (2004)
	Cooking for 97°C for 35 min	Kidney beans	−(58 to 63)	Shimelis and Rakshit (2007)
	Ordinary boiling	White and red kidney beans	−(24.5 to 26.8)	Rehman and Shah (2005)
	Autoclaving for 30 min	Sugar beans	−85	Şat and Keleş (2004)
	Autoclaving at 121°C for 20 min	White and red kidney beans	−(38.8 to 41.8)	Rehman and Shah (2005)
Trypsin inhibitors	Boiling for 45 min	Kidney beans	−100	Khattab and Arntfield (2009)
	Autoclaving at 121°C for 25 min	Kidney beans	−100	Khattab and Arntfield (2009)
Lectin	95°C for 1 hr	Red kidney, pinto, navy and black beans	−99.81	Shi et al. (2018)
Oligosaccharides				
Raffinose	Cooking for 97°C for 35 min	Kidney beans	−(47 to 55)	Shimelis and Rakshit (2007)
	Boiling for 45 min	Kidney beans	−(63 to 65)	Khattab and Arntfield (2009)
	Autoclaving at 121°C for 30 min	Kidney beans	−(65 to 72)	Shimelis and Rakshit (2007)
	Autoclaving at 121°C for 25 min	Kidney beans	−78	Khattab and Arntfield (2009)
Stachyose	Cooking for 97°C for 35 min	Kidney beans	−(62 to 68)	Shimelis and Rakshit (2007)
	Boiling for 45 min	Kidney beans	−(61.5 to 65)	Khattab and Arntfield (2009)
	Autoclaving at 121°C for 30 min	Kidney beans	−(76 to 78)	Shimelis and Rakshit (2007)
	Autoclaving at 121°C for 25 min	Kidney beans	−77	Khattab and Arntfield (2009)

(Continues)

TABLE 4 (Continued)

Component	Processing conditions	Bean sample	% Change	References
Nutritional factors				
Starch				
Total starch digestibility	Ordinary boiling	Red and white kidney beans	88.5 to 90.2	Rehman and Shah (2005)
	Autoclaving at 121°C for 20 min	Red and white kidney beans	125.1 to 136.4	Rehman & Shah (2005)
Rapidly digestible starch (RDS)	Boiling for 30 min	Pinto, red kidney, black and navy bean starches	744.7 to 936	Du et al. (2014)
Slowly digestible starch (SDS)	Boiling for 30 min	Pinto, red kidney, black and navy bean starches	−(78.9 to 91.6)	Du et al. (2014)
Resistant starch (RS)	Boiling for 30 min	Pinto, red kidney, black and navy bean starches	−(85 to 87.5)	Du et al. (2014)
Protein				
Protein digestibility	Cooking for 97°C for 35 min	Kidney bean	11 to 12	Shimelis and Rakshit (2007)
	Autoclaving at 121°C for 30 min	Kidney bean	15 to 16	Shimelis and Rakshit (2007)
	Ordinary boiling	Red and white kidney beans	86 to 93.3	Rehman and Shah (2005)
	Autoclaving at 121°C for 10 min	Red and white kidney beans	95.7 to 105	Rehman and Shah (2005)
	Autoclaving at 121°C for 90 min	Red and white kidney beans	76 to 79	Rehman and Shah (2005)
Amino acid composition				
-Essential amino acids	Boiling for 3 hr	Kidney beans	−(31 to 65)	Candela et al. (1997)
-Nonessential amino acids	Boiling for 3 hr	Kidney beans	−(37 to 67)	Candela et al. (1997)
	Autoclaving at 121°C for 20 min	Kidney beans	13	Mbithi-Mwikya et al. (2000)
Minerals				
Calcium bio-accessibility	Cooking for 30 min	Black beans	−64	Oliveira et al. (2018)
	Cooking at 95°C for 120 min	Canadian wonder	−16.7	Rousseau, Kyomugasho, et al. (2020)
Zinc bio-accessibility	Pressure cooking (15 psi) for 10 min	Dry beans	−16.6	Hemalatha et al. (2007)
	Cooking for 30 min	Black beans	−35	Oliveira et al. (2018)
	Cooking at 95°C for 120 min	Canadian wonder	−31	Rousseau, Kyomugasho, et al. (2020)
Iron bio-accessibility	Pressure cooking (15 psi) for 10 min	Dry beans	15.7	Hemalatha et al. (2007)
	Cooking for 30 min	Black beans	−12.5	Oliveira et al. (2018)
	Cooking at 95°C for 120 min	Canadian wonder	−38	Rousseau, Kyomugasho, et al. (2020)

(Continues)

TABLE 4 (Continued)

Component	Processing conditions	Bean sample	% Change	References
Polyphenols				
Total free phenolic acids	Regular boiling for 90 min	Pinto and black beans	–52 and –68	Xu and Chang (2009)
		White beans	–(17 to 27)	ElMaki et al. (2007)
	Pressure boiling (15 psi) 10 min	Pinto and black beans	–60 and –62	Xu and Chang (2009)
	Pressure cooking (10.2 to 11.6 psi) for 15 min	Regular cranberry beans	–22	Chen et al. (2015)
Total flavonols	Regular boiling for 90 min	Pinto and black beans	–42 and 65.5	Xu and Chang (2009)
	Pressure boiling (15 psi) 10 min	Pinto and black beans	–41 and –62.4	Xu and Chang (2009)
Dietary fiber				
Soluble dietary fiber (SDF)	Boiling at 98 to 100°C for 40 min	Pinto beans	34	Kutoš et al. (2003)
	Boiling for 3 hr	Kidney beans	124	Candela et al. (1997)
	Pressure cooking (14.6 psi) for 20 min	Common bean	7.4	Costa et al. (2006)
Insoluble dietary fiber (IDF)	Boiling at 98 to 100°C for 40 min	Pinto beans	–11.6	Kutoš et al. (2003)
	Boiling for 3 hr	Kidney beans	–21.7	Candela et al. (1997)
	Pressure cooking (14.6 psi) for 20 min	Common bean	13.5	Costa et al. (2006)

Negative sign before the values signifies a reduction.

Kyomugasho et al., 2020), as well as enzyme inhibitors such as α-amylase and trypsin inhibitors that inhibit enzyme activities, hence impairing the digestions of starch and proteins. Additionally, toxic compounds such as lectins widely present in beans are capable of binding on to carbohydrate residues causing toxicity (Gabius et al., 2011). In general, raw common beans are known to contain higher amounts of ANFs than their cooked counterparts.

Phytate, a salt form of phytic acid, is a heat stable component that is not easily degraded during cooking (Kumar et al., 2010). A significant reduction of phytate with cooking has been reported for some white bean cultivars where lower contents of phytate were recorded for beans cooked after soaking compared to the un-soaked (ElMaki et al., 2007). Similarly, Rehman and Shah (2005) reported a significant decrease in phytate (28.0% to 51.6%) and tannin content (33.1% to 45.7%) in white and red kidney beans at higher temperature and longer cooking times (121°C for 90 min). The decrease of phytic acid during cooking is reported to be mainly due to leaching out of this compound into the cooking water (Soetan & Oyewole, 2009). Unlike phytate, tannins, which are polyphenolic compounds that can bind proteins reducing their digestion, are more heat labile and are also water soluble which explains their increased reduction with longer cooking time and higher temperatures (Khattab & Arntfield, 2009). Some authors have also suggested that the decrease in tannin content of beans during cooking could be as a result of changes in their solubility brought about by binding to other organic substances for instance, formation of insoluble protein–tannin complexes or change in chemical reactivity which limits their detectability (Reddy et al., 1985; Şat & Keleş, 2004).

Trypsin inhibitors are low molecular weight proteins that can bind to trypsin and chymotrypsin, thus preventing protein digestion (Luo & Xie, 2013). These inhibitors are heat labile, therefore their activity is dependent on both temperature and time of cooking. Some authors have reported complete inactivation of trypsin inhibitors when soaked common beans were autoclaved at 125°C for 30 min (Khattab & Arntfield, 2009; Van Der Poel, 1990).

Lectin content, determined by the level of hemagglutinating activity, is drastically reduced through thermal treatment due to the resulting structural degradation (Luo & Xie, 2013). Whereas bean poisoning has been reported as a result of consumption of raw or inadequately heat processed beans (Rodhouse et al., 1990), thorough cooking (at 95°C for 1 hr) of soaked beans has been shown to result in complete inactivation or reduction of undetectable limits of lectins (Luo & Xie, 2013; Shi et al., 2018; Van Der Poel, 1990). Although soaking led to significant reductions in lectin content, the cooking process was more effective with reductions of up to 99% being reported.

Generally, research shows that most ANFs are reduced significantly by hydrothermal processing both at atmospheric condition and under pressure (Soetan & Oyewole, 2009) with longer cooking time at higher temperature resulting in their strong reduction. There is a higher reduction of some ANFs such as phytates when beans are soaked and cooked after discarding the soaking water compared to when they are cooked in soaking water and or un-soaked (Fernandes et al., 2010). Nevertheless, the loss of essential nutrients with heat exposure for long times and the associated consequence cannot be ignored.

Alpha-galacto-oligosaccharides (α-GOS) also known as the raffinose family oligosaccharides (RFOs) or oligosaccharides, in beans mainly consist of stachyose, raffinose, and verbascose in beans. They are made up of galactose units linked to sucrose through α-1,6 linkages which are not hydrolysable in the human gastrointestinal tract due to lack of α-galactosidase enzyme (Guillon & Champ, 2002). Consequently, they pass undigested to the large intestines where they are fermented to produce short chain fatty acids (flatus). Although they are considered as prebiotics due to the simulation of the activity of the colonic microbiota, flatus formation is a concern for many bean consumers. Thermal processing of beans has been shown to significantly reduce the content of oligosaccharides with a combination of soaking and cooking being more effective (Abdel-Gawad, 1993; Shimelis & Rakshit, 2007).

Several different definitions of dietary fiber (DF) have been used around the world as reviewed by Buttriss and Stokes (2008) and Perry and Ying (2016). However, the common description entails carbohydrate polymers that are not digestible in the gastrointestinal tract of humans. DF can be broadly classified as soluble DF (SDF) which has been linked to cholesterol lowering in the blood and insoluble DF (IDF) linked to fecal bulking (Perry & Ying, 2016). Common beans contain considerably higher amount of DF (14% to 19%) than cereals and is one of the components that has been associated with the health benefits of beans. The ratio of soluble to insoluble fiber has been reported to change during processing. Cooking is reported to increase the SDF content and decrease the IDF content of beans (Kutoš et al., 2003). Although Costa et al. (2006) reported similar results for common beans, the increase in IDF was not statistically significant.

6.2 | Nutritional factors

6.2.1 | Starch

Starch is the main (30% to 60%) carbohydrate in beans and is composed of two components, linear amylose and highly branched amylopectin organized into semi-crystalline structures. According to Englyst et al. (1992), starch can be broadly classified into rapidly digestible starch (RDS), SDS, and resistant starch (RS) based on the rate of glucose release in the gastrointestinal tract. Resistance of starch to enzymatic hydrolysis is related to its structure and nature in the food matrix. RS is thus categorized into physically entrapped starch (RS1), native granules of B-starches (RS2), retrograded starch (RS3), chemically modified starch (RS4), and amylose-lipid complex (RS5) (Jeong et al., 2019). RS is resistant to enzyme digestion in the small intestine and is rather fermented in the large intestines. When compared to other starch-rich sources, such as cereals, the starch digestibility of legumes is relatively poor and has a lower postprandial glycemic response (Dhital et al., 2017). The lower digestibility has been attributed to several reasons among them, the physical entrapment or encapsulation of starch cells with the cell wall matrix which provides a barrier for the action of amylase (Dhital et al., 2016). Cooking increases the accessibility of starch to human pancreatic amylase as a result of structural conformations that occur (Ma et al., 2017; Yin et al., 2018). Thus, cooking decreases RS content and increases RDS content. For instance, the RDS, SDS, and RS of raw common bean starches has been reported to be 9.4% to 10.6%, 10.8% to 16.8%, and 73.8% and 78.5%, respectively, whereas that of cooked beans is 80.6% to 91.3%, 0.7% to 8.7%, and 8.0% to 10.7%, respectively (Du et al., 2014; Ma et al., 2017). Subsequently, the type and time of processing/cooking have an influence on the digestibility of starch. In fact, different extents of starch hydrolysis have been observed for individual common bean cotyledon cells obtained after varying exposure to processing times (Pallares et al., 2018a). Similarly, in a study on isolated common bean cotyledon cells, Pallares et al. (2018b) demonstrated that the role of cell wall as a barrier for simulated starch digestion can be modified through changing thermal processing intensities. More specifically, a faster increase in digested starch coupled with faster emptying of cells was observed for longer processed samples (180 min) compared to shorter processed samples (30 min) as digestion time increased. Edwards et al. (2020) have recently elucidated the role of starch encapsulation for precooked cell powders prepared from various legumes in the retardation of starch digestibility (compared to flours of the same source where the starch granules were not encapsulated) thus providing resistance to digestion and improved glycemic properties. The benefits have also been confirmed in human studies replacing wheat flour with legume cell powders in food products (Bajka et al., 2021). These data indicate that the positive effects of a retarded starch degradation are to be expected from cooked common beans, which upon mastication will lead to single cells and cells clusters encapsulating the gelatinized starch and not necessarily from flours originating from beans.

6.2.2 | Protein quality

Plant sources such as common beans are among the richest sources of dietary proteins (16% to 33%). Proteins can be broadly grouped into storage, structural, and biologically active proteins (González-Pérez & Arellano, 2009), however, the proteins in beans are mainly storage proteins. Storage proteins can further be classified according to their solubility in aqueous solutions and water-soluble albumins and salt-soluble globulins make up the main storage proteins in beans (Boye et al., 2010). Though protein content is an important nutritional attribute, protein quality, which is dependent not only on the amino acid composition but also the digestibility of the protein to meet the daily requirement, is paramount.

During cooking, protein quality is improved due to inactivation of proteinase inhibitors such as tannins and trypsin inhibitors, as well as to the heat-induced structural changes that facilitate proteolysis (Drulyte & Orlien, 2019; Liener & Thompson, 1980; Van Der Poel, 1990). Improved *in vitro* protein digestibility with cooking has been reported for common bean varieties and was attributed to increased chain flexibility leading to accessibility to proteases (Shimelis & Rakshit, 2007). Similarly, Rehman and Shah (2005) reported an improvement in protein digestibility of red and white kidney beans by 86% to 93.3% and 95.7% to 105% with ordinary boiling and autoclaving (121°C for 10 min), respectively. On the other hand, long exposure to heat treatment could also compromise digestibility due to protein aggregation brought about by inter- and intra-molecular interactions between amino acids containing thiol groups (Drulyte & Orlien, 2019). A reduction in protein digestibility of about 11% and 14% for red kidney and white kidney beans, respectively, has been shown when the cooking times were increased from 10 to 90 min at 121°C (Rehman & Shah, 2005). Of particular importance in determining protein quality of foods is the composition and content of essential amino acids as these amino acids after protein hydrolysis represent the digested proteins. Overheating caused by either high temperatures and/or exposure time to heat could have an adverse effect on the content of certain amino acids such as arginine, lysine, methionine, and cystine in bean proteins (Margier et al., 2018; Van Der Poel, 1990). For instance, Candela et al. (1997) reported a significant decrease in the content of both essential and nonessential amino acids of kidney beans boiled for 3 h. It is not clear whether this decrease was as a result of leaching into the cooking water or degradation of these amino acids. Heat treatments especially at longer times caused significant reduction in the apparent retention of methionine, cystine, and tryptophan in cooked faba beans (Ziena et al., 1991). Mbithi-Mwikya et al. (2000) did not see any significant change in essential amino acids of red kidney bean after autoclaving at 121°C for 20 min. They however reported a significant increase by 13% of alanine.

The current global focus on plant-based diets to enhance sustainability has seen a rapid rise of veganism and vegetarianism. This rise is driving food processors to manufacture protein ingredients such as protein isolates and concentrates which are further processed into meat substitutes (Kumar et al., 2020; Smetana et al., 2015). Various processing technologies are used for the extraction and separation of proteins from their native plant sources and further conversion into products that can imitate meat in terms of texture and taste (Kumar et al., 2020). These processes which include among others, thermal treatment, dehydration, homogenization, and membrane filtration cause physical and chemical changes in proteins which affect their functionality and ultimately consumer acceptability of the products (Aryee et al., 2018; Pathania et al., 2019). Knowledge on the influence of processing on protein modifications is important in meeting the increasing demand in order to capitalize the potential of protein functionalities for applications in improving existing and production of novel food products.

6.2.3 | Minerals and vitamins

Minerals are heat stable and are therefore not destroyed during cooking but rather may leach out into the cooking water during prolonged cooking. Some researchers have also reported that cooking has no significant effect on the contents of calcium, iron, and zinc in beans (Ferreira et al., 2014; Wang et al., 2010). Though minerals are not chemically altered by thermal processing, their bio-accessibility and bioavailability could be affected. During thermal processing, as a result of matrix changes, minerals are released from the physical entrapment due to changes or alterations in macronutrients in the matrix and/or degradation of the mineral–antinutrients interactions (Oliveira et al., 2018; Rousseau, Pallares et al., 2020). According to Ferreira et al. (2014), cooking on the one hand, leads to enhancement of solubility and eventual bio-accessibility of minerals such as iron as a result of degradation of iron–protein bonds as well as loss of antinutrients (Fernandes, Nishida & Da Costa Proença, 2010). On the other hand, iron has also been reported to form complexes during cooking, rendering it unavailable for absorption (Carrasco-Castilla et al., 2012; Petry et al., 2015). Additionally, decreases in iron and zinc bio-accessibility have also been reported for some common bean varieties (Oliveira et al., 2018) while contrasting effects of heating have been reported in others (Hemalatha et al., 2007). A recent elaborated and systematic study on the effect of the common bean food chain on mineral concentration and bio-accessibility concluded that (i) ageing (during postharvest storage) and cooking result in a reduction of mineral bio-accessibility, (ii) the presence of mineral chelating antinutrients (phytic acid, phenolics, and pectin) is the determining factor for mineral bio-accessibility, that is, the level of mineral chelation, which is increasing with storage time and cooking time, is responsible for the reduced mineral bio-accessibility. *In vitro* digestion did not affect the level of mineral chelation (Rousseau, Celus et al., 2020; Rousseau, Pallares et al., 2020).

There is limited information in the literature on the influence of cooking time and temperature on the vitamin content of beans. However, in contrast to minerals, vitamins mainly present in beans such as niacin, thiamine, riboflavin, and vitamin B6, are not only water soluble but are also thermal labile which leads to their losses during soaking and subsequent cooking (Prodanov et al., 2004; Schroeder, 1971). Niacin is generally regarded as the most stable water-soluble vitamin whereas riboflavin is mainly very sensitive to light with greater losses occurring as a result of lengthy boiling (Lešková et al., 2006). On the other hand, thiamine and vitamin B6 are highly unstable especially during processing at neutral pH (Ottaway, 2010). In general, it can be inferred that losses of vitamins occur mainly due to leaching into the cooking water and these losses may vary depending on the extent of the cooking conditions.

6.2.4 | Polyphenols

Polyphenols are the predominant bioactive compounds in beans that have attracted great attention due to their functional and health-promoting properties. Structurally, polyphenols are composed of one or more phenol units (aromatic ring bound to a hydroxyl group) (Sakaki et al., 2018; Telles et al., 2017). The most common polyphenols in beans are flavonoids, phenolic acids, and condensed tannins. The seed coat has been shown to contain not only higher levels of phenolic compounds but also phenolic profiles that differ from those of the cotyledon (Ranilla et al., 2007; Rocha-Guzmán et al., 2007). Moreover, the concentrations of phenolic compounds in seeds vary depending on the cultivar, growing location, and environmental conditions (Yang et al., 2018). Higher content of polyphenols has been reported in beans with a darker pigmented seed coat (black, red, or pinto) compared to light colored seed coats.

Thermal processing has a reported significant influence on the phenolic content of beans and the changes depend on the processing method and conditions. Xu and Chang (2009, 2011), for instance, observed a significant decrease in total phenolic content for both pinto and black beans after atmospheric boiling and pressure cooking. They however reported a greater retention of antioxidant activities for steam cooked beans which they attributed to the reduced losses of phenolic compounds compared to the traditional boiling. Similar results have been reported for common beans and cranberry beans (Chen et al., 2015; Valdés et al., 2011; Yang et al., 2018). It should be noted that although the total phenolic content is reduced during cooking, the individual phenolic compounds such as different phenolic acids may be affected differently by the cooking process (Chen et al., 2015).

7 | INFLUENCE OF COOKING TIME ON VOLATILE FLAVOR COMPOUNDS

Besides texture, flavor is an important sensorial quality attribute determining the acceptability of cooked beans. The flavor of fresh uncooked beans, often referred to as "beany" or "musty," mainly emanates from physical disruption of the bean tissue and oxidative (enzymatic and nonenzymatic) degradation of unsaturated fatty acids present. Compounds such as hexanal and 1-octen-3-ol have been reported to be responsible for this flavor (Chigwedere, Tadele et al., 2019; Khrisanapant et al., 2019). On the other hand, the flavor of cooked beans is as a result of chemical reactions taking place during thermal processing (Ma et al., 2016). The main compounds reported to contribute to the flavor of cooked beans are aldehydes, alcohols, ketones, sulfur compounds, and some heterocyclic compounds (Khrisanapant et al., 2019).

During cooking, significant reduction of aldehydes (74% to 82%), alcohols (0.8% to 86%), and terpenes (44% to 81%) coupled with formation of ketones (100% to 334%), pyrazines (505%), and sulfur compounds (78% to 569%) linked to the overall aroma of cooked beans, has been reported in red kidney beans (Mishra et al., 2017). Formation and or increase of these compounds during cooking is as a result of heat-induced oxidative degradation of unsaturated fatty acids, lignin pyrolysis, Strecker degradation, and Maillard reactions, extents and rates of which depend on the temperatures and cooking time (Ma et al., 2016; Mishra et al., 2017). During cooking, the evolution of these volatile compounds is time and temperature dependent, they might even change during subsequent storage. So both during cooking and storage, the kinetics of these compounds are important. Chigwedere, Tadele et al. (2019) for instance, showed that the evolution of marker compounds with increased cooking time, dependent on the compound of interest, followed zero order, first order, and first order fractional conversion reaction kinetics. Based on the reaction kinetics, formation of the volatile compounds is explained to be independent of precursor concentrations, to be from reactions involving a change in only one molecule or to be as a result of complex chain reactions such as those involving Maillard reactions respectively (Chigwedere, Tadele et al., 2019).

8 | CONCLUSION AND FUTURE PERSPECTIVES

Although common beans have recognized benefits to human nutrition and health, long cooking times are a key contributor to their limited utilization, even in the most traditional markets. As highlighted in this review, cooking time of beans is intricately dependent upon variety, previous storage history, and processing conditions. Further in-depth research into the interplay between these intrinsic (genetic factors) and extrinsic (storage and processing conditions) factors is necessary in order to gain insight on their role as well as prompt developing strategic solutions for addressing the challenge of long cooking time of beans. Although changes in cooking time observed when using cooking media with different composition (e.g., monovalent and divalent cations, pH) seem understood, mechanistic details explaining both the difference in cooking times of freshly harvested dry beans and the difference in sensitivity to develop HTC largely remain unresolved.

Given that consumers are increasingly concerned with the quality and nutritive value of products, optimization of processing conditions, such as heating time and temperature to balance safety and quality aspects of thermal processing is vital. In this context, considering the complexity of the interplay between various factors involved in cooking time of beans, there is need for a balance/compromise between processing conditions to achieve palatability while ensuring optimal nutrient retention and quality. Optimal cooking protocols will largely depend on the overall context, for example, research versus food processing, bean accession/variety, pre-processing, brine used, processing intensity (pasteurization versus sterilization), industrial versus home cooking. For ordinary household cooking, the authors propose an optimal cooking protocol that typically entail soaking, as a (pre)processing step, in soft water at room temperature (22°C) for at least 12 hr or at temperatures not exceeding 45°C for at least 3 hr. Subsequently, soaking water should be discarded and cooking of whole soaked beans should be done at boiling temperature or, when a pressure cooker can be used, a higher temperature (110 to 121°C) for a shorter time (dependent on the bean type and storage history).The amount of water should be enough to ensure minimal to no residual cooking water once the beans have cooked. Besides an increasing importance of fresh or minimally processed foods, there is also a growing trend for ready-to-eat, fast cooking convenience foods. Therefore, food processors could broaden their focus into product development that incorporates beans into existing and novel convenience foods to help promote utilization of beans. Additionally, there is potential to have precooked dehydrated bean products that can be reconstituted by simple addition of hot water without the need for long boiling. The structure of these food systems might be crucial to maintain the benefits that have been attributed to cooked beans (rate of starch digestion). In line with this, kinetic studies to investigate changes of constituents taking place during storage and/or cooking to influence both texture and nutritional quality of beans should be conducted.

Lastly, breeding for new common bean cultivars has in the past majorly focused on development of high yielding cultivars with increased tolerance to biotic and abiotic stress. More research should be done on development of (molecular) breeding or selection tools for fast cooking traits in addition to improved nutritional qualities. This is crucial toward developing varieties that result in acceptable cooking times, are less sensitive to HTC development, can deliver high quality nutrients (in terms of amounts and bio-accessibility) and at the same can meet the challenges of climate change (drought resistance). To sum up, there is a need for a multisectoral collaboration between breeders, processors, and nutritionists in order to harness the full potential of beans and pulses in general, so as to enhance food and nutrition security especially in developing countries where problems of malnutrition and micronutrient deficiencies are still rampant. Pulses in general and beans in particular are/can be an important staple source of proteins, minerals and vitamins.

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AUTHOR CONTRIBUTIONS

Irene Wainaina: conceptualization, Data curation, formal analysis, methodology, visualization, writing—original draft; Elizabeth Wafula: conceptualization, data curation, formal analysis, methodology, visualization, writing—review and editing; Daniel Sila: conceptualization, data curation, formal analysis, funding acquisition, methodology, project administration, supervision, visualization, writing—review and editing; Clare Kyomugasho: conceptualization, data curation, formal analysis, methodology, supervision, writing—review and editing; Tara Grauwet: conceptualization, data curation, formal analysis, methodology, supervision, visualization, writing—review and editing, supporting; Ann Van Loey: conceptualization, data curation, formal analysis, methodology, supervision, visualization, writing—review and editing; Marc Hendrickx: conceptualization, data curation, formal analysis, funding acquisition, methodology, project administration, supervision, visualization, writing—review and editing.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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