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A cyclically pressurised soaking process for the hydration and aromatisation of cannellini beans

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ABSTRACT

Hydrating beans before cooking reduces cooking time, increases their tenderness and weight and improves their appearance after cooking. In this paper, we describe a process of cyclically pressurised soaking for the rapid hydration of cannellini beans at room temperature. This hydration process is approximately ten-fold faster than the traditional soaking procedure, and the microbial load developed by the end of this process is much lower compared to that obtained using the traditional process. This bean hydration process was achieved with a new extraction technique using the Naviglio extractor, which subjected the water containing the beans to cycles of pressurisation in which the pressure values ranged between 0 (atmospheric pressure) and 10 bar. This innovative hydration process (I) reduced the time required for the complete hydration of the beans to approximately 60 min and produced a product saturated with the same final amount of moisture as the product obtained from the conventional soaking process (T) that lasts 12–20 h. The numerical simulation of the hydration process (I) has provided useful indications on how the diffusion of humidity inside the beans occurred during the pressurised soaking process. The treated beans were packaged, and organoleptic tests, including taster panel tests, were conducted. Finally, the aromatisation of the legumes was conducted in conjunction with the hydration process to introduce flavouring elements used in some famous traditional recipes for Italian cuisine.

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1. Introduction

Beans are one of the most important sources of food protein after meat and eggs. Their cost is lower than meat and eggs; for this reason and due to their ease of preparation in the kitchen, the consumption of beans has been increasingly growing over time. Unfortunately, legumes cannot always be consumed fresh, and because they are perishable, after harvest, most are dried by various drying processes (e.g., hot air, microwave) that decrease the moisture in the beans to below 10% (w/w), thus ensuring their preservation. The dried product cannot be consumed directly because of its hard consistency, and it is necessary to soak the product for approximately 10–12 h until it becomes completely rehydrated and ready to be cooked. This process is still being performed in our kitchens and has also been adopted in industry; therefore, in this context, beans are subjected to a process of soaking for 8–18 h (depending on the type and variety of the legumes). Because not all beans are intended for consumption immediately after this hydration process, they are subjected to a sterilisation process that enables storing the final product. The hydration process to which the beans are

subjected constitutes a very delicate phase of their processing in that it represents an essential prerequisite that affects the entire production process. The process of hydration currently used in the industry is based on soaking, meaning that the legumes are placed in large tanks that are then filled to about one-third of the total volume and covered with water, taking into account that their volume will have doubled by the end of the process. At this point, the rehydrated product is ready for the subsequent stages. The traditional rehydration performed in farm industries has some drawbacks that have been described by Carpi et al. (1997), such as the notable movement of the raw material, remarkable encumbrance of space, necessity to evaluate the quantity of product for use after rehydration, progressive filling of the rehydration tanks, long period until recovery, discontinuity in the production line and the hygiene problems caused by the long rehydration period that may often provoke fermentation with the resulting formation of foam and development of malodorous gas, thus necessitating rigorously washing the tanks. In addition, it is important to note that during the soaking process (maceration), structural degradation of the product inevitably begins, which increases with time, because of the long duration over which the beans are in contact with water. The structural degradation during the soaking reaches an equilibrium state well before the saturation humidity does, and for indus-

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trial purposes, it is therefore important to identify the hydration step in which major changes of the texture occur (Abu-Ghannam, 1998). Because of the great quantities of dry beans treated, a flow of inert gas (nitrogen) has been injected into the tanks in an upward direction to improve the remixing of the beans in the tanks. This was performed both to avoid crushing the beans and to inhibit microbiological growth. During the soaking process, water enters through the hylum of the beans and infiltrates the peripheral part of the seed wall, thus causing wrinkles. After some time, the hydration and expansion process results in swollen seeds that have doubled both their volume and weight; this is when hydration is complete. Moreover, during the beans' hydration, some important transformations occur, such as starch gelatinisation, changes in texture, and increases in the available proteins. Contemporaneously, toxic substances, such as lecithins, goitrogen factors, tannins and trypsin inhibitors, are naturally eliminated. Finally, it should be noted that many mesophilic bacteria proliferate during the soaking process (and at room temperature); therefore, to reduce the microbiological risks, farms perform a blanching process (i.e., scorching with an aqueous vapour) or use salts to increase the alkalinity of the soaking water, which impedes or inhibits the development of microorganisms (Gowen et al., 2007). In other cases, increasing the temperature of the soaking water has been tested, which involves a reduction of the cooking time caused by the de-activation of the phytase enzyme. When the phytase enzyme is activated, it destroys the phytic acid that, in combination with calcium and/or magnesium, forms soluble salts that are useful for cooking. Nevertheless, the increase in the temperature of the soaking water also increases the loss of calcium, magnesium, thiamine, riboflavin, niacin and some oligosaccharides (Halaby et al., 1982). For several decades, researchers have been looking for an alternative to the traditional soaking method that could be implemented in the rehydration process, thus decreasing the time of solid–liquid contact to obtain a more economically favourable process and possibly reducing the development of microbial flora. In the literature, different attempts at accelerating the industrial hydration process of beans have been reported, particularly those using warm water, because the temperature is the primary variable that affects the diffusion of water into the beans, and it is easily possible to make alterations to accelerate this process. However, water heating not only requires huge amounts of energy to bring the soaking water to operating temperature, but it also promotes the uncontrolled growth of microorganisms naturally present in legumes (Abu-Ghannam, 1998). The results of this study primarily showed that the rate of hydration of beans treated in the traditional manner can be reached in a shorter time but with a reduction in the quality of the final product in terms of their content of vitamins and other nutrients that can be degraded at high temperatures (Amarowicz and Pegg, 2008). Furthermore, we must consider microbiological development (Ogwal and Davis, 1994; Haladjian et al., 2007). Because soaking beans in hot water in a static system had the effects described above, an apparatus to hydrate dried legumes with alternating baths of hot or cold water at predetermined time intervals has been constructed and studied (Carpi et al., 1997). This system reduces the soaking time but is not economically advantageous, as the authors stated, because it is a batch process and requires large quantities of water to be heated. Systems operating at extremely high pressures and plants using the process of legume irradiation to facilitate hydration have been designed and manufactured (Çelik et al., 2004). However, in all cases, the high costs of the plants and their management have pushed entrepreneurs to use technologies with low production costs and a low initial cost. Finally, to illustrate that the problem in improving the process of rehydration of beans has not yet been completely solved, the use of enzymes has also recently been tested; however, using enzymes in this practice increases the fixed cost

of production and has an uncertain benefit for yields (Okatch et al., 2003). Therefore, methods and equipment to rehydrate beans in a procedure that differed from the traditional procedure were tested to eliminate or reduce the drawbacks of traditional hydration and simultaneously provide results at least equal to those of the traditional procedure. To date, however, none of these methods was convenient from the industrial point of view because they were more expensive than the traditional soaking. Furthermore, it has been observed that performing the processes of pressurised soaking with constant pressure (with different values of the real pressure including 2, 4, 6, 8 or 10 bar) did not appreciably reduce the time necessary for the hydration process compared with that of the traditional soaking. However, when performing a cyclically pressurised soaking process by changing the pressure values during the rehydration process, an appreciable reduction of the time necessary for rehydrating the beans was attained (compared with that of the traditional process of rehydration). Thus, in this report, an innovative method of bean hydration is proposed that utilises a process of cyclically pressurised soaking, i.e., a process in which the actual pressure applied to the water in which the dry beans are immersed for hydration varies cyclically in a range between 0 and 10 bar. This process was conducted using a solid–liquid extractor called the Naviglio extractor (Naviglio, 2003). The process was performed at room temperature, and the energy cost was primarily due to the liquid pressurisation.

2. Material and methods

Experimental tests for the hydration of cannellini beans via a process of cyclically pressurised soaking, obtained with a rapid, dynamic solid–liquid extractor (Naviglio extractor[®], Atlas Filtri Ltd., Padua, Italy) were conducted (Fig. 1). This apparatus allows accelerating the solid–liquid extraction by means of cyclical pressure, with pressure values ranging between 0 (atmospheric pressure) and 10 bar, applied to the liquid in contact with the plant material to extract the active ingredients (Naviglio, 2003; Naviglio et al., 2006).

The Naviglio extractor[®] mod. 1000 ml was used. The apparatus is formed by two extraction chambers, each constituted of a steel cylinder with a piston. Two porous septa that allow only the liquid phase to pass are on the bottom of the chambers. The two extraction chambers are connected by a pipe with an electric valve that is closed during the program of the hydration process and opened to evacuate the liquid from the system at the end of the cycle. When the maximum value of the programmed pressure is reached, it is maintained for a predetermined time (generally 2 min); in this manner, the equilibrium between the solid and liquid matrices (static phase) is established. After this time (static phase), the pressurised air that acts on the pistons is quickly evacuated, with a consequent pressure reduction, and consequently, a negative pressure gradient is attained between the inside and outside of the solid matrix (dynamic phase). During this phase, compounds not chemically bonded to the solid matrix are physically extracted and transferred to the liquid phase, and the extraction of the active ingredients is thus obtained. For this research, the rapid dynamic solid–liquid extractor described was used for the process of rapid hydration of beans because the cyclic pressure on the water in which the beans are immersed increases the diffusion of the liquid within the solid compared with the traditional process of soaking, favouring a faster rehydration of the beans. Each cycle of rehydration is characterised by a static and dynamic phase. The forced entry of the liquid into the solid phase accelerates the humidification of the beans. The rapid fall of pressure outside the solid matrix causes some of the liquid that had entered to come out quickly. The repeated series of cycles of intake and outlet of liquid from



Fig. 1. Front and rear views of a Naviglio extractor with a capacity of 1 l.

the initial matrix due to the progressive increase of its moisture and volume results in the progressive hydration of the beans in a very short time compared with the usual time for the traditional (static) hydration process that is based only on the diffusion of water into the beans. Bean samples were placed in a steel basket with a porosity of 1 mm inside an extraction chamber. The chamber was filled with water and with aromatic spices. Using a basket helps maintain legumes within a limited volume. Once loaded, the extraction chamber was set to a predetermined maximum pressure of approximately 10 bars. The operating parameters for the process of hydration were set as follows: number of load cycles: 30, total duration of cycles: 2 h, number of shots in the dynamic phase: 12, extent of the phase time: 2 min, and time of the dynamic phase: 2 min. After this process, a series of measurements were performed to compare the results obtained with this experimental process (I) and those obtained with the conventional method (T).

2.1. Experimental tests

Some experimental tests were performed to evaluate the water absorption of the beans in the two processes under consideration, (I) and (T). Beans of the cannellini type were chosen. The samples consisted of the raw material used by a famous cannellini bean farm in Salerno (Italy) in jute bags from countries in Central America. The samples had been stored at 10 °C in tightly sealed plastic containers to prevent changes in the moisture content and were mixed several times for 2 min.

The beans were cleaned and left on a tray under laboratory conditions for a period of two weeks to allow them to reach a uniform moisture content (M_i). Before the hydration process, the moisture content of the beans was determined by heating them in an oven at 103 °C for 36 h (ASAE, 1997). The size of beans, including the length, width, and thickness, were measured using a digital caliper. From these values, the sphericity and geometric mean diameter (GMD) of the beans were determined (Jain and Bal, 1997). These values were used in the numerical simulations.

Samples consisting of 100 g of beans were weighed with a balance with 0.01 g accuracy (Gibertini Europe 1700) to measure the initial volume. To evaluate the volume without changes in the moisture content, the beans were sealed with plastic material (food-grade polyethylene) that adhered perfectly to the shape of

the beans, and the volume was measured as the initial total (V_{pt}) by immersion for a few seconds in 5 ml of water in a graduated 10 ml cylinder.

From this total initial volume (V_{pt}), the volume of the masses accessory (V_a), which was previously determined, was subtracted, and the result was the volume (V_p) of the sample, which was determined as follows: $V_p = (V_{pt} - V_a)$. After the determination of the initial weight and volume, the samples were subjected to the processes of hydration considered (I) and (T). Determinations of the weight and volume, performed as described above, were repeated every 20 min for an hour on samples hydrated by process (I), while the determinations were made every hour for 15 h on samples hydrated by the traditional soaking process (T), which had been put to soak in a beaker with 500 ml of water at room temperature. The samples hydrated using the traditional method (T) were put in an open beaker with 500 ml of water to soak at room temperature, thus simulating the industrial process while maintaining a solid/liquid ratio of 1:5 (100 g of beans in 500 ml of water). The samples hydrated by method (I) were subjected to programmed cycles of pressure applied to the liquid in contact with the product, as described above, while maintaining the same solid–liquid ratio. All experiments were repeated three times, and the maximum difference between the results obtained was never more than 5%; thus, the averages were used for modelling and analyses. In addition, other types of samples to be submitted to the rehydration process (I) were prepared by introducing spices and flavourings associated with traditional Italian cuisine into the extraction chamber of the rapid dynamic solid–liquid extractor in addition to the legumes. The flavourings used were chili, basil, celery and parsley. These samples were prepared according to a basic formulation (weight percentage): legumes (60%), salt (1%) and water (39%).

At the end of this process, 200 g of solid food matrix (drained beans) was transferred into boxes by adding a solution of water and salt. After complete filling, the boxes were crimped and transferred to a pilot plant for sterilisation (autoclave), subjecting the solid food matrix (legumes) to heat treatment for 35 min at a temperature of 118 °C. The whole preparation procedure was repeated to make 60 samples of canned legumes.

The following other tests were also conducted: Sensory analysis using a panel test to determine whether there were differences in the perceptions and pleasantness of the dried product that had

been hydrated using the different methods (I) and (T); microbiological analysis of the products; analytical and numerical analysis of the processes under consideration for a better understanding of the phenomenon of water diffusion into the beans under the operating conditions considered, comparing the results of the experimental tests with those obtained using the analytical and numerical approaches described in current literature and applied successfully to other foods.

2.2. Sensory analysis

Sensory analysis of the treated beans was conducted in collaboration with sensory laboratory of Annalisa SpA (Salerno, Italy). Before the complete evaluation of the samples, a series of preliminary measurements of their texture was performed. Discriminative methods were used to determine whether there was a perceptible difference between two or more products, to select the judges, and occasionally, to ascertain the magnitude of the difference. Among the different discriminative tests chosen was the triangular test, a method used to determine if sensory differences between two samples are homogeneous and do not generate a strong sensory fatigue. To execute this type of test, each taster was presented with three samples encoded in a different manner, two identical and one different. The order of presentation of the samples was randomised using a block table that allowed exactly six sequences of possible presentation to be repeated. Each taster was presented with a card listing the codes of the assigned samples and asked to assess only the texture of each different sample. Eighteen regular consumers of beans were selected for the test, 9 men and 9 women aged between 24 and 62 years. During the assessment phase, three samples of beans were presented to each tester. Each 30 g sample of legumes was presented with a small aliquot of liquid, with the aim of not dehydrating the surface of the beans. The samples, encoded with three-digit numerical codes, were served anonymously and randomly. A second sensory analysis was conducted according to a hedonic method to verify whether the product that had been hydrated with the Naviglio extractor (I) was more pleasing than that traditionally hydrated (T).

Sixty tasters were used for this test. Six samples of beans were considered using a MasterCard table. Each sample was identified with a number, and the results were analysed using a statistical analysis program. The tasters provided responses using a guide book in which the tasters were asked to taste the samples and judge the pleasantness of the product from a minimum of one to a maximum of nine. Samples from boxes processed on the same day from the same lots of raw materials were used for both tests.

2.3. Microbiological analyses and comparisons (sampling systems)

The samples of beans rehydrated using the two methods (I) and (T) were subjected to microbiological analyses; the results obtained are shown in Tables 4 and 5. The samplings were made according to the actual norms ISO (4832, 4833, 7937, 6579, 16649-2, and 7954) and have been provided for the following phases:

2.3.1. Conventional procedure (T)

2.3.1.1. First Phase.

1. Collecting 500 g of raw material.
2. Transferring the raw material to a sterile bag with a label indicating the raw material, product, quality, batch and date of sampling.
3. Maintaining the raw material at a temperature of +4 °C.

2.3.1.2. Second phase.

1. Sampling (250 g) the raw material at the end of the rehydration process and before the selection.

2. Transferring the raw material into two sterile bags with a label indicating procedure (traditional), starting and final time of the rehydration process, product, quality, batch and date of sampling.

2.3.1.3. *Third phase.* Sampling of ($n = 20$) boxes after crimping and before the sterilisation process with a label on the boxes with a label indicating procedure (traditional), final time of crimping, product, batch and date.

2.3.1.4. *Fourth phase.* Collecting ($n = 20$) boxes at the end of the sterilisation process with a label on the boxes indicating procedure (traditional), final time of the sterilisation process, product, batch and date.

2.3.2. Procedure with the Naviglio extractor (I)

2.3.2.1. *First phase.* The first phase of the procedure with the Naviglio extractor was identical to that of the traditional procedure because the raw material (500 g) initially taken was separated into two batches.

2.3.2.2. Second phase.

1. Sampling (200 g) of raw material from the Naviglio extractor at the end of the rehydration process.
2. Transferring the raw material into a sterile bag with a label indicating the Naviglio procedure, final time of rehydration, initial time, final time, product, quality, batch and date of sampling.

2.3.2.3. *Third phase.* Sampling of ($n = 20$) boxes at the end of crimping process and before the sterilisation process, with a label on the boxes indicating Naviglio procedure, final time of crimping, product, batch and date).

2.3.2.4. *Fourth phase.* Sampling of ($n = 20$) boxes at the end of the sterilisation process with a label on the boxes indicating Naviglio procedure, final time of sterilisation, product, batch and date.

2.4. Analytical approach

During a diffusion process at a constant temperature, it is assumed that the process follows Fick's second law of diffusion. For an axisymmetric diffusion, Fick's three-dimensional (3D) equation is given as follows:

$$\frac{\partial M}{\partial t} = D \left(\frac{\partial^2 M}{\partial x^2} + \frac{\partial^2 M}{\partial y^2} + \frac{\partial^2 M}{\partial z^2} \right) \quad (1)$$

where M is the instantaneous moisture content at a specified time t and D is the diffusion coefficient. A solution using the above equation for an object with a spherical shape with a radius r was presented by Crank (1975) as follows:

$$MR = \frac{M - M_i}{M_e - M_i} = 1 - \left(\frac{6}{\pi^2} \right) \sum_{i=1}^{\infty} \left(\frac{1}{i^2} \right) \exp \left(-Di^2 \pi^2 \frac{t}{r^2} \right) \quad (2)$$

where MR is the moisture ratio and M_i and M_e are the initial and equilibrium moisture contents of the object during a moisture transformation process, respectively. In most cases, only a finite number of Eq. (2) is used to estimate MR values. In fact, most researchers use only the first two terms of this equation. In this study, the experimental MR values at specific time intervals were calculated and used as input to the curve-fitting toolbox of the MATLAB (R2006a) software, and the diffusion coefficient of the beans, D , was estimated. Because the general shape of a typical bean

is closer to an ellipsoid than a sphere, the coefficient of diffusion should be adjusted in Eq. (1). Gaston et al. (2004) presented a procedure to estimate the coefficient of diffusion for an ellipsoid (D_e) using the following equation:

$$D_e = f_e^2 \times D \quad (3)$$

where f_e is the sphericity factor of the ellipsoid. The coefficient of diffusion D in Eq. (2) should then be replaced by the calculated D_e .

2.5. Finite element approach for hydration with the cyclically pressurised soaking process

For the best understanding of rehydration process (I), which used cycles of programmed pressurised soaks, a numerical simulation was obtained using the ANSYS software program, which allowed an evaluation of the water exchange between the beans and mass of water as well as the pressure distributions during process (I). The time-dependent moisture distribution was numerically determined at given time intervals using the finite element model. For a certain value of the initial moisture content and proper diffusion coefficient of the material, the analysis evaluated the time-dependent moisture distribution at the nodes. A similar approach has been used to determine the moisture and temperature fields during the cooling process in the cryo-maceration of grapes (Carillo et al., 2011).

In a finite element approach, an estimated value for D is supplied to Eq. (1), and the MR values are numerically determined for specified locations at given time intervals. In applying this approach, the following assumptions were made for the individual beans:

1. The diffusion coefficient is independent of the moisture concentration.
2. The beans are isothermal, and heat transfer during the hydration process is neglected.
3. The beans are homogeneous and isotropic.
4. Throughout the hydration process, the surface of a bean maintains saturation of the moisture content, M_e (the boundary condition).
5. The initial moisture content of the beans is constant and uniformly distributed within a bean, M_i (initial condition).

The geometry of a bean was considered an ellipsoid. For modeling a bean, one quarter of an ellipse was used in a time-dependent axisymmetric two-dimensional (2D) analysis. The grids for each

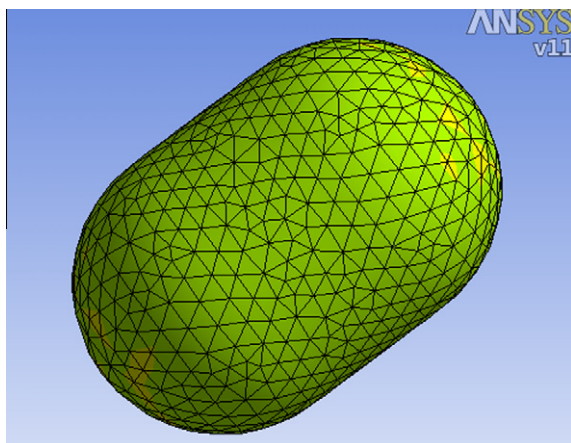


Fig. 2. Finite element grid for a single bean.

bean consisted of 370 elements with 850 nodes (Fig. 2). The commercial finite element analysis software ANSYS (Rel. 13.0) was used to evaluate the instantaneous moisture distribution at the nodes. The coefficient of diffusion estimated by fitting Eq. (2) to the experimental data was provided to the software, and the moisture content of each node was calculated at one-second time intervals. The overall moisture content for a bean was also calculated at every time point (20 min), which was determined by averaging the moisture content at the nodes. All of these data were obtained for hydration process (I).

2.6. Peleg model

To simplify the mode of water absorption by food materials, a two-parameter, non-exponential empirical equation was proposed that later became known as the Peleg equation (Peleg, 1988). The Peleg model is one of the most frequently used empirical models for estimating the overall moisture content M as a function of time t during a moisture absorption process and is defined as follows:

$$M = M_i + \frac{t}{k_1 + k_2 t} \quad (4)$$

$$\text{As } t \rightarrow \infty \quad M_e = M_i + \frac{1}{k_2}$$

where M is the overall moisture content at time t during a moisture absorption process, M_i is the initial moisture content (decimal, dry basis), M_e is the equilibrium moisture content (decimal, dry basis), and k_1 and k_2 are the two constants known as the Peleg rate constant (h^{-1}) and Peleg capacity constant ($\%^{-1}$), respectively (Abu-Ghannam and McKenna, 1997).

These two constants must be determined for a particular product under a particular moisture absorption process. We used the Peleg model to estimate the overall moisture content of the beans during the hydration process. The data for overall moisture contents at specified time points were used as input to the curve-fitting toolbox of the MATLAB commercial software, and the two constants of the Peleg model were determined.

2.7. Comparison and evaluation of the models

The goodness of the adjustments made to the finite element model, analytical solution and Peleg model was evaluated by calculating the coefficient of determination (R^2) and root mean square error (RMSE) using the following formulae:

$$R^2 = \frac{(\sum MR_e MR_p)^2}{\sum MR_e^2 \sum MR_p^2} \quad (5)$$

$$RMSE = \sqrt{\frac{\sum (MR_p - MR_e)^2}{n}} \quad (6)$$

where MR_e and MR_p are the experimental and predicted moisture ratios, respectively. A model having a high value of R^2 (close to 1) and low value of RMSE (close to 0) is considered a well-fitted model.

3. Results and discussion

The results obtained from the experimental tests for the two systems of rehydration, i.e., (I) and (T), and compared in this study are reported below. The results obtained via numerical analysis for process (I) are also discussed.

Table 1
Some physical characteristics of the experimental beans.

Min	L_1 length (mm)	L_2 width (mm)	L_3 thickness (mm)	GMD = D (mm)	Sphericity ϕ	Sphericity factor f_e
0	11.07 ± 1.68	4.15 ± 1.11	3.18 ± 1.02	3.63 ± 1.09	0.818 ± 0.03	0.830 ± 0.02
20	12.05 ± 1.72	5.01 ± 1.25	4.03 ± 1.06	4.49 ± 1.18	0.846 ± 0.06	0.868 ± 0.04
40	12.33 ± 1.85	5.56 ± 1.37	4.21 ± 1.14	4.83 ± 1.29	0.857 ± 0.08	0.872 ± 0.07
60	12.71 ± 1.98	5.90 ± 1.52	4.43 ± 1.20	5.11 ± 1.42	0.863 ± 0.12	0.877 ± 0.11

Data are expressed as the mean ± SD. GMD: geometric mean diameter.

3.1. Hydration using the cyclically pressurised soaking process (I): results

The measured physical characteristics of the beans before and after hydration process (I) are presented in Table 1. From their dimensions, it is possible to deduce that the bean's geometry is nearly ellipsoid and retains its general shape after the hydration process. However, due to a relative increase in the thickness and width of the beans resulting from moisture gain, the sphericity ϕ of the beans increased from 0.818 to 0.863. This increase in dimensions was due to the migration of water between and within the bean cells, which causes an overall swelling of the beans. Ahromrit et al. (2006) provides detailed discussion on the changes in dimensions during the hydration process.

During the pressurised soaking process for beans, there is a rapid initial water uptake most likely due to the filling of capillaries on the surface of the seed coats and hilum (Hsu et al., 1983). As the process of water absorption proceeds, the rate begins to decline due to the effect of the increased extraction of soluble material from the beans and the filling of capillaries and intermicellar spaces with water (Plhak et al., 1989). Consequently, the amount of water absorbed in the later soaking stages is minimal until an equilibrium is attained, signalling the maximum water capacity of the legume.

The principle element controlling the rate of water absorption during legume soaking is the seed coat. In this study, the pressurised soaking process (I) was found to have a significant effect on increasing the hydration rates of cannellini beans, and the equilibrium conditions were thus attained in much shorter times compared with the soaking (only) process (T). Cyclically pressurised soaking has the advantage of enhancing the plasticity of the seed coat and eliminating the presence of hard-shelled beans that fail to imbibe water during soaking by alternating the pressure values (0–10 bar). The rapid changing of pressure values (0–10 bar) produces impulsive forces that allow the opening of new channels within the beans through which the water flows, increasing its overall humidity. That does not occur when the pressure value remains constant during the process because it does not induce the formation of new channels within the beans. The experimental volume and weight changes of beans during hydration processes (I) and (T) are shown in Figs. 3 and 4. During the first 20 min of hydration process (I), the volume and weight of beans increased rapidly from 70 to nearly 140 ml and from 100 to nearly 160 g, respectively.

Then the rate of water absorption gradually decreased until saturation values at 170 ml, and 195 g was reached at 60 min. Thus, under the conditions examined, it requires approximately 60 min for the beans to reach their saturation moisture level. The moisture percentages, both on wet and dry bases prior and after soaking, absorbed by the beans are presented in Table 2.

We observed that the rehydration times of the cannellini beans with process (I) were approximately 60 min (mean value) during all of the tests performed. The volume increase of the cannellini beans during process (I) was much greater than that obtained with the traditional process (T). Within 20 min of rehydration using pro-

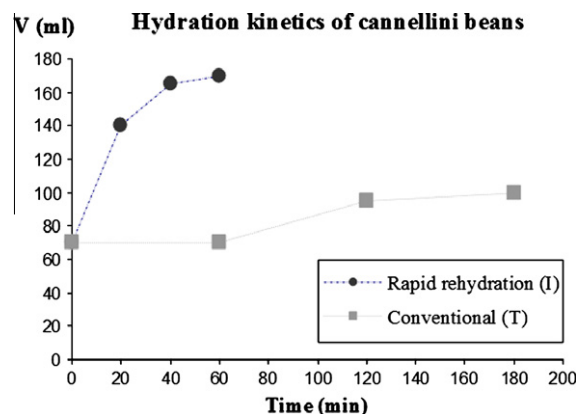


Fig. 3. Hydration kinetics of cannellini beans throughout the process of rapid rehydration (I) or process of slow rehydration (T) (volume as a function of time). After 12 h, curve (T) reached the same final value that curve (I) reached after 60 min.

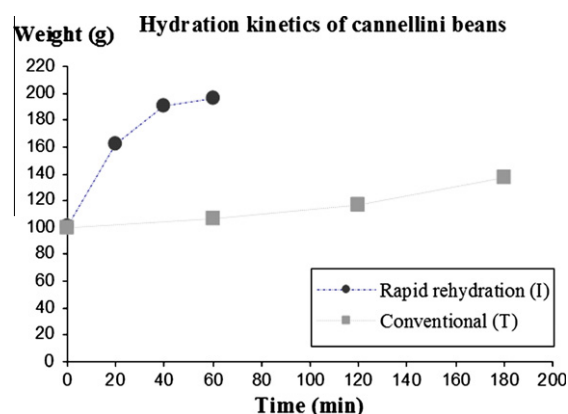


Fig. 4. Hydration kinetics of cannellini beans throughout the process of rapid rehydration (I) or process of slow rehydration (T) (weight as a function of time). After 12 h, curve (T) reached the same final value that curve (I) reached after 60 min.

Table 2
Humidity values detected on a wet basis and on a dry basis during the process (I).

Time (min)	W_p (g)	M wet (%)	M dry (%)
0	100	0	0
20	160	0.468	0.88
40	191	0.555	1.235
60	195	0.564	1.294

cess (I), the increase in weight attained was nearly double the weight obtained over 3 h using traditional hydration process (T).

The “sphericity factor” (f_e) for an average bean was calculated to be between 0.830 and 0.877. Using Eqs. (2) and (3), the coefficient of diffusion D_e was calculated to be within the range of 4.7×10^{-7} –

Table 3
MR values (dry basis) determined by experimental, numerical and Peleg methods.

Time (min)	W _p (g)	MR exper.	MR numerical	MR Peleg
0	100	0	0	0
20	160	0.629	0.638	0.616
40	191	0.947	0.989	0.855
60	195	1	1	1

$2.17 \times 10^{-9} \text{ m}^2/\text{s}$ in the operative condition of cyclically pressurised soaking. This computational procedure was used by Gaston et al. (2004), who calculated the coefficient of diffusion for wheat kernels to be between 1.35×10^{-11} and $6.88 \times 10^{-11} \text{ m}^2/\text{s}$ in the soaking process (T process), and by Bakalis et al. (2009), who estimated the coefficient for rice to be $7 \times 10^{-10} \text{ m}^2/\text{s}$ in a soaking condition (T).

The higher D_e calculated for beans indicates that the beans in the cyclically pressurised soaking conduction (I) absorbed water at a higher rate than wheat and rice grains in soaking condition (T). The obtained coefficient of diffusion was supplied to Eq. (1), and this equation was solved using the finite element approach to estimate the moisture distribution within the beans (at chosen time intervals). The MR values calculated (on a dry basis) from the experimental data on moisture absorption and their different fitted models are presented in Table 3.

3.2. Sensory analysis results

From the sensory point of view, the “consumer test” that was performed showed that a group of regular bean consumers (18 individuals: 9 men and 9 women) to whom anonymous samples of product were submitted using the triangular test method did not successfully identify which samples were prepared using the Naviglio extractor in a meaningful manner. For this number of tasters, the number of correct answers, i.e., the number of individuals

correctly identifying which of the three samples was different, must be ≥ 10 for the results to be significant at the 95% confidence level (i.e., an error factor α equal to 0.05).

The tasters provided only three correct answers; based on these results, we can conclude that the products obtained with the two systems have similar texture characteristics. The data obtained in the preference tests, however, suggest that the samples prepared with the Naviglio extractor, although there were fewer of them, had an average preference value higher than that obtained with the traditional method (5.13 versus 7). These preliminary results showed that the two systems of hydration yielded analogous results and can therefore be considered equivalent in terms of texture. Furthermore, as the tests performed have demonstrated, the Naviglio extractor can also be used for the simultaneous aromatisation of legumes. The samples were taken from the hydration room and tasted, and the passage of the aroma into the legume was detected. This is explained by the extractor having a double functionality: the depressive phase of the extractor provokes the passage of many active ingredients, including aromatics, such as the spices, in the hydration water. The high pressure forces both water and aromatics into the beans, thus moisturising and aromatising the beans simultaneously.

3.3. Microbiological analysis results

The results of the microbiological tests performed on the beans are reported in Tables 4 and 5. The data obtained provide evidence that the hydration process performed with the Naviglio extractor resulted in the development of a lower microbial load comparison with that obtained using the traditional process. This can be considered a great qualitative advantage; in fact, a blander sterilisation treatment is required for a product with a ten-fold smaller microbial load, with consequent economic savings for the global process while maintaining the high quality of the final product.

Table 4
Microbiological parameters of beans produced by the traditional process expressed as CFU/g.

Traditional process (T)									
Microbiological parameter	Stages of sampling								
	Raw material		After rehydration		After the canning process		After sterilisation		
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Total bacterial count	864	150.5	9×10^5	8×10^4	6.3×10^4	1.2×10^4	<10	1	
<i>Faecal streptococci</i>	<10	1	17.5	9.5	1420	148	<10	1	
Sulphite-reducing <i>Clostridia</i>	13.5	5.8	<10	1	<10	1	<10	1	
Total coliforms	186	38	1.4×10^5	1.2×10^4	994	293	<10	1	
<i>Escherichia coli</i>	<10	1	1260	181.5	728	156	<10	1	
Yeasts and molds	144	45.5	92.5	44.5	<10	1	<10	1	
<i>Salmonella</i> spp.	ND		ND		ND		ND		

Table 5
Microbiological parameters of beans produced using the Naviglio extractor expressed as CFU/g.

Process using the Naviglio extractor (I)									
Microbiological parameter	Stages of sampling								
	Raw material		After rehydration		After the canning process		After sterilisation		
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Total bacterial count	864	150.5	1.02×10^6	6.9×10^4	3900	548	<10	1	
<i>Faecal streptococci</i>	<10	1	<10	1	12.5	5	<10	1	
Sulphite-reducing <i>Clostridia</i>	13.5	5.8	<10	1	<10	1	<10	1	
Total coliforms	186	38	6.8×10^4	1.9×10^4	182	111	<10	1	
<i>Escherichia coli</i>	<10	1	226	78	190	77	<10	1	
Yeasts and molds	144	45.5	206	36.5	<10	1	<10	1	
<i>Salmonella</i> spp.	ND		ND		ND		ND		

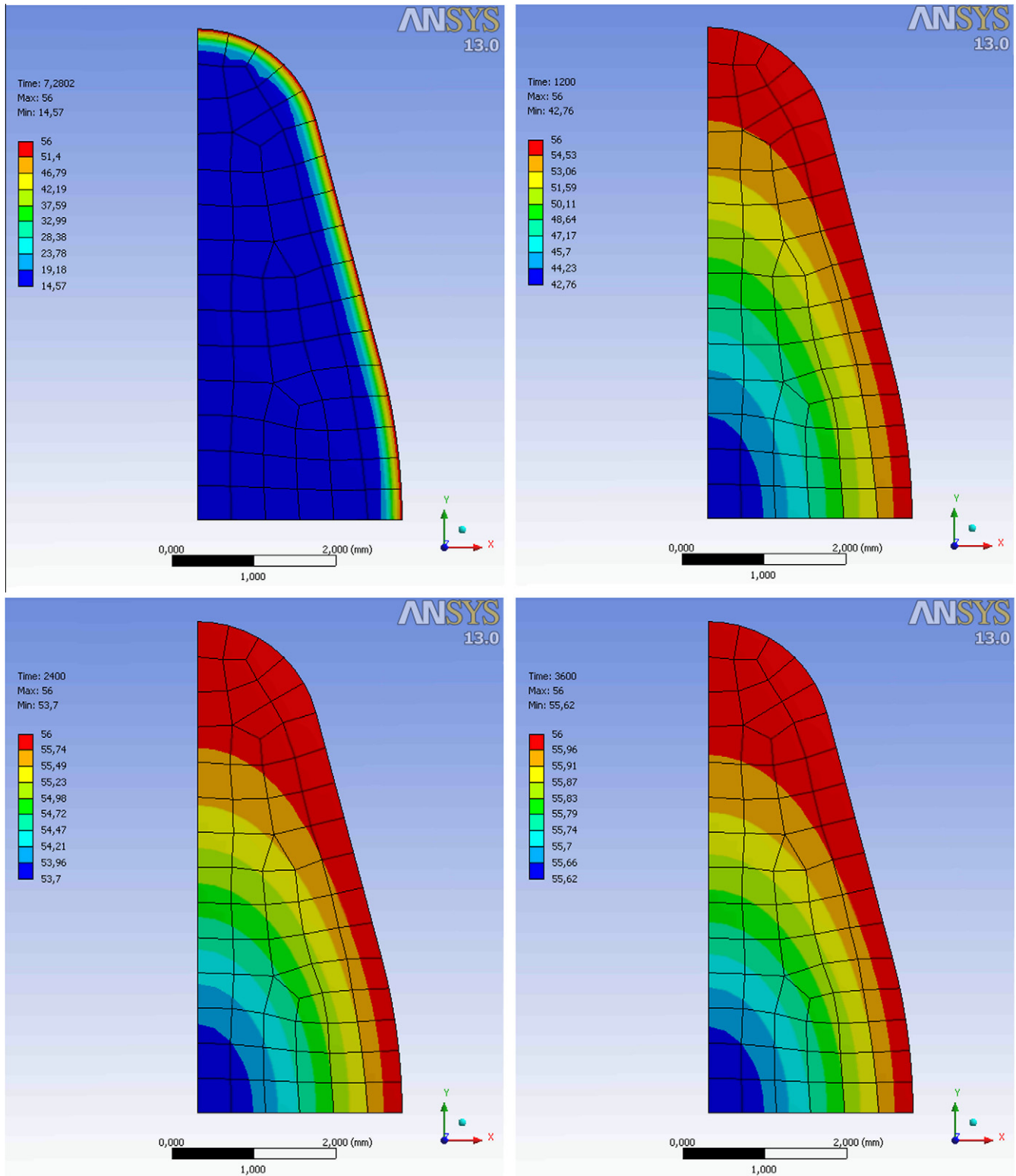


Fig. 5. Typical distribution of moisture in beans during the hydration process, as determined by finite element analysis at (a) 0 min, (b) 20 min, (c) 40 min, and (d) 60 min. The side bar indicates the level of moisture content (%) within a region of a bean at a given time.

3.4. Numerical simulation results

It was possible to evaluate the kinetics of hydration of the beans as a function of time using a numerical simulation of the considered model.

The MR values calculated from moisture absorption using the experimental data, numerical simulation and Peleg model are presented in Table 3. The predicted MR values calculated using the finite element method were similar to those determined with the Peleg model. As shown in Table 3 the finite element model slightly

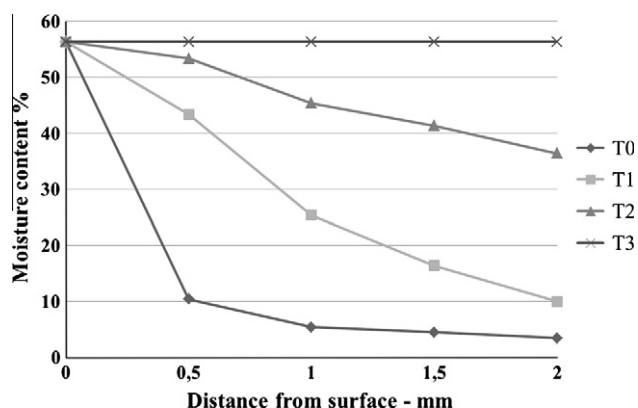


Fig. 6. Moisture content at various points along the cross section from the surface to the centre (r bean = 4 mm).

Table 6

Estimated coefficients of determination (R^2) and root mean square errors (RMSE) for the three models.

Model	R^2	RMSE
Finite element	0.999	0.0303
Peleg	0.988	0.0657

overestimated the MR values for the intermediate stages, with values of $t = 20$ and $t = 40$ min. The Peleg model generally underestimated the MR values. The visualisation of finite element predictions for the moisture content is presented in Fig. 5, with values of 0, 20, 40, and 60 min after the commencement of the hydration process. Fig. 5 shows a gradual migration of the water from the surface to the centre of a bean. Theoretically, the finite element model, as shown in Fig. 5, indicates that even at the end of the hydration process, the moisture content throughout the bean is not uniform.

In a practical sense, as shown in Fig. 5, moisture content reached its saturation level, ($M_e = 0.564$, on wet basis, with a final total weight of 195 g) after 60 min. Fig. 6 indicates that the moisture gradient within a bean is high during the initial stages of the hydration process and that the gradient decreases with the progress of hydration process. After 60 min, the moisture content is nearly uniform and reaches a saturation level at all nodes. The shortcoming of the finite element model, with respect to the Peleg model, is that the former relies on a coefficient of diffusion developed by other sources, i.e., analytical modelling or experimental values.

Using the experimental data for the moisture content of beans at different time intervals and the curve-fitting toolbox of the MATLAB commercial software, the constants k_1 and k_2 , which had values of $k_1 = 0.1738$ and $k_2 = 0.894$, were determined using the Peleg Equation (4). The following model was obtained based on the Peleg formula:

$$M = 0.176 + \frac{t}{0.1738 + 0.894 \cdot t} \quad (7)$$

The Peleg model, as shown in Table 3, underestimated the MR values at the intermediate stages of the hydration process. The Peleg model is inferior to finite element models for predicting the water absorption by beans in comparing the R^2 value. The R^2 and RMSE values calculated for the finite element and Peleg models are shown in Table 6. The R^2 value was 0.999 for the finite element model. However, the finite element model slightly overestimated the MR values of the beans at intermediate stages, while the Peleg

approach generally underestimated these values (Table 3). The superiority of the finite element model is due to its power to predict moisture content changes at specified nodes within a bean rather than estimating an overall moisture transfer for a bean.

4. Conclusion

The results obtained demonstrate that the process of cyclically pressurised soaking accomplished with the Naviglio extractor (a rapid dynamic solid–liquid extractor) can be advantageously used in the process of bean rehydration. The pressure cycles to which beans are subjected to rehydrate the product increases the penetration of the liquid inside the pulses and thus reduces the hydration time approximately ten-fold. Our results showed that not only was processing time greatly reduced compared with traditional soaking but also that microbial growth was slowed. After approximately 1 h of treatment, the legumes reached an average of twice the weight and volume compared with prior to treatment, were not subject to an appreciable disruption and maintained satisfactory entirety and texture. The product obtained at the end of the process was visually better (i.e., more intact) than that obtained from traditional soaking. In addition, the first tests of microbiological analysis, as described above, showed that it is possible to reduce the time of product sterilisation and thus obtain considerable economic savings. Furthermore, it was observed that the Naviglio extractor can also be used for the simultaneous aromatisation of legumes. Therefore, the use of the Naviglio extractor is a quick alternative to the traditional procedures used for hydrating legumes. In addition, the FEM analysis indicated that the finite element approach, which is based on Fick's law, fits well with the experimental data. However, the RMSE values calculated for the finite element model were slightly higher than the experimental values. The values obtained using the Peleg model were lower than those obtained with experimental tests, and the finite element model predicted the total moisture content for the bean as a function of time. The finite element model was also able to predict the distribution of moisture in any given point within the bean as a function of time during the soaking process.

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