Heliyon xxx (2019) e01613

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.heliyon.com

Kinetic modelling of polyphenol degradation during common beans soaking and cooking

O.I. Mba, E.M. Kwofie, M. Ngadi *

McGill University, Department of Bioresource Engineering, 21111 Lakeshore, Ste-Anne-de-Bellevue, Québec, H9X 3V9, Canada

ARTICLE INFO

Keywords:
Food science
Chemistry

ABSTRACT

Phenolic compounds are phytonutrients with anti-inflammatory attributes that are significant for brain, heart and gut health. Losses of natural phenolic compounds in foods occur due to degradation during processing. The extent of degradation depends on the processing conditions applied. In this study, the degradation of total phenolic compounds during the processing of common beans (*Phaseolus vulgaris L.*) cultivars was investigated. The effects of soaking time, soaking water temperature and cooking conditions on polyphenol degradation were examined. The total phenolic compounds were determined as gallic acid equivalents. The result shows that increase of hydration time and process water temperature significantly ($p < 0.05$) increased polyphenol degradation. There was a strong positive Pearson correlation ($r > 0.85$) between the rate of water uptake and polyphenol degradation regardless of the water temperature and cultivar. The rate of degradation varied from 0.041 – 0.098 and 0.014–0.069 mg/g per hour for *Kabulangeti* and *Maine* cultivar, respectively. The addition sodium chloride (NaCl) and potassium carbonate (K_2CO_3) during cooking to soften the beans significantly increased the degree of degradation. The activation energy for degradation was estimated as 45.4 and 26.3 kJ/mol for *Kabulangeti* and *Maine* cultivar, respectively.

1. Introduction

Common beans (*Phaseolus vulgaris* L.) like many other pulses have been an important source of food for many in the world. It has been used to alleviate protein-energy malnutrition in less affluent societies. Besides being an essential source of protein and carbohydrates, they are also considered as food sources with high functionality. For instance, the dietary fiber constituent of common beans and other pulses has been associated with comparatively higher reduction (10.6–25.0%) in the risk of prostate and colorectal cancer than cereal grains such as rice (1.3–3.5%), corn (7.3–8.5%) and wheat (10.5–12.7%) [1]. Common beans are a rich source of dietary phenolic compounds which represent an essential source of anti-inflammatory and antioxidant compounds for the human body [2]. These phenolic compounds are primarily phenolic acids (including caffeic acid, ferulic acid, and hydrolyzable tannins), flavonoids (including flavonols, flavones, isoflavones, flavanones, anthocyanin and flavanols), stilbenes and lignans [3].

Phenolic compounds have generated much research interest due to their known health benefits such as in the treatment and prevention of cancer [4, 5] and cardiovascular diseases [6, 7]. Additionally, there are also reports indicating other health benefits such as anticarcinogegenic [8], antiatherogenic [9], antithrombotic [10], anti-inflammatory [11], anticoagulant [12], antiallergenic [13] and anti-microbial [14] properties.

It has been established that processing of foods generally degrades their nutritional quality. However, the extent of degradation is dependent on the processing method used. Even for the method chosen, the processing conditions are crucial in determining the overall nutrient loss. Considering the hard-to-cook behavior of common beans, several softening techniques including soaking [15], ultrasound assisted hydration [16], salts addition [17], blanching [18], and autoclaving and extrusion [19, 20, 21] have been reported. Since uncooked common beans are a rich source of health beneficial phenolic compounds and are widely consumed in the cooked form, the need exists to investigate the impact of processing and different softening techniques on the loss of native phenolic compounds.

The objective of this study is therefore to (1) examine total polyphenol degradation during common bean hydrodynamic processing (2) determine the effect of bean softening techniques on the polyphenol degradation during hydration processing (3) to establish the correlation between bean water uptake and polyphenol degradation during soaking and (4) model the kinetics of polyphenol degradation during bean

* Corresponding author.
E-mail address: michael.ngadi@mcgill.ca (M. Ngadi).

https://doi.org/10.1016/j.heliyon.2019.e01613
Received 6 October 2018; Received in revised form 1 February 2019; Accepted 26 April 2019

soaking.

2. Materials and methods

2.1. Materials

Five common beans cultivars harvested from the Kameme and Lufita communities in the Chitipa district of Malawi were used for this work. The cultivars (*Kabulangeti, Maine, Msiska, Masusu, and Magungulu*) used were harvested during the March/April 2016 harvest season. Prior to the experiments, the seeds were cleaned by removing foreign materials such as stones, dirt and broken bean seeds. The initial moisture content of the bean seeds was determined using the ASAE S352.2 DEC 97.

2.2. Soaking experiments

Soaking experiments were conducted using randomly selected 100 g seeds of each cultivar. The seeds were soaked in 200 ml of distilled water at different temperatures (25, 35, 45 and 55 °C). The selected temperatures were below the gelatinization temperature of the beans starch. Prior to the experiment, the soak water and container were maintained at the desired temperature in a water bath (Grant Instruments Ltd., Cambridge, UK). The water bath helped to establish the desired thermal equilibrium. The temperature of the water bath and soaking media was verified with a digital thermometer with a probe. The bean seeds were soaked for 8, 12, and 16 h. At the end of each experimental run, the water was drained, and the samples placed on sample dishes lined with paper towel.

The water absorption capacity was evaluated using Eq. (1) [22, 23]

$$W_a = \frac{W_f - W_i}{W_i} \times 100 \quad (1)$$

Where W_a is the water absorption (d.b. %), W_f is the final weight of seeds after soaking (g) and W_i is the initial weight of seeds prior to soaking (g).

The samples were dried in a vacuum oven at 40 °C for 18 h and milled prior to the total polyphenol content determination.

2.3. Cooking experiments

Cooking experiments were done using 100 dry beans of each selected cultivars (*Masusu*, *Magungulu,* and *Msiska*). The beans were cooked in 200 ml of distilled water in a water bath (Grant Instruments Ltd., Cambridge, UK) at 96 °C until fully cooked. The beans were classified as fully cooked when a predetermined average compression force of 3.75 ± 0.88 N measured with TA-HD Plus texture analyzer (Stable Micro Systems Ltd, Surrey, UK) was reached.

To test the effect of cooking conditions on total polyphenol content, another set of 100 dry raw beans each of the selected cultivars were either soaked for 8 h prior to cooking using 200 mL distilled water or cooked in 200 mL of 5% salt solutions of NaCl and K_2CO_3. NaCl and K_2CO_3 are the common salt and potash, respectively that are commonly used by the local communities in beans cooking. The control beans samples were cooked in 200 mL of distilled water without prior soaking nor salt addition. The beans were considered cooked when the predetermined cooked bean hardness (softness) for each cultivar was attained. The samples were dried in a vacuum oven at 40 °C for 18 h and milled prior to the total polyphenol content determination.

2.4. Chemical properties

Proximate analysis of the dried and milled bean samples was conducted. The Dumas combustion method (NDA 701, VELP Scientifica, Usmate, Italy) was used to determine the total nitrogen content of the bean powders. The crude protein was estimated using a conversion factor of 6.25 in accordance with AOAC method 968.06 [24]. The moisture content of samples was measured using the hot air oven method (AOAC Method 925.09 [24]. Crude fat was determined as crude ether extract after solvent extraction according to Randall technique using SER 148/6 solvent extractor (VELP Scientifica, Usmate, Italy). The extraction solvent used was petroleum ether (AOAC method 963.15).

2.5. Total phenolic compounds content determination

The total phenolic compounds content of raw and processed beans samples was determined following the adapted Folin-Ciocalteu method [25]. This method has the advantage of measuring both the level of phenolic compounds and the reductive substances [26]. Ten mL of 95% methanol was added to 1.0 g of milled beans flour and shaken in the dark for 1 hr at 150 rpm. This was followed by centrifugation at 4000 x g for 10 min. The extract was recovered and kept in the dark. This was repeated two more times with 10 ml and 5 mL methanol, respectively. The extracts were pooled together to a final volume of 25 mL and vortexed. Some 0.1 mL of the extract was pipetted into clean tubes and 7.9 mL of deionized water and 0.5 mL of Folin-Ciocalteu reagent were added and the mixture allowed to stand for 3 min. Lastly, 1.5 mL of 20 % sodium carbonate solution was added. The mixture was vortexed and left to stand for 2 h in a dark cabinet at room temperature. The absorbance was measured at 760 nm against reagent blank using Unicam UV series spectrophotometer (model UV1 – 091309, Thermo Spectronic, Rochester, NY). The absorbance of de-ionized water blank and sample blanks was also measured. A standard calibration curve of gallic acid at a concentration range of 0–500 μg/mL was prepared from the blank corrected absorbances. The total phenolics as gallic acid equivalents (GAE) was calculated using the regression equation obtained from the calibration curve. All the experiments and absorbance readings were done in triplicates.

2.6. Kinetic modeling of phenolic compounds degradation

Chemical reaction occurring in food during processing have been found to follow either a pseudo-zero or first order kinetics. Considering the fact that polyphenol degradation during soaking or cooking is as a result of the oxidation of the polyphenol in the presence of oxygen according to the equations shown in Fig. 1.

The kinetics of these oxidation reactions resulting in polyphenol degradation can be expressed using Eqs. (2) and (3) [27].

$$-r_A = k_A c_A^a \quad (2)$$

$$r_{H_2O} = k_B c_{H_2O}^b \quad (3)$$

Where, r_A is the rate of polyphenol oxidation (kg kg $^{-1}$ soaked bean h^{-1}), r_{H2O} is the rate of water uptake (kg kg $^{-1}$ soaked bean h^{-1}) during

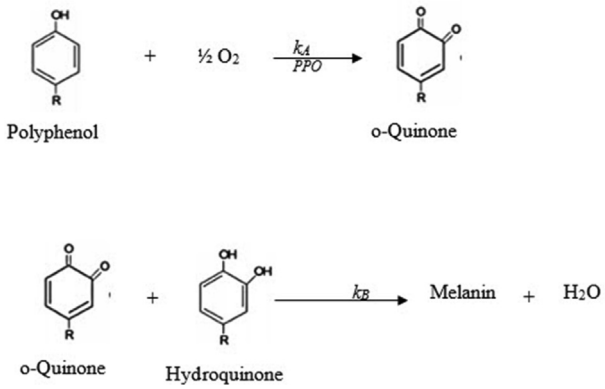


Fig. 1. Polyphenol degradation equations.

soaking or cooking, c_A is the concentration of polyphenol (kg kg $^{-1}$ soaked or cooked bean), c_{H2O} is the concentration of water (kg kg $^{-1}$ soaked or cooked bean), k_A and k_B are the rate constants (h^{-1}) and a and b are the reaction orders of the reactions (Fig. 1). It is important to note that the concentration of water during soaking or cooking may vary due to the two-stage sorption process which usually occurs during hydration of legumes and grains.

The water absorbed during hydration of legumes and grains has commonly been estimated using the Peleg model [28], a two parameter sorption equation [23, 29, 30, 31]. According to the model, the rate of water absorption can be defined as:

$$r_{H_2O} = \frac{dM}{dt} = \frac{k_1}{(k_1 + k_2)^2} \tag{4}$$

In its linearized form, the water absorption capacity is given by Eq. (5)

$$\frac{t}{M_t - M_o} = k_1 + k_2 t \tag{5}$$

Where, t is the soaking time in min, M_t is the moisture content (d.b.) at time t (%), M_o is the initial moisture content (d.b.), k_1 is the Peleg rate constant, min/% m.c. (d.b.), and k_2 is the Peleg capacity constant 1/% m.c (d.b).

Since the rate of polyphenol degradation is proportional to the concentration of polyphenol at a given time (Fig. 1), the effect of temperature on the rate can be determined using the Arrhenius equation given in Eq. (6)

$$k_A = K_{ref,f} \exp\left[-\frac{E_a}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right] \tag{6}$$

However, the rate of water uptake estimated as the Peleg rate constant k_1 is inversely proportional to the moisture content at any given time. Therefore, the effect of temperature can be estimated using Eq. (7) [18, 23]

$$\frac{1}{k_1} = K_{ref,f} \exp\left[-\frac{E_a}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right] \tag{7}$$

Where, K_{ref} is the coefficient of hydration at reference temperature; E_a is the activation energy expressed in $kJmol^{-1}$; R, is the universal gas constant ($8.314 Jmol^{-1}K^{-1}$); k_1 is the Peleg rate constant, min/% m.c. (d.b.), T, the experimental temperature (K) and T_{ref} is the reference temperature (K). The reference temperature was chosen as the average of the experimental temperatures to lessen the co-linearity of K_{ref} and activation energy.

In the linearized form Eqs. (6) and (7) become Eqs. (8) and (9), respectively:

$$\ln k_A = \ln K_{ref,f} + \left(\frac{E_a}{R}\right)\left(\frac{1}{T} - \frac{1}{T_{ref}}\right) \tag{8}$$

$$\ln\left(\frac{1}{k_1}\right) = \ln K_{ref,f} + \left(\frac{E_a}{R}\right)\left(\frac{1}{T} - \frac{1}{T_{ref}}\right) \tag{9}$$

A plot of $\ln k_A$ and $\ln\left(\frac{1}{k_1}\right)$ against $\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)$ gave a linear graph with $\left(\frac{E_a}{R}\right)$ as slope for polyphenol degradation and water uptake, respectively. The activation energy E_a was then determined form the slope.

2.7. Statistical methods and data analysis

The experimental design used was completely randomized factorial and all treatments and analysis were done in triplicates. Data analysis and mean comparison were performed by employing the JMP statistical software version 5.0 (SAS Institute, Cary, NC, USA), and Duncan's multiple range test at 95% confidence interval.

3. Results and discussions

3.1. Chemical properties

Table 1 shows the proximate analysis of the five bean cultivars used in the study. Protein, fats, and carbohydrates contents varied from 23.93 to 28.53%, 1.12–1.48% and 57.20–61.65%, respectively. Analysis of the variance of the chemical composition of all cultivars shows no statistical significance ($p < 0.05$) among the measured protein content and ash but the fat and moisture content were significantly different ($p < 0.05$). Overall, the *Masusu* and *Maine* cultivars showed the least and highest protein content, respectively. The protein content reported in this work were similar to those reported by [32] but higher than those reported by other researchers [19, 33]. The ratio of protein to carbohydrate was not significantly different among the cultivars. This showed that the process of conversion of the unusable nitrogen gas into ammonium which the bean plants then used in protein synthesis were similar in all the cultivars. The protein values shown in Table 1 (25–28%), is much higher than other sources of vegetable protein (U.S.D.A. Nutrient Database). Macronutrients studies have shown that protein is more satiating than carbohydrates or lipids [34]. It has also been reported that proteins in in pulses and soybeans provide excellent satiety. However, it is not yet fully understood if this is due to a specific attribute of the proteins or the inherent high amounts of these proteins [35]. Regular intake of dried beans is highly recommended as they provide satiety and are useful sources of protein at a low cost compared to animal protein sources like beef, pork, and chicken.

3.2. Effect of soaking condition on phenolic compounds degradation

The effect of soaking water temperature and time on polyphenol degradation for *Kabulangeti* and *Maine* is shown in Fig. 2. The results show that both factors significantly influenced polyphenol degradation. The extent of polyphenol degradation depended not only on the processing conditions but also on the type of cultivar being processed. For instance, a downwards concave trend was observed in the *Kabulangeti*, while an upwards converse trend was seen in the *Maine* cultivar. A sharp rise in polyphenol reduction was observed in *Kabulangeti* reaching up to 45% within the first 8 hours. Beyond 8 hours the rate of degradation proceeded at slower but steady pace. The polyphenol degradation within the first 8 hours at higher temperatures was significantly different from those at room temperature ($p < 0.05$). At 55 °C, the *Kabulangeti* cultivar showed almost a perfect linear degradation implying that soaking at a temperature beyond 45 °C will result in a complete degradation of phenolic compounds. This may be attributed to the increase in water permeability as the temperature rises. On the other hand, *Maine* cultivar, showed a much slower reduction in phenolic compounds (less than 25% even at 55 °C) within 8 hours of soaking prior to a rapid reduction (up to 82%) after 16 hours of soaking, as shown in Fig. 2b. Soaking *Maine* cultivar for more than 8 hours significantly increased loss of native phenolic compounds in the beans. Chinedum, Sanni [36] also observed polyphenol degradation of beans during processing. The authors found a 29.4% reduction in total flavonoids when common beans are boiled at 100 °C for 90 min although, they found no significant different in the total phenolic acids.

Since polyphenol degradation is an oxidation process, it will be influenced by the rate of water absorption during soaking. It is therefore important to evaluate the water uptake characteristics of these cultivars to establish the relationship between water uptake and polyphenol degradation. Fig. 3 shows the impact of water uptake at different times and water temperature during soaking. It is evident that water uptake is relatively slower in the *Maine* cultivar than in *Kabulangeti* within the initial 8-hour of soaking. This may be attributed to varietal characteristics of the beans under study. The difference in water uptake behavior of the beans seems to correlate well with the polyphenol degradation. A pairwise correlation shows a strong positive correlation coefficient ($r >$

Table 1
Proximate analysis of common beans (d.b.).

Bean Cultivar	Protein (%)	Ash (%)	Moisture (%)	Fat (%)	Carbohydrates (%)	Gross Energy (kJ/100 g)
Masusu	24.91 ± 0.98^{b}	3.21 ± 0.20^{b}	8.88 ± 0.01	1.35 ± 0.00^{d}	61.65	1496.45
Msiska	26.34 ± 1.52^{ab}	3.32 ± 0.22^{b}	10.45 ± 0.03	1.47 ± 0.01^{a}	58.42	1470.91
Kabulangeti	26.90 ± 1.63^{ab}	3.46 ± 0.09^{ab}	9.25 ± 0.01	1.26 ± 0.00^{c}	59.13	1484.20
Magungulu	27.06 ± 1.58^{ab}	3.62 ± 0.17^{a}	8.52 ± 0.13	1.13 ± 0.01^{e}	59.67	1490.99
Maine	28.41 ± 0.12^{a}	3.35 ± 0.03^{ab}	9.56 ± 0.11	1.48 ± 0.00^{b}	57.20	1485.48

Values are means ±SD of three measurements. Means within each column with different letters (a–e) differ significantly ($p < 0.05$).

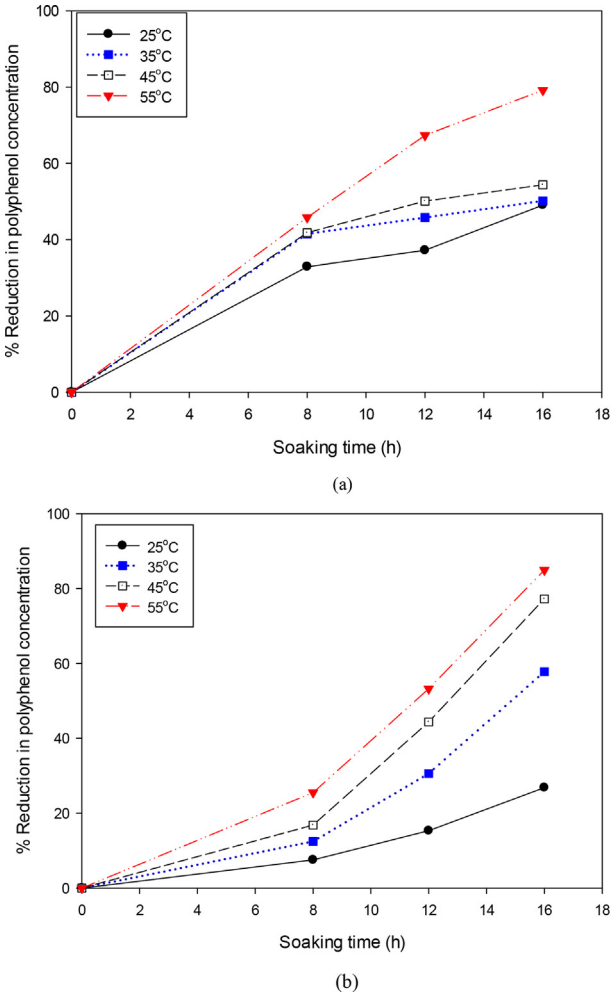


Fig. 2. Effect of time and water temperature on total polyphenol content during soaking of different common beans cultivars (a) *Kabulangeti* (b) *Maine*.

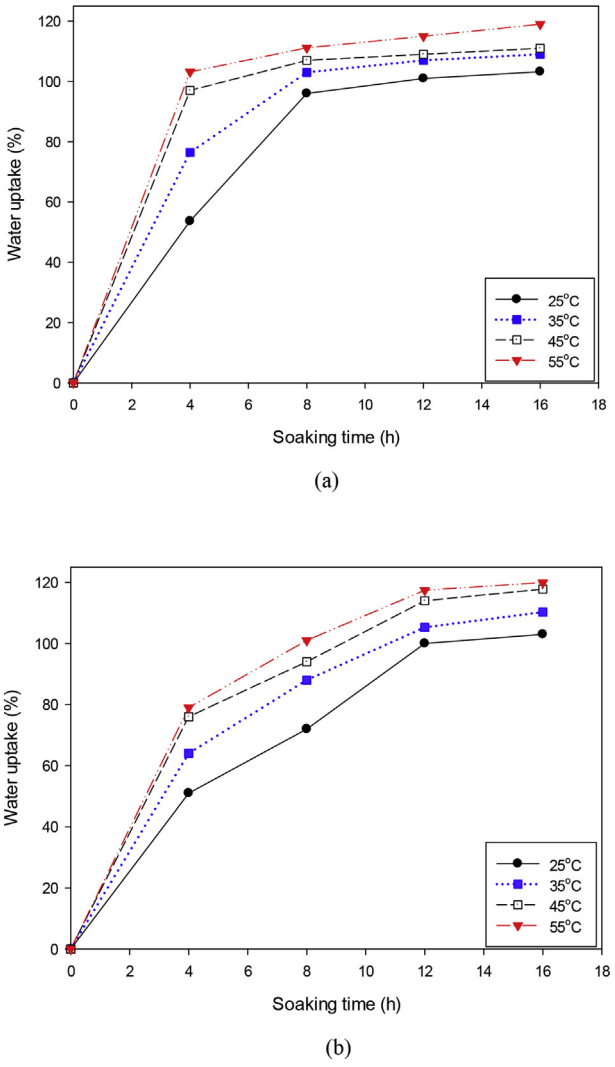


Fig. 3. Effect of time and water temperature on water uptake during soaking of different common beans cultivars (a) *Kabulangeti* (b) *Maine*.

0.85) at all soaking temperatures, regardless of the cultivar. The correlation coefficient varied for the different temperatures. Fig. 4 shows the variation of the pairwise correlation coefficient for the two cultivars at different soaking temperatures.

The difference in the polyphenol reduction between the two cultivars shown in Fig. 2 could be further explained by the results of the water uptake shown in Fig. 3. In the *Kabulangeti* cultivar, equilibrium water uptake was reached within 8 hours of soaking. Thus, beyond 8 hours, the loss in polyphenol compounds was marginal. On the other hand, water uptake in the *Maine* cultivar further increased considerably beyond 8 hours of soaking hence, a more pronounced increase in its polyphenol degradation was observed. It is obvious that the rate of degradation may be dictated by the water uptake. It is important to note that during beans hydration, the hilum serves as the primary point of entrance of water before it is distributed to the cotyledon due to the impermeable behavior of the seed coat. The seed coat is then hydrated from the inside before diffusion and capillary water transfer occurs. Therefore, the size of the hilum, the characteristics of the seed coat and the composition of the cotyledon all influence the rate of water uptake and consequently impact polyphenol degradation [37]. In this study, the two cultivars have different hydration characteristics which is reflected in the degradation of their polyphenols.

The result also shows that, although similar equilibrium water uptake was achieved after 16 hours of soaking in both cultivars, the degree of polyphenol degradation varied significantly. This is an indication that water uptake may not be the only parameter accounting for the polyphenol degradation.

It is clear from these plots that long hours of soaking and higher temperatures considerably reduced native phenolic compounds in the

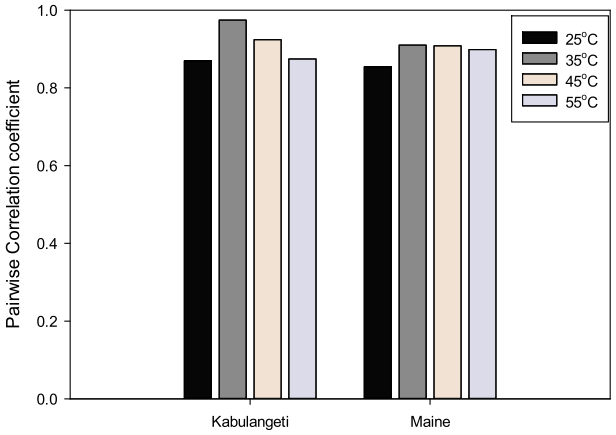


Fig. 4. Pairwise correlation between phenolic compounds degradation and water uptake during soaking of common beans.

beans. Consequently, consuming beans processed under these conditions has reduced health benefits associated with polyphenol-rich beans.

3.3. Effect of cooking conditions on phenolic compounds degradation

Cooking of common beans is the primary processing step prior to consumption. Beans may be soaked prior to cooking or directly cooked. Also, to reduce cooking time bean softeners are added during cooking. Whichever cooking process is used there is a higher tendency of polyphenol loss during this hydro-thermal process. Fig. 5 shows the result of polyphenol degradation of the different bean cultivars during cooking. The degree of polyphenol loss depended on the initial polyphenol content of the raw beans. For cultivars like *Msiska*, which had up to 14.2 GAE mg/g, a higher reduction, 82 %, was observed compared to 32% reduction recorded for the *Maine* cultivar which initially had 2.69 GAE mg/g total polyphenol. The results indicated that cooking reduced the polyphenol content to a range of 1.4–2.8 GAE mg/g in all the beans cultivars when the beans are cooked for more than 3 hours (typical cooking time for most common beans cultivars). The results seem to suggest that to conserve more phenolic compounds in the cooked beans, softening techniques that reduce the cooking time must be integrated into the hydro-thermal processing of beans.

Fig. 6 shows the effect of softening techniques on polyphenol degradation. The three cultivars with the highest degradation during cooking, namely, *Masusu*, *Msiska,* and *Magungulu*, were evaluated. The result indicated that although the softening techniques reduced the cooking time considerably, they also intensified the polyphenol

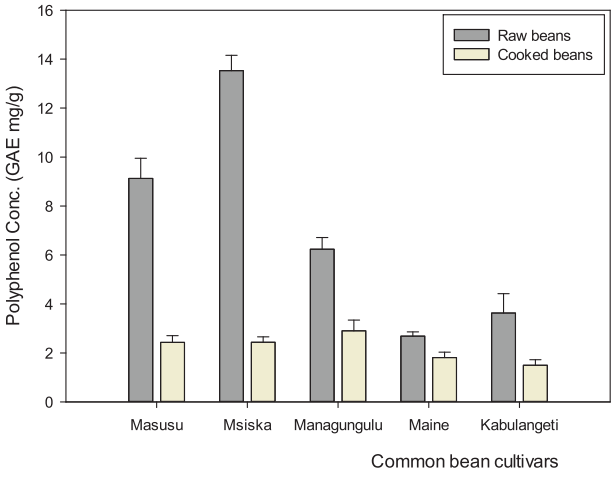


Fig. 5. Effect of cooking on total phenolic compounds concentration.

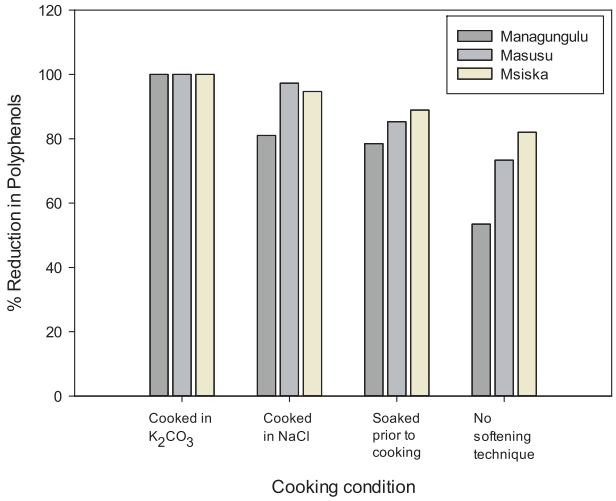


Fig. 6. Effect of cooking conditions on phenolic compounds degradation.

degradation. At least 80% of the total polyphenol was lost regardless of the softening techniques. Among the techniques evaluated in this study, the order of further loss of phenolic compounds was soaking in water < sodium chloride addition < potash addition. Although the addition of potash reduced cooking time by 57%, it presented the highest risk to nutritional quality degradation. It resulted in the total loss of the native phenolic compounds present in the beans. The presence of potash possibly led to the alkylation of the phenolic compounds to other hydroxy propyl by-products [38]. Perhaps, concentrations of the potash solution lower than the 5% used in this study may result in lower degradation but this ought to be investigated. Addition of NaCl to cooking water expectedly increased the cooking time and by extension increased the polyphenol degradation. It is therefore recommended that salt could be added later during cooking rather than from the onset. Again, since the beans were soaked for a maximum 16 hours (to estimate the maximum degradation possible), it is possible that soaking for the recommended 8 hours or less could result in less polyphenol degradation while achieving a 40% reduction in cooking time.

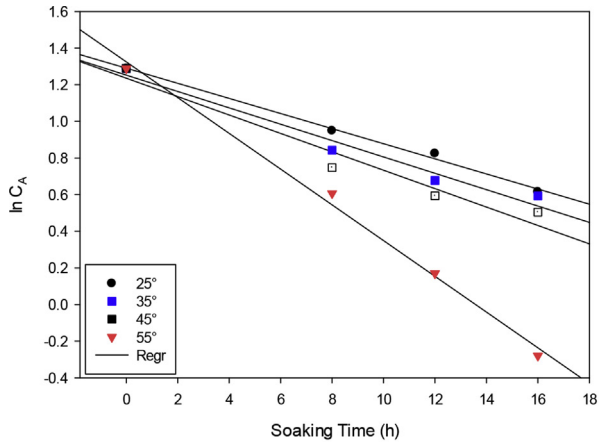
3.4. Kinetic modeling of phenolic compounds degradation

3.4.1. Determination of k_1

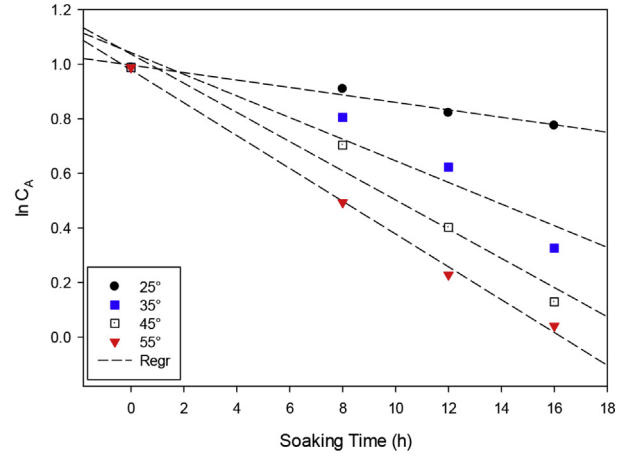
The rate of phenolic compounds degradation at different temperatures were estimated for two cultivars using the linearized form of the polyphenol oxidation equation. Fig. 7 shows the logarithmic plot of phenolic compounds degradation during soaking. The rate constant, k_1, for polyphenol oxidation for the different cultivars are also shown in Table 2. The rate of polyphenol oxidation increased with increasing temperature. At temperatures below 45 °C, the rate constant of the *Kabulangeti* cultivar was estimated to be <0.005 GAE mg/g per hour. This rate increased significantly to 0.048 mg/g over a 10 °C temperature rise. This may be attributed to higher water permeability at higher temperature hence rapid polyphenol oxidation. This is an indication that for commercial processing where soaking is done at higher temperatures, the recommended temperature for soaking should be <45 °C to ensure higher retention of total phenolic compounds. The rate constants for *Maine* at different soaking temperatures ranged from 0.014 – 0.069 h^{-1}. This implied that for the *Maine* cultivar, there was about one and half fold increase in the rate of loss of phenolic compounds with increase in soaking-water temperature. The results demonstrated that the rate of polyphenol degradation depended on the processing temperatures and the inherent characteristics of the cultivar being processed.

3.4.2. Determination of k_2

The rate of water uptake was modeled using the linearized form of the



(a)



(b)

Fig. 7. Correlation of the logarithm of total phenolic compounds during soaking of common beans (a) *Kabulangeti* cultivar (b) *Maine* cultivar.

Table 2
Phenolic compounds degradation reaction rates at different water temperature during soaking of common beans.

Temperature (°C)	*Kabulangeti*		RMSE	*Maine*		RMSE
	k_A (h^{-1})	R^2		k_A (h^{-1})	R^2	
25	0.0408 ± 0.0003	0.989	0.0507	0.0136 ± 0.0003	0.974	0.0190
35	0.0443 ± 0.0006	0.918	0.0957	0.0350 ± 0.0002	0.921	0.0854
45	0.0503 ± 0.0003	0.954	0.0920	0.0558 ± 0.0009	0.905	0.1367
55	0.0985 ± 0.0002	0.985	0.0996	0.0689 ± 0.0007	0.940	0.0737

Peleg model [28] shown in Eq. (5). The model constants estimated from the non-linear regression analysis are shown in Table 3. The two model constants represent the Peleg rate constant (k_1) expressed in min/% m.c. (d.b), and the Peleg capacity constant (k_2) expressed in 1/% m.c. From the table, rate of water uptake decreases with increasing water temperature for both cultivars. This is expected due to the inverse relationship between the water uptake capacity and the rate.

Within the selected temperature, the rate of water uptake k_1 varied from 4.806 – 0.901 and 1.949–0.889, respectively, for *Kabulangeti* and *Maine* cultivars. The Peleg rate constant k_1 was not statistically different

Table 3
Model parameters of the Peleg model.

Bean cultivar	Temperature (°C)	k_1 (min/% m.c) (d.b)	k_2 (1/% m.c.) (d.b)	R^2	RMSE
Kabulangeti	25	4.806 ± 0.44	0.039 ± 0.0005	0.901	0.108
	35	2.761 ± 0.19	0.030 ± 0.0002	0.945	0.078
	45	1.884 ± 0.11	0.028 ± 0.0004	0.977	0.052
	55	0.901 ± 0.09	0.027 ± 0.0002	0.993	0.044
Maine	25	1.949 ± 0.34	0.030 ± 0.0005	0.958	0.098
	35	1.467 ± 0.27	0.028 ± 0.0003	0.991	0.039
	45	1.231 ± 0.15	0.027 ± 0.0007	0.982	0.054
	55	0.889 ± 0.08	0.026 ± 0.0004	0.992	0.051

($p < 0.05$) for soaking at higher temperatures (above 25 °C) for both cultivars. Similar results were found at temperatures above 40 °C by Turhan, Sayar [31]. The higher water uptake during bean hydration has been associated with water temperature, soaking duration, presence, and concentration of salt [23, 39, 40]. At higher temperature, there may be partial gelatinization of the endosperm resulting in partial expansion of starch and protein molecules, and subsequent softening and expansion of seed which could lead to the increase mass transfer. This led to the opening of more pores and cracks hence faster water transmission through the seeds. Beside soaking conditions (temperature and time), other inherent seed characteristics such as cell wall structure, seed composition and compactness of cells in the seeds have been mentioned as contributing to the higher rate of transfer [41, 42].

Similarly, the maximum water absorption capacity (k_2) was found to decrease with increasing water temperature as shown in Table 3. There was no statistically significant difference among the varieties studied, implying that the maximum water holding capacity of the varieties were the same even at different temperatures provided there was sufficient time to reach equilibrium water uptake.

Following the strong correlation between water uptake and polyphenol degradation, it can be suggested by extension, that the rate of polyphenol degradation (k_1) will be strongly related with the rate of water uptake (k_2).

3.4.3. *Activation energy for phenolic compounds degradation during soaking*

Temperature dependence of the phenolic compounds degradation has been estimated using the Arrhenius equation expressed in Eq. (6). The activation energy for *Kabulangeti* and *Maine* cultivars were found to be 45.41 and 26.31 kJ/mol, respectively. The influence of temperature on the initial rate of water absorption was also modeled. The kinetic parameters for phenolic compounds degradation and water uptake are shown in Table 4. The magnitude of the activation energy E_a for water uptake was within the range of values typical of grains and legumes, 11.1–136.5 kJ/mol [31, 43].

Table 4
Kinetic parameters of phenolic compounds degradation and water uptake during soaking of common beans.

Bean Cultivar	E_a(kJ/mol)	k_{ref} (h^{-1})	R^2
Polyphenol degradation			
Kabulangeti	45.4	0.058	0.987
Maine	26.3	0.024	0.954
Water uptake			
Kabulangeti	52.6	0.522	0.964
Maine	27.5	0.714	0.874

4. Conclusion

This study evaluated the degradation of total phenolic compounds during soaking and cooking of common bean cultivars. The effect of water temperature, soaking time and softening techniques on the degree of degradation was evaluated and modeled kinetically. The study established that the rate of polyphenol degradation increased as temperature and soaking duration increased. Soaking beyond 8 hours can significantly impact on the polyphenol content of beans regardless of the process water temperature. There is a strong positive correlation between water uptake and polyphenol degradation. Hence, conditions that lead to increased water uptake will reduce the nutritional quality of the beans. Softening techniques reduced cooking time and increased water uptake and resulted in higher polyphenol degradation. This ultimately had a negative effect on the nutritional quality of the beans especially phenolic compounds retention in cooked beans.

Declarations

Author contribution statement

Ogan Mba Conceived and designed the experiments; Performed the experiments.

Ebenezer Kwofie Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Michael Ngadi Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.

Funding statement

This work was supported by the International Fund for Agricultural Development (IFAD) through IFAD project grant 2000000974.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

[1] J.A. Gutiérrez-Uribe, D. Guajardo-Flores, L. López-Barrios, Legumes in the diet, in: Encyclopedia of Food and Health, Academic Press, Oxford, 2016, pp. 539–543.
[2] B.A. Graf, P.E. Milbury, J.B. Blumberg, Flavonols, flavones, flavanones, and human health: epidemiological evidence, J. Med. Food 8 (3) (2005) 10.
[3] T. Ozdal, E. Capanoglu, F. Altay, A review on protein–phenolic interactions and associated changes, Food Res. Int. 51 (2) (2013) 954–970.
[4] D. Chen, et al., ECGG, green tea phenolic compounds and their synthetic analogs and prodrugs for human cancer prevention and treatment, Adv. Clin. Chem. 53 (2011) 155–177. PMCID: PMC3304302.
[5] C.-J. Weng, G.-C. Yen, Chemopreventive effects of dietary phytochemicals against cancer invasion and metastasis: phenolic acids, monophenol, polyphenol, and their derivatives, Cancer Treat Rev. 38 (1) (2012) 76–87.
[6] S. Kuriyama, et al., Green tea consumption and mortality due to cardiovascular disease, cancer, and all causes in Japan: the ohsaki study, J. Am. Med. Assoc. 296 (10) (2006) 1255–1265.
[7] J. Mursu, et al., Flavonoid intake and the risk of ischaemic stroke and CVD mortality in middle-aged Finnish men: the kuopio ischaemic heart disease risk factor study, Br. J. Nutr. 100 (4) (2008) 890–895.
[8] W.Y. Jeong, et al., Determination of phenolic compounds in three Capsicum annuum L. (bell pepper) varieties using high-performance liquid chromatography-tandem mass spectrometry: their contribution to overall antioxidant and anticancer activity, J. Sep. Sci. 34 (21) (2011) 2967–2974.
[9] E.E. Mulvihill, M.W. Huff, Antiatherogenic properties of flavonoids: implications for cardiovascular health, Can. J. Cardiol. 26 (2010) 17A–21A.
[10] N. Han, et al., Antithrombotic activity of fractions and components obtained from raspberry leaves (Rubus chingii), Food Chem. 132 (1) (2012) 181–185.
[11] I.N. Beara, et al., Comparative analysis of phenolic profile, antioxidant, anti-inflammatory and cytotoxic activity of two closely-related Plantain species: plantago altissima L. and Plantago lanceolata L, LWT Food Sci. Technol. (Lebensmittel-Wissenschaft -Technol.) 47 (1) (2012) 64–70.
[12] M. Bijak, et al., Anticoagulant effect of phenolic compounds-rich extracts from black chokeberry and grape seeds, Fitoterapia 82 (6) (2011) 811–817.
[13] M.A. Schmitz-Eiberger, M.M. Blanke, Bioactive components in forced sweet cherry fruit (Prunus avium L.), antioxidative capacity and allergenic potential as dependent on cultivation under cover, LWT - Food Sci. Technol. (Lebensmittel-Wissenschaft -Technol.) 46 (2) (2012) 388–392.
[14] J.C. Silva, et al., Antimicrobial activity, phenolic profile and role in the inflammation of propolis, Food Chem. Toxicol. 50 (5) (2012) 1790–1795.
[15] M. Pujolà, A. Farreras, F. Casañas, Protein and starch content of raw, soaked and cooked beans (Phaseolus vulgaris L.), Food Chem. 102 (4) (2007) 1034–1041.
[16] M. Ghafoor, et al., Ultrasound assisted hydration of navy beans (Phaseolus vulgaris), Ultrason. Sonochem. 21 (1) (2014) 409–414.
[17] L.F. de León, L.G. Elías, R. Bressani, Effect of salt solutions on the cooking time, nutritional and sensory characteristics of common beans (Phaseolus vulgaris), Food Res. Int. 25 (2) (1992) 131–136.
[18] A. Gowen, et al., Influence of pre-blanching on the water absorption kinetics of soybeans, J. Food Eng. 78 (3) (2007) 965–971.
[19] Y. Ai, et al., Effects of extrusion cooking on the chemical composition and functional properties of dry common bean powders, Food Chem. 211 (2016) 538–545.
[20] R. Alonso, A. Aguirre, F. Marzo, Effects of extrusion and traditional processing methods on antinutrients and in vitro digestibility of protein and starch in faba and kidney beans, Food Chem. 68 (2) (2000) 159–165.
[21] R. Alonso, E. Orúe, F. Marzo, Effects of extrusion and conventional processing methods on protein and antinutritional factor contents in pea seeds, Food Chem. 63 (4) (1998) 505–512.
[22] K.H. McWatters, et al., Functional, nutritional, mycological, and akara-making properties of stored cowpea meal, J. Food Sci. 67 (6) (2002) 2229–2234.
[23] S.M. Shafaei, A.A. Masoumi, H. Roshan, Analysis of water absorption of bean and chickpea during soaking using Peleg model, J. Saudi Soc.Agric. Sci. 15 (2) (2016) 135–144.
[24] AOAC, Official Methods of Analysis, Association of Official Analytical Chemists, Arlington, VA, 2005.
[25] V.L. Singleton, R. Orthofer, R.M. Lamuela-Raventós, Analysis of total phenols and other oxidation substrates and antioxidants by means of folin-ciocalteu reagent, Methods Enzymol. 299 (1999) 152–178.
[26] J. Alean, F. Chejne, B. Rojano, Degradation of phenolic compounds during the cocoa drying process, J. Food Eng. 189 (2016) 99–105.
[27] T.M. Kyi, et al., The kinetics of polyphenol degradation during the drying of Malaysian cocoa beans, Int. J. Food Sci. Technol. 40 (3) (2005) 323–331.
[28] M. Peleg, An empirical model for the description of moisture sorption curves, J. Food Sci. 53 (4) (1988) 1216–1217.
[29] N. Abu-Ghannam, B. McKenna, Hydration kinetics of red kidney beans (Phaseolus vulgaris L.), J. Food Sci. 62 (3) (1997) 520–523.
[30] V.S. Sharanagat, V. Kansal, K. Kumar, Modeling the effect of temperature on the hydration kinetic whole moong grain, Journal of the Saudi Society of Agricultural Sciences (2016).
[31] M. Turhan, S. Sayar, S. Gunasekaran, Application of Peleg model to study water absorption in chickpea during soaking, J. Food Eng. 53 (2) (2002) 153–159.
[32] M. Joshi, et al., Water uptake and its impact on the texture of lentils (Lens culinaris), J. Food Eng. 100 (1) (2010) 61–69.
[33] G.E. de Almeida Costa, et al., Chemical composition, dietary fibre and resistant starch contents of raw and cooked pea, common bean, chickpea and lentil legumes, Food Chem. 94 (3) (2006) 327–330.
[34] D.S. Weigle, et al., A high-protein diet induces sustained reductions in appetite, ad libitum caloric intake, and body weight despite compensatory changes in diurnal plasma leptin and ghrelin concentrations, Am. J. Clin. Nutr. 82 (1) (2005) 8.
[35] M.A. McCrory, et al., Pulse consumption, satiety, and weight management, Adv. Nutr. 1 (1) (2010) 13.
[36] E. Chinedum, et al., Effect of domestic cooking on the starch digestibility, predicted glycemic indices, polyphenol contents and alpha amylase inhibitory properties of beans (Phaseolis vulgaris) and breadfruit (Treculia africana), Int. J. Biol. Macromol. (2017).
[37] A.C. Miano, P.E.D. Augusto, The hydration of grains: a critical review from description of phenomena to process improvements, Compr. Rev. Food Sci. Food Saf. 17 (2018) 352–370.
[38] A. Arbenz, L. Avérous, Chemical modification of tannins to elaborate aromatic biobased macromolecular architectures, Green Chem. 17 (5) (2015) 20.
[39] O. Corzo, N. Bracho, Application of Peleg model to study mass transfer during osmotic dehydration of sardine sheets, J. Food Eng. 75 (4) (2006) 535–541.
[40] P.K. Kinyanjui, et al., Hydration properties and texture fingerprints of easy- and hard-to-cook bean varieties, Food Sci. Nutr. 3 (1) (2015) 39–47.
[41] J. Khazaei, N. Mohammadi, Effect of temperature on hydration kinetics of sesame seeds (Sesamum indicum L.), J. Food Eng. 91 (4) (2009) 542–552.
[42] A.C. Miano, P.E.D. Augusto, From the sigmoidal to the downward concave shape behavior during the hydration of grains: effect of the initial moisture content on Adzuki beans (Vigna angularis), Food Bioprod. Process. 96 (2015) 43–51.
[43] A.N. Calzetta Resio, R.J. Aguerre, C. Suarez, Analysis of simultaneous water absorption and water–starch reaction during soaking of amaranth grain, J. Food Eng. 68 (2) (2005) 265–270.