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Factors affecting the cooking quality of stored carioca beans (*Phaseolus vulgaris*)

Juliana Aparecida Correia Bento[1], Karen Carvalho Ferreira[1], Priscila Zaczuk Bassinello[2*], B. Dave Oomah[3†]

[1]School of Agronomy, Federal University of Goiás—UFG, Goiânia, Brazil; [2]Embrapa Rice and Beans, Santo Antônio de Goiás, Brazil; [3]Summerland Research and Development Centre, Agriculture and Agri-Food Canada, Summerland, BC, Canada

[†]Retired.

***Corresponding Author**: Priscila Zaczuk Bassinello, Embrapa Rice and Beans, PO Box 179, Santo Antônio de Goiás, Goiás, 75375-000, Brazil. Email: priscila.bassinello@embrapa.br

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REVIEW

Abstract

The culinary quality of carioca beans is related to their market value and consumer acceptability. The depreciation of the cooking/technological quality of the product occurs mainly because of the integument browning and the longer cooking time of the grains, which are influenced by the storage time and conditions. The loss of culinary quality reduces the market value of carioca beans because consumers reject darkened grains that are attributed to a longer cooking time. As a result, cooking time (resistance to cooking), the color of the integument, and the texture of the cooked beans are determinant factors in the acceptance of carioca bean cultivars. The browning of the grain integument and the cooking time mainly depends on the environmental conditions, storage time, the tegument of each genotype, and the chemical and physical properties of the cotyledons. Therefore, this review aims to survey the scientific literature on the extrinsic and intrinsic factors that affect the culinary quality of carioca beans.

Keywords: browning; cooking time; polyphenolic compounds; quality loss; storage

Introduction

Beans are cultivated during the whole agricultural year, in distinct ecosystems, principally in developing countries, which are responsible for 86.7% of world consumption. In 2019, five countries (Myanmar, India, Brazil, China, and the United Republic of Tanzania) accounted for 59% of the world's dry bean production (~30.2 million tons; Food and Agriculture Organization of the United Nations, 2019). Beans are rich in essential nutrients like (i) proteins with high lysine content (essential amino acid); (ii) high complex carbohydrate content as oligosaccharides, and dietary fibers with their recognized hypocholesterolemic and hypoglycemic effects; and (iii) complex vitamins and minerals (calcium [Ca], iron [Fe], copper [Cu], zinc [Zn], phosphorus [P], potassium [K], and magnesium [Mg]); bioactive antioxidant compounds including saponins, polyphenols, and anthocyanins (Ganesan and Xu, 2017; Lovato *et al.*, 2017; Oliveira *et al.*, 2017; Celmeli *et al.*, 2018; Yang *et al.*, 2018; Jeepipalli *et al.*, 2020; Liu *et al.*, 2020;). Therefore, regular consumption of this pulse benefits human health. The US Department of Health and Human Services (US-DHHS, 2015) recommends eating about three cups of beans like pinto, kidney, or black beans/per week because of their health benefits.

Brazil is the largest global producer of common beans, mainly for domestic consumption, with an average per capita bean consumption of 16 kg in 2013 (Rawal and

Navarro, 2019). The national market in Brazil predominantly consists of two classes of beans: carioca (70%) and black bean (20%; Souza *et al.*, 2020). Carioca beans are seasonally produced beans in Brazil and many other countries. So, to maintain bean supply throughout the year and prevent scarcity between harvests, the storage of this variety is crucial. However, improper storage can cause undesirable changes in the carioca beans leading to consumer rejections (Carbonell *et al.*, 2010; Scariot *et al.*, 2017; Alvares *et al.*, 2020). These changes occur in the integument of some carioca bean cultivars because some genotypes darken very quickly, and the bean also hardens itself rapidly. These processes reduce the culinary quality of the carioca beans economically, depreciating the product (Bento *et al.*, 2020a, 2020b; de Farias *et al.*, 2020; Bento *et al.*, 2021a).

The loss of culinary quality reduces the market value of carioca beans because consumers reject darkened grains that are considered resistant to cooking. Consequently, determinant factors in the acceptance of carioca bean cultivars are cooking time (resistance to cooking), the color of the integument, and the texture of the cooked beans. Therefore, this review aims to survey the scientific literature on factors that affect the culinary quality of carioca beans during storage.

Culinary Quality

Culinary quality of beans refers to their sensory attributes, technological properties, such as water absorption before and after cooking, cooking time or resistance to cooking, percentage of soluble solids in the broth, integument color, and the broth. Crop production, postharvest drying, and storage conditions are responsible for bean quality when it reaches its destination, either at the consumer's table or back in the field to be used as seed. Generally, beans subjected to improper handling or even storage conditions will influence the culinary quality, resulting in consumer rejection of the product.

Breeding new carioca bean cultivars emphasize high technological and cooking quality prioritizing preferential selection for lighter grains, 250–300 g 1000 seed weight, elliptical shape, semi-full degree of grain flatness, and cooking time less than 25 minutes (Kaur *et al.*, 2009; Wani *et al.*, 2013, 2017; Yadav *et al.*, 2018; Ribeiro *et al.*, 2019;). Bean coats are rich in water-insoluble fibers and polyphenols. Their cotyledons have higher soluble fibers, oligosaccharides, and resistant starch (Singh, 2017). Hardening of the husk during bean storage occurs mainly when the air humidity is high, hindering hydration during preparation for consumption. The increased air humidity accompanied by high temperatures increases the incidence of a hardshell and hard-to-cook (HTC) grains, thereby reducing consumer's acceptance, digestibility, and protein absorption (Oliveira *et al.*, 2011).

Briefly, 52% of surveyed consumers preferred commercial brands of carioca beans for their technological (lighter color grains [53 and 6.2; L^* and a^* values, respectively], medium-sized beans [28 g], elliptical shape, and semi-full flatness), cooking (fast cooking time ~15 min), and nutritional (high protein and minerals [K, P, Ca, Zn and Cu] contents) quality traits (Ribeiro *et al.*, 2019).

Resistance to cooking/cooking time

The time for beans to reach the desired degree of softness, determined as cooking time, is a critical attribute for consumers. Cooking time can also be evaluated by the resistance to cooking generally determined using the Mattson cooker (Figure 1; Proctor and Watts, 1987; Bento *et al.*, 2020a). Freshly harvested grains have less resistance to cooking. However, when stored under ambient conditions, carioca beans increase their resistance to cooking or take longer to cook (Alvares *et al.*, 2020; Bento *et al.*, 2020a, 2020b; de Farias *et al.*, 2020; Alvares *et al.*, 2020; Bento *et al.*, 2021a).

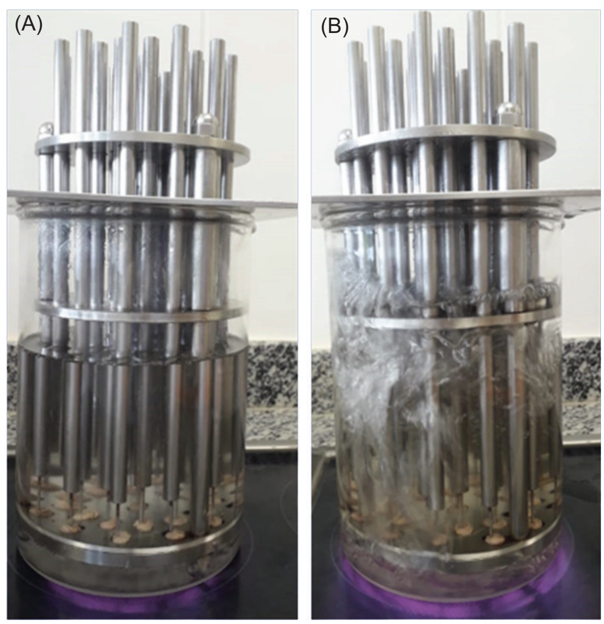

Figure 1. Mattson apparatus for bean resistance classification to cooking based on the scale defined by Proctor and Watts (1987). The time (t_{13}) is recorded until the drop of the 13th rod and is converted into a rank (RMC) of resistance to cook, as described by Bento *et al.* (2020a). Beans in the Mattson apparatus (A). The cooking progress of beans in Mattson apparatus (B).

Beans are soaked in water (1–12 h [overnight]) before cooking to reduce the cooking time. The beans are hydrated, swollen, and smooth during immersion, which reduces cooking time (Yadav *et al.*, 2018). Immersion also promotes the uniform expansion of the seed coat and cotyledon. The extent of hydration and swelling of the grains during immersion depends on the hydration capacity of the grains and varies among different bean cultivars and is related to cooking quality (Singh *et al.*, 2004; Kaur *et al.*, 2009). Therefore, the bean water absorption capacity is a pivotal factor for the technical quality of the grains and is causally related to their resistance to cooking, as the cooking time decreases because of its occurrence before cooking (Kaur *et al.*, 2009). Hence factors like the type of grain (i.e., size or shape), moisture level, genetics, storage time, and storage conditions influence the bean water absorption rate (Delfino and Canniatti-Brazaca, 2010).

The hydration kinetics of carioca beans is complex and mostly related to the seed coat. They are associated with bean composition (fat and K contents, protein to lipid ratio that correlates with the lag phase time) and structure (specific surface and seed coat impermeability to water; Miano *et al.*, 2018). Alkaline conditions (pH 6–12) increase hydration kinetics (rate and water absorption) of the carioca bean (cv. IAC Eté) and reduce the lag phase (83%), affecting the mass transfer behavior in both the seed coat and cotyledons, indicating variations in proteins and polysaccharides (Oladele *et al.*, 2018). Hydration with ferrous sulfate ($FeSO_4$; 0.271% w/v) solution accelerates carioca bean softening and cooking, particularly with ultrasound (91 W/L; 25 kHz) at 25 °C (Miano and Augusto, 2018). This process also fortifies the beans with iron (60 vs. 34 mg Fe/100 g wet basis [510 min, with and without ultrasound]). Moreover, the iron content of the seed coat, cotyledons, and whole carioca beans (cv. IAC Imperador) increased 68, 5, and 16 folds, respectively when soaked in $FeSO_4$solution for 510 minutes compared to conventional hydrate (distilled water) for the same time.

One of the defects (hardshell) that is observed in grains stored under conditions of inadequate temperature and humidity is alleviated bean water absorption, even after long periods of maceration. The hardshell phenomenon can be a consequence of grain storage in high humidity and high temperatures, which also causes the HTC phenomenon (Yadav *et al.*, 2018). That refers to grains requiring a longer cooking time to soften or fail to soften even when subjected to boiling water for extended periods. Storage under ambient conditions of temperature and humidity for 6 months induces HTC phenomenon in common beans and consequently increases the cooking time. For most carioca bean cultivars, only 3 months of storage is sufficient to observe enhanced hardness (Alvares *et al.*, 2020; Bento *et al.*, 2020a; Alvares *et al.*, 2021). The HTC defect manifests itself differently depending on the cultivar, planting, and storage conditions. These defects reduce the culinary quality of beans, causing depreciation and often a rejection of the product (Njoroge *et al.*, 2015, 2016).

The HTC phenomenon has not yet been completely elucidated, despite several studies trying to understand it. Some theories have been postulated to explain the HTC phenomenon: (i) polymerization of phenolic compounds or lignification, (ii) production of insoluble pectates or phytase-phytate-pectin, (iii) changes in protein and starch, and (iv) a multiple mechanism theory (Nasar-Abbas *et al.*, 2008; Siqueira *et al.*, 2016a; Jombo *et al.*, 2018; Siqueira *et al.*, 2018). In the lignification theory of cotyledon tissues, the development of grain hardening is related to the polymerization of phenolic compounds, mainly from phenolic-rich seed coats. The polymerization reaction is mediated by oxido-reducing enzymes and by cross-links formation between the phenolic compounds and the cotyledon cell wall proteins (Nasar-Abbas *et al.*, 2008). However, other studies by Siqueira *et al.* (2014, 2016a, 2018) showed the inadequacy of the lignification mechanism. Demonstrating that the HTC in carioca beans during storage cannot be attributed to changes in the total phenol content or the oxidoreductase activities. According to the most widely accepted "phytase-phytate-pectin" theory (Jombo *et al.*, 2018; Yang *et al.*, 2018), water-soluble pectin allows water absorption by legume seeds. Both phytates and carboxyl groups of soluble pectin can complex with Ca or Mg ions, but phytates preferably bind to divalent cations. If phytates complex with Ca or Mg ions, legume seeds are easy to cook. However, phytates can be hydrolyzed by phytase during storage, reducing their chelating potential. Then the Ca or Mg ions complexes with the carboxyl groups of the soluble pectin to form insoluble Ca and Mg pectates which are not readily dissolved when heated, thus restricting cell separation and inhibiting water absorption resulting in HTC defect (Jombo *et al.*, 2018; Yang *et al.*, 2018; Bento *et al.*, 2020a). Finally, the theory that associates changes in starch during storage (Rupollo *et al.*, 2011) was discredited. Since the noninvolvement of starch or protein in the hardening of carioca bean genotypes was known. In addition, the authors obtained results confirming that the hardening of carioca beans is related to structural changes in the cell wall and middle lamella. Genotypes susceptible to the HTC phenomenon display intense structural changes (Shiga, 2004; Siqueira *et al.*, 2018).

Integument color

Consumers have different requirements. But generally attribute the dark color in carioca beans to prolonged cooking, and therefore low culinary quality (Ribeiro *et al.*, 2008; Coelho *et al.*, 2009; Cichy *et al.*, 2019; Rodrigues *et al.*, 2019; Alvares *et al.*, 2020; Bento *et al.*, 2020a; de Farias *et al.*, 2020;). According to Bolsinha de SP (Brazilian platform with bean market price information), the market negotiates the price of carioca beans, considering the color of the grain. The color is evaluated visually and subjectively based on an unofficial ascending color grade scale that ranges between 5 and 10, and in practice, the product with a grade below 8.5 is devalued (Bento *et al.*, 2020b; Bolsinha, 2020). In short, carioca beans with dark coloring are depreciated, as they are considered of low culinary quality.

Studies generally show that the luminosity (L^*) of the grains and the Hue angle ($H°$, color angle) decrease during storage and are influenced by storage time. On the other hand, the value of Chroma (C^*), a variable that measures the opacity of the grains and the total color difference (ΔE), increase during storage (Siqueira *et al.*, 2014, 2016b; Bento *et al.*, 2020a; Coelho *et al.*, 2020; de Farias *et al.*, 2020;). These changes in the instrumental color parameters indicate the darkening of the carioca bean; the grains leave the cream color with brown streaks and become dark brown (Figure 2).

Changes in color parameters during storage are often associated with grain genotype, indicating that cultivars have a genetic predisposition to faster or slower browning (darkening) when stored. da Silva *et al.* (2008) verified that storage time accentuated the differences between quick and moderate browning carioca beans. Moreover, genotype influenced the browning/darkening rate of five carioca bean cultivars stored for 5 months under environmental conditions (Siqueira *et al.*, 2014). In short, genotypes are sensitive to the browning process, exhibiting difference in intensity among genotypes even when stored under high relative humidity, a factor known to promote browning (Rani *et al.*, 2013).

The rate of grain darkening is linked to the genetics of the strains, storage conditions, and storage time (Coelho *et al.*, 2009, 2013; Rani *et al.*, 2013; Spitti *et al.*, 2019; de Farias *et al.*, 2020). Considering that small farmers do not always have the technology or resources to invest in controlled storage of beans (under low temperature and humidity), commercial damage is inevitable, leading to the accumulation of low-value grains in the producers' warehouses, filling stations, and supermarkets. Thereby limiting the production and commercialization of good-quality beans. However, some bean genotypes that darken regardless of storage conditions do not necessarily harden or lose nutritional and functional value, and vice versa (Alvares *et al.*, 2020; Bento *et al.*, 2020b; de Farias *et al.*, 2020).

The browning of stored beans has been extensively studied, although its association with culinary quality is limited in routine breeding programs (Cichy *et al.*, 2019; Rodrigues *et al.*, 2019; Miklas *et al.*, 2020), which can lead to the development of apparently suitable materials in terms of appearance (color). These results in genotypes that are resistant or tolerant to factors that accelerate grain browning or darkening, but not necessarily resistance to the hardening process, masking its culinary quality (Alvares *et al.*, 2020). Therefore, bean breeding programs must consider nutritional properties, culinary properties, and color when selecting genotypes.

Texture

Textural parameters are also used to assess the culinary quality of beans, as grain hardness or resistance

Figure 2. Freshly harvested carioca beans from slow darkening cultivar BRSMG Madrepérola (A), TAA Dama (B), darkening cultivar BRS Notable (C), and IAC Imperador (D). The corresponding grains after 6 months storage (27.5 ± 1.6 °C / 56.9 ± 10.0% relative humidity-RH) (E–H).

to compression strength is one of the primary sensory properties of foods. It refers entirely to the feeling of hardness that the food presents during chewing and can be objectively measured by mechanical means in fundamental units of mass or strength.

The texture parameters for beans refer to the evaluation of the hardness of raw or cooked grains, generally using the texturometer with a return-to-start analysis method that determines the strength required to compress/puncture the bean (Revilla and Vivar-Quintana, 2008; Siqueira *et al.*, 2013, 2014, 2016a; Bento *et al.*, 2020a). Other studies evaluate grain texture through texture profile analysis (TPA) that provides information on hardness, cohesiveness, elasticity, gumminess, and resilience of bean samples (Koriyama and Kasai, 2019; Wani *et al.*, 2013, 2017; Yadav *et al.*, 2018). The best evaluation of carioca bean texture is the method that measures the force necessary to drill the grain with a 2 mm probe (P2) according to Revilla and Vivar-Quintana (2008) and Siqueira *et al.* (2013). The small area of this probe penetrates the integument. They can differentiate similar samples, even when these grains have soft cotyledons but hard integument.

The hardness of raw and cooked common beans varies (10–30 and 0.2–0.8 kgf, respectively). The texture of the cooked grains depends on the degree of cooking, and consequently if the grain is difficult to cook or exhibits HTC defect that will present greater hardness. Physical and chemical changes such as protein denaturation, carbohydrate solubilization, and starch gelatinization occur when the beans are cooked. Starch can exhibit different gelatinization patterns. Furthermore, depending on the cultivar, these changes can occur with greater or lesser intensity, favoring the reduction of grain hardness (Wani *et al.*, 2017; Yadav *et al.*, 2018). Moreover, Carbonell *et al.* (2010) associated the increase in the hardness of some cultivars with genetic characteristics of the grain or the susceptibility in the interaction of genetic and environmental factors, which can accelerate with inadequate storage.

The method of bean preparation to evaluate the texture of the cooked grain interferes with the results obtained. The difference in hardness of fresh and aged carioca beans after distilled water (1:2 w/v) soaking (18 hours, 25 °C) has been evaluated by five cooking methods: Mattson Bean Cooker, hot air oven, hotplate, boiling water bath, and autoclave (Siqueira *et al.*, 2013). Generally, cooking time and temperature affect bean hardness. Mattson Bean Cooker and hot air oven undercook the beans with hardness above 4 Newtons (N). Increasing cooking time from 30 to 60 minutes on a hotplate reduces bean hardness whereas, mild autoclave condition (105 °C/10 minutes) differentiates fresh and aged bean hardness (3 N vs. 3.4 N) and severe environment (115 °C/20 minutes) produce softer beans (0.8 N vs. 1N for fresh and aged beans, respectively). The hotplate (45 or 60 minutes) and autoclave (110 °C/15 minutes) cooking promote grain softening and discriminate fresh and aged beans. Hence are, therefore, suitable procedures to prepare carioca beans for instrumental texture analyses (Marles *et al.*, 2008). Hardness has also been used to evaluate the effects of irradiation on widely consumer accepted commercial carioca beans. Irradiation (5 kGy) almost doubled the rupture force or hardness of cooked (autoclave 121 °C/15 minutes) carioca beans compared with nonirradiated grains. This increase in grain hardness is presumably associated with starch retrogradation after cooking (Mendes *et al.*, 2011). Industrial canning (rotating autoclave 120 °C, 2 hours/35 minutes cooking) showed no significant difference in the texture or maximum compression (90% of initial height using 50 kg texture meter analyzer) force (0.60–0.75 N/grain) of carioca beans from three cultivars (Schoeninger *et al.*, 2020).

Bean hardness increases in raw and cooked grains when stored (Siqueira *et al.*, 2014, 2016a). This increase in hardness of aged bean is attributed to the loss of cell membrane integrity, which increases soluble solids loss in HTC grains during the immersion and cooking processes and may explain the changes in water permeability (Siqueira *et al.*, 2013, 2014, 2016a, 2018). These results demonstrate that carioca beans hardening is related to structural changes in the cell wall and middle lamella during storage.

Field Management/Environmental Influence

The management of bean cultivation and grain harvest is the first control point for good culinary quality beans acquisition. Adverse environmental conditions, inadequate harvest time, incomplete drying, and severe threshing showed grain breakage (or the appearance of cracks in the seed coat), which favors rotting, the development of fungi, and bruchid attacks (Mutungi *et al.*, 2020). Grains grown in tropical conditions (for example, high temperature and high humidity) may have long cooking times, and cotyledons have higher resistance to softening during cooking (Cichy *et al.*, 2019; Kigel, 1999). Cichy *et al.* (2019) recommended future research to differentiate the effect of the growth and storage environment on the culinary quality of beans. In short, the growth conditions affect pests and microflora development cycles and regulate progression rates of the biochemical reactions of bean grains, thereby influencing grain quality (Mutungi *et al.*, 2020). However, some genotypes exhibit stable cooking times in different production environments (Cichy *et al.*, 2019).

The best harvest period for most grains is close to their physiological maturity, wherein the grains present maximum dry matter accumulation and quality. At this stage the grains have high (30–45%) water contents depending on the type and cultivar (Faroni *et al.*, 2006; Scariot *et al.*, 2017). Thus, the grains are left in the field until they absorb water appropriate for threshing or mechanized harvesting. However, field drying can compromise grain quality since the grains are susceptible to the environmental climate, such as temperature and relative humidity variations that accelerate the respiratory rate of grains, increasing the consumption of reserves and attacks by insects and fungi. According to Scariot *et al.* (2017), beans harvested with 16.6% water content had lower physiological quality and 1000 seed weight than those with higher water content (25.2% and 35.2%). Similarly, Faroni *et al.* (2006) confirmed that beans harvested with 11.7% water content had lower technological classification over those with higher water content (18.7%), demonstrating the negative effects of delayed harvest.

Postharvest Management

Drying

The reduction of water content limits the availability of water for physical-chemical and biological processes of the grains, and the development of fungi, bacteria, and insects is mainly responsible for degradation and loss during storage (Mutungi *et al.*, 2020). Therefore, drying is extremely important before enhanced safe storage. The first stage of bean drying occurs initially at the plant itself in the field, before harvesting, and is called predrying. This is not sufficient to maintain the grain for prolong storage. Drying in the sun or at high temperatures (10 °C above ambient air) under tarpaulins or land, mainly by small farmers, is carried out. Here the grain layer must not exceed 5 cm, and periodical mixing of grains is necessary to standardize drying. This method may not reduce the water content of the grains to ideal levels or delay this process, causing losses of culinary quality in the product and are contaminated by fungi (Rani *et al.*, 2013; Scariot *et al.*, 2017).

The removal of water performed inappropriately by drying can negatively influence the physical, physiological, chemical, and cooking characteristics of beans. The main factors that affect the quality of the grains are the drying air temperature and the initial water content of the grains. The use of high temperatures for drying the grains, mainly combined with high water contents, can cause damage such as cracks and fissures, which can become a gateway for fungal attack during storage, in addition to reducing quality after drying (Faroni *et al.*, 2006; Rani *et al.*, 2013; Scariot *et al.*, 2017). Drying beans at temperatures above 40 °C reduces their physical and physiological quality, such as 1000 seed weight, germination, and vigor (Scariot *et al.*, 2017).

There are no current reports on drying methods that aim to reduce the loss of the culinary quality of beans. Additionally, few studies report the effects of the drying process on the organoleptic, nutritional, and culinary characteristics of the grains. However, increasing the grain drying temperature to 60 °C increased the cooking time after 225 days of storage than the lower drying temperatures (Elias *et al.*, 2016).

Storage

The last step before the commercialization of dry grains is storage. During this period, monitoring of some factors is pivotal to maintain bean quality and quality. While stored, grains undergo chemical and physical changes that alter their characteristics(loss of cooking quality and weight reduction). These are linked to the consumption of dry matter because of breathing and attack by pests. The absence of effective grain handling and storage techniques significantly decreases the quantity and quality of grains during the postharvest phases (Affognon *et al.*, 2015; Mutungi *et al.*, 2020). Hardening and reduction of the permeability of the tegument occur when grains are stored in inadequate conditions of temperature and relative humidity, increasing their resistance to cooking. These quality losses can be considered a hardshell when the tegument loses its water absorption ability and HTC when beans have increased resistance to cooking (Oliveira *et al.*, 2011).

Temperature and relative humidity also influence grain quality during storage. The high temperature, combined with high relative humidity (RH) of the air during storage, favors an increase in respiratory rate, culminating in accelerated deterioration rate, as well as increased fungi and insect contamination. Therefore, low temperature and relative humidity are necessary to maintain grain quality during storage (Rani *et al.*, 2013; Coelho *et al.*, 2020; de Farias *et al.*, 2020). Grains stored in cold rooms (8 °C and 45% RH, 360 days) show no increase in cooking time. On the other hand, grains stored under normal environmental conditions increased their cooking time with longer storage time (Morais *et al.*, 2010). Moreover, de Almeida *et al.* (2017) reported shorter cooking times in beans stored for 108 days at 15 °C and 45% RH than those stored at 27 °C and 75% RH.

Some countries, such as Australia, Brazil, Africa, and Argentina, have adopted a system of hermetic storage for pulses using polyethylene (PET) silo bags. The silo bag is constructed with high-density polyethylene in three layers: two black internal layers and one white external layer made of titanium dioxide. The level of oxygen within the bag drastically falls, whereas carbon dioxide increases once the product is wrapped and the bag is sealed (Hell *et al.*, 2014; Freitas *et al.*, 2016). Thus, this technology is based on creating storage environments harmful to pests by one of the following methods: bio-generated modified atmosphere and hermetic vacuum or gas hermetic fumigation (Freitas *et al.*, 2011; Hell *et al.*, 2014; Mutungi *et al.*, 2015; Freitas *et al.*, 2016). An advantage of the hermetic silo bags is the nonchemical alternative to postharvest quality control in terms of moisture content, specific mass, germination, and electrical conductivity, for up to 120 days (Mutungi *et al.*, 2015; Magalhaes and de Sousa, 2020). Common beans (red beans) storage in silo bags with 17.8% RH presented higher cooking time than those stored in PET bottles or a glass recipient (closed with organza fabric; Freitas *et al.*, 2011). Information is limited on the hermetic storage using PET silo bags, silo bags with temperature control, or even PET bottles influence in cooking culinary quality of carioca beans.

Type of Cultivar/Genotype

The darkening of common beans is an undesirable characteristic for consumers, generally associated with old beans and consequently extended cooking time. However, the factors that influence darkening include environmental and genetic factors. The latter do not show any darkening pattern among different grain types and do not strongly affect the environment (Alvares *et al.*, 2019; Spitti *et al.*, 2019). Seed coat postharvest darkening depends on beans genotype (Islam *et al.*, 2020).

Postharvest darkening (PHD) of seed coat gradually changes the seed coat color of some dry bean market classes during storage. Genotypic and environmental factors influence the rate and extent of PHD, and darkening occurs rapidly in environments subjected to high temperatures, humidity, and light exposure. There are at least three PHD phenotypes: (i) non-darkening (ND), (ii) slow darkening (SD), and (iii) regular darkening (RD). SD and ND genotypes have already been identified in common beans (Elsadr *et al.*, 2011).

According to Spitti *et al.* (2019), darkening is closely linked to the growing environment regardless of the cultivated genotype, or the genotype and environment interaction affect the bean seed coat darkening, requiring the characteristic evaluation in various climates of genetic control and strains selection (Silva *et al.*, 2014). Seed coat darkening and cooking resistance increased in different carioca bean genotypes over 6 months of storage under varied environmental conditions (Siqueira *et al.*, 2014).

Darkening gene

Genetic variation occurs in seed coat darkening of many bean classes including carioca beans (Rodrigues *et al.*, 2019). The variation can be monogenic or oligogenic, which means their inheritance is controlled by one or a few genes (Silva *et al.*, 2018). In carioca beans, the darkening phenotype is controlled by a single recessive gene "Sd," the slow darkening is represented by the "sd" recessive allele (Silva *et al.*, 2008). However, oligogenic control has also been proposed (Elsadr *et al.*, 2011; Silva *et al.*, 2014). A model with two genes interacting under epistasis was suggested by Elsadr *et al.* (2011), where the "J" gene modulates darkening or interacts with a second Sd gene, responsible for regulating the darkening rate. Similarly, Spitti *et al.* (2019) described that this characteristic is oligogenic or even polygenic from significant results obtained by the genotype and environment interaction.

Islam *et al.* (2020) demonstrated yet another allele in the P gene (Psd) responsible for the SD trait in common beans, "P" is a transcription factor that restores the seed coat color. The sequence comparison of this gene in several beans differing in the seed coat postharvest darkening provided insights into the molecular mechanism that governs this characteristic and the development of new specific gene markers for potential use in bean breeding programs. Selecting lines with slow seed coat darkening is possible despite conflicting results regarding the control of beans darkening (Silva *et al.*, 2014). However, selection based on the evaluation of only one environment can generate sufficient gains for this characteristic, even in the presence of genotype and environment interaction, which would explain the inconsistencies between the patterns of genetic control in each location (Alvares *et al.*, 2016).

The elucidation of the genetic control of grain darkening is of fundamental importance to establish breeding programs for developing cultivars with slow seed coat darkening during storage (Silva *et al.*, 2014). Microsatellites are notable in genetic diversity studies. Polymerase chain reaction (PCR)-based markers are developed for a many plant species, including commercial crops. A panel of 24 microsatellites has been built for the common bean specifically for studying the genetic diversity available to the scientific community and has been routinely used for this type of analysis in Brazil (Métais *et al.*, 2002; Blair *et al.*, 2003; Morais *et al.*, 2016). Thousands of single nucleotide polymorphism markers are currently available for the common bean. This number increased immensely because of the species genome sequence publication (*Phaseolus vulgaris* v1.0; http://www.phytozome.net; Schmutz *et al.*, 2014; Morais *et al.*, 2016). Even if the choice of breeding lines and the development of cultivars with the slow darkening trait are relatively simple, given its high heritability and simple genetics, the genetic complexity of many interesting characteristics makes this selection difficult in breeding programs. However, the slow darkening trait is expressed maternally and inherited recessively (Silva *et al.*, 2018; Alvares *et al.*, 2019).

Oxidative Enzymes Related to Beans Aging

During storage, cell damage occurs with advanced grain aging, and the physical barrier that separates enzymes and substrates is lost, enabling the oxidation of phenolic compounds by oxidoreductases. Complex processes and enzymatic reactions are activated in postharvest beans and intensify during storage, initiating the aging and darkening phenomenon (Siqueira *et al.*, 2016b). Postharvest darkening of the bean seed coat, both enzymatic and nonenzymatic, has already been attributed to the presence of phenolic compounds (Spitti *et al.*, 2019) because of their involvement in oxidative steps and subsequent changes in the flavonoid skeleton, as well as by the formation of quinones or similar enzyme-mediated reactions (Marles *et al.*, 2008; Siqueira *et al.*, 2016b; Bento *et al.*, 2021a).

Polyphenol oxidase is associated with the enzymatic activity of peroxidase. It produces a dark compound that causes grain integument darkening called melanin (Siqueira *et al.*, 2016b). RD is strongly associated with increased polyphenol oxidase activity in some strains of beans (Marles *et al.*, 2008). Likewise, Alves *et al.* (2021) evaluating, a fast darkening and hardening cultivar that demonstrated high peroxidase and polyphenol oxidase activity in the process. Higher polyphenol oxidase activity is noted in bean cultivars with lighter tegument than in dark tegument cultivars during the complete aging process. This activity confirms that oxidative processes of phenolic compounds linked to polyphenol oxidase activity contribute to color changes in the bean grain coat (Siqueira *et al.*, 2016b). Polyphenol oxidase and peroxidase activities are attenuated during controlled bean storage at cooling temperature, thereby inhibiting/suppressing grain darkening (Demito *et al.*, 2019). Therefore, the highest color change occurs at higher storage temperatures because of high enzymatic activity, mainly polyphenol oxidase, which degrades polyphenols and reduces the bioactive value of these grains.

Oxidation by environmental oxygen can trigger the darkening and hardening process of carioca beans. Previous research by Bento *et al.* (2020a) found the predominant superoxide dismutase (SOD) activity in the grain integument. But its byproduct, hydrogen peroxide, was only noted in the integument. The high SOD activity suggests that the seed tissue (like cotyledons) maintains strict airway control. Another study by Siqueira *et al.* (2016b) also stressed the importance of analyzing the separate cotyledon integument because of these enzyme variations activities. Nevertheless, according to Bento *et al.* (2020a), the presence and activity of SOD indicate that oxidative stress occurs during storage.

The hardening of beans during storage is also related to low humidity and hydration defects. High temperatures and low relative humidity in the presence of light and oxygen are the main factors that hinder water absorption, in which shows grain hardening consequently, contributing to the HTC phenomenon because of changes in phenolic content related to lignification and loss of phytates (Junk-Knievel *et al.*, 2008). The lignification process relates the hardening with the polymerization of the phenolic compounds from the integument, mediated by polyphenol oxidases, and the formation of cross-links between phenolic compounds and cell wall proteins of the cotyledon. Peroxidase is involved in the polymerization reaction of phenolic compounds. An increase in its activity may be associated with the cell wall lignification process (Alves *et al.*, 2021). The hardening process can also be explained by the SOD activity in oxidative stress (Bento *et al.*, 2020a).

Polyphenolic Compounds

Polyphenolic compounds are associated with the plant defense system, ensuring resistance to pest attacks at considerable levels but, they can accelerate the grain darkening process (Spitti *et al.*, 2019). According to Chen *et al.* (2015), bean darkening is rapid and more common in cultivars with high phenolic content in the tegument. Other studies have also associated bean darkening to the content of phenolic compounds, where darkening is more prevalent in cultivars with high phenolic content in the tegument, and the degree of darkening is proportional to the loss of phenolics (Martín-Cabrejas *et al.*, 1997; Beninger *et al.*, 2005; Luthria and Pastor-Corrales, 2006; Nasar-Abbas *et al.*, 2009). In a recent study, the content of phenolic compounds decreased for fast darkening grains but did not change or increased in slow darkening carioca beans during storage (Bento *et al.*, 2021a). Furthermore, kaempferol was suggested as the marker to differentiate fast and slow darkening cultivars since it decreased in quick darkening cultivars during storage.

The bean darkening has also been associated with the presence of proanthocyanidins (condensed tannins) in the seed coat (Junk-Knievel *et al.*, 2007), which accumulate at higher levels in regular darkening than in the slow darkening genotypes, just like most flavonoids (Duwadi *et al.*, 2018). Proanthocyanidins are oligomeric flavonoids composed mainly of catechin and epicatechin units. The synthesis of proanthocyanidin shares the flavonoids pathway with anthocyanins to leukocyanidin/cyanidin (Duwadi *et al.*, 2018). The presence of catechin and kaempferol was identified by Beninger *et al.* (2005), and the significant increase in aging suggesting that the formation of these compounds occurred during the oxidative process. Therefore, these compounds can interfere with the culinary quality of beans once the dimer procyanidin B-type contributes to the seed coat darkening process because of the oxidation of proanthocyanidin in reactive quinones (brown colored compound; Ranilla *et al.*, 2007; Bento *et al.*, 2021a).

Alternative Uses of Beans with Low Culinary Quality

The aged beans with low culinary quality and consequently low commercial value can be used as ingredients in food formulation. In the same way, bean byproducts (i.e., broken beans) may be used for food development since they present similar nutritional value compared with whole grains. Both can be transformed into flours that constitute a new way of using materials with low added value that can contribute to the sustainability of the bean production chain. The bean flour usage is aligned with the current trends and consumption habits, based on sensory quality, practicality, diversity, and healthiness. Bean flours can also be used in the gluten-free and vegan products development, one of the most successful markets in the food industry. Thus, various studies report an effective way to apply aged dry beans flour as a base ingredient in many foods, such as tempeh (Bento *et al.*, 2020c), baked snacks (tortillas), and instant pasta (Bento *et al.*, 2021b), vegan tempeh burger (Bento *et al.*, 2021c), mix for cakes (Gomes *et al.*, 2015; Bassinello *et al.*, 2020). In these studies, the aged beans were heat treated (e.g., extrusion, cooking in an autoclave, or the traditional pressure-cooking method) to mitigate some unpleasant flavors in the bean flours (Pasqualone *et al.*, 2020).

Other studies have also used bean as ingredient for the development of spaghetti and ravioli (Gallegos-Infante *et al.*, 2010; Ringuette *et al.*, 2018), extruded snacks (Bassinello *et al.*, 2015), light red kidney bean porridge (Nyombaire *et al.*, 2011), snack bars (Ramírez-Jiménez *et al.*, 2018), cookies (Pérez-Ramírez *et al.*, 2018), bread and chips (Hooper *et al.*, 2019), and extruded snacks made with maize and bean (7:3; Félix-Medina *et al.*, 2021). In addition, there is significant interest presently in dry and wet fractionation of pulses into starch, protein, and fiber concentrates for use in both food and nonfood products (Tyler *et al.*, 2017). Additionally, the consumption of bean products is associated with health benefits such as the reduced risk for cardiovascular disease and cancer, the management of type 2 diabetes, metabolic syndrome, and obesity, and contributes to overall health and wellness (Tyler *et al.*, 2017; de Lima *et al.*, 2019; Mullins and Arjmandi, 2021).

Conclusion

The culinary quality of beans is influenced by intrinsic and extrinsic factors and involves sensory attributes and technological properties that directly reflect consumer choice. The cooking time, color, and texture are the determining properties in the acceptance of the grain, which can be affected during storage mainly by temperature and humidity. The type of cultivar directly influences the darkening and hardening of the grain. The literature presents this control as oligogenic or monogenic. Moreover, different cultivars have a varied genetic makeup for darkening. Specific phenolic compounds present in the tegument play an important role as a substrate for oxidation reactions, and the type of pigments determine the final color of the grain, that is, the post-harvest darkening rate. The future perspectives to enhance bean quality may be related to the use of different techniques for enhanced preservation of the grains appearance and composition, such as the system of hermetic storage using polyethylene silo bags. Additionally, the breeding programs can recommend new bean cultivars in the market, which are resistant to long-term storage without losing their culinary quality. A study of factors influencing bean properties acceptable by the final consumer is critical to encourage breeding programs and increase the demand for this high nutritional food. The use of bean flour as a food ingredient is an alternative for the use of aged beans with low culinary quality and improves food industry diversity. In addition, they are the excellent raw material for protein extraction in plant-based products applications, a market that has been growing in recent years. Additionally, aged beans or broken grains have potential for use in gastronomy (as flour) because of their technological, nutritional, and functional properties, as well as their versatile application. It is also an option to enrich school meals and the diet of low-income populations, in addition to specific demands (gluten-free, low glycemic index, vegan, etc.).

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