Received: 15 November 2022 | Revised: 12 April 2023 | Accepted: 14 April 2023

DOI: 10.1111/jtxs.12764

RESEARCH ARTICLE

Journal of Texture Studies WILEY

Mechanical approach for the evaluation of the crispiness of food granular products

Imen Boudina[1,2] | Michèle Delalonde[2] | Laurène Koegel[1,2] | Isabelle Maraval[2] | Nelly Forestier-Chiron[2] | Romain Domingo[2] | Julien Ricci[2] | Tahmer Sharkawi[1] | Eric Rondet[2]

[1]ICGM, CNRS, ENSCM, Université Montpellier, Montpellier, France

[2]QualiSud, Université de Montpellier, Avignon Université, CIRAD, Institut Agro, IRD, Université de la Réunion, Montpellier, France

Correspondence
Eric Rondet, QualiSud, Université de Montpellier, Avignon Université, CIRAD, Institut Agro, IRD, Université de la Réunion, Montpellier, France.
Email: eric.rondet@umontpellier.fr

Funding information
Algerian Ministry of High Education and Scientific Research

Abstract

Crispiness of food products is a key parameter for consumer acceptance. Available methods to evaluate this attribute are subjective and have limitations. They are particularly difficult to implement when granular products are considered. The present study aims to provide a physical characterization of the crispiness of food granular products (gari and grinded corn flakes) based on the compression cycle modeling and the determination of the Py (yield pressure) parameter of the Heckel model. High Py values attributed to the brittle behavior, are indicative of product crispiness. Furthermore, Py parameter showed sensitivity to the plasticizing effect of water. This developed physical method was validated through sensory analysis and acoustic measurements which are both considered as reference methods for crispiness evaluation. The brittle/plastic behavior attributed to crispy/non crispy products respectively was confirmed through image analysis using X-ray microcomputed tomography. The latter made it possible to distinguish the brittle from the plastic behavior through the particle size distribution evolution. This work suggests that the Py value is a relevant indicator for the crispiness evaluation of granular products. This physical characterization is expected to contribute in food engineering as an alternative method for granular products crispiness in a simpler and a more objective way.

KEYWORDS
brittle, compression cycle, crispiness, granular materials, yield pressure

1 | INTRODUCTION

Food texture is one of the most important and critical parameters for consumer acceptance and perception. Among textural characteristics, crispiness is a greatly sought attribute which is expected for many food products such as fries, chips, breakfast cereals, breadcrumbs, appetizer cakes, as well as other products less known and specific to some countries such as gari in west of Africa and Brazil (Escobar et al., 2021).

According to Chen et al. (Chen et al., 2005), "crispy" is the most frequently used word describing a textural attribute. There is a general agreement that "crispy" and "crunchy" sensations are related to the fracture properties of food materials (Luyten et al., 2004; Roudot, 2004), however, there is no clear distinction between the

This article was published on AA publication on: 11 May 2023

meaning of these two attributes (Luyten et al., 2004). "Crispy" is sometimes used to characterize attributes described by others as "crunchy" (Chauvin et al., 2008) and vice versa. Considering the mechanical properties, crispy and crunchy food products are difficult to deform plastically, they behave as a brittle material that breaks easily. Difference between crispy and crunchy could lies in the fact that a series of successive mechanical events is required for crunchy behavior, but a single fracture event may serve for the crispy products (Luyten et al., 2004). These mechanical events produce high-frequency sounds for crispy products, and low frequency ones for crunchy products (Luyten et al., 2004; Tunick et al., 2013). Nevertheless, the crispiness perception varies widely depending on individuals and country of origin (Bourne, 2002). One of the most important factors that can affect the crispiness of food products is their water content (Primo-Martín & Van Vliet, 2009; Raleng et al., 2019; Sauvageot & Blond, 1991; Silva-Espinoza et al., 2020; Silva-Espinoza et al., 2021). Its increase can dramatically decrease the crispiness of the product as a result of the change in glass transition temperature affecting the brittle-ductile transition (Li, 2010).

The most popular way to measure the crispiness or crunchiness is the sensory panel test based on human perception. Several studies were reported using a sensory descriptive evaluation on potato chips (Salvador et al., 2009), corn flakes (Andreani et al., 2020; Chaunier et al., 2005; Dias-Faceto et al., 2020) and other dry foods (Andreani et al., 2020; Dias-Faceto et al., 2020). However, the sensory analysis presents some limitations: it is expensive, time consuming and subjective to panel perception, consumers' cultural background (Lawless & Heymann, 1999; Roudot, 2004), and terminologies that are used to describe the attribute (Hanada, 2020; Lawless & Heymann, 1999).

Texture analysis seems to be the most common instrumental technique to measure the crispiness or crunchiness objectively and efficiently. It lies on the evaluation of structural properties determined by mechanical deformation based on the resistance to compression. Nevertheless, each compression probes and operating conditions can differently solicit the product, and identify several food textural parameters. This makes it difficult to have standard instrumental measurement method (Andreani et al., 2020; Kilcast, 2004). Correlating the latter with sensory evaluation may increase the efficiency and accuracy of texture measurement (Gilbert et al., 2013). Concerning acoustic evaluation of food texture, the limitation lies in the fact that it provides a series of signals that are difficult to interpret. In some cases, the data should be filtered in a way to eliminate the noise associated to the texture analyzer. Furthermore, the microphone used must be sensitive enough to detect all the sounds released by the food material. The perception of the texture associated with the acoustic measurements has been reported in several studies and generally correlated with previous sensory analysis (Andreani et al., 2020; Çarşanba et al., 2018; Chen et al., 2005; Dias-Faceto et al., 2020; Jakubczyk et al., 2017; Salvador et al., 2009). However, these studies differ in terms of the protocols used which are dependent on the nature of the analyzed food product.

The evaluation of crispiness or crunchiness is even more complex when considering food granular materials, which are being increasingly used by the food industry (Bhandari, 2013). There are many examples of these food products being consumed for their textural attribute: breadcrumbs that are sprinkled on some food products so as to increase the crispiness sensation, preparations based on brewer's yeast and cereals sprinkled on dishes or salads extemporaneously, breakfast cereals, cassava powders called gari consumed as snacks or sprinkled on stews particularly sought after by the west African and Brazilian consumers (Escobar et al., 2021).

To the best of our knowledge, reported studies about physical and sensory crispiness or crunchiness characterization of food products, focus on large non granular matrix such as corn-based snacks (Diaz et al., 2015), French fries (Gouyo et al., 2021) and cereal extrudates (Zhang et al., 2014). No attention has been paid to the physical evaluation of crispiness or crunchiness of food granular samples. Due to difficulties in sample positioning but also to statistical significance of the results, small particles whose diameter is lower than a few millimeters and whose forms are irregular cannot be investigated individually when considering mechanical or acoustical properties. To overcome this limitation, a possible approach consists in measuring the acoustical and mechanical behavior at the scale of a particle granular bed. The mechanical behavior can be measured under compression stress to obtain parameters linked to the deformation at the individual particle scale. These parameters are obtained after stress–strain curves modeling using various models such as Heckel, Walker, Kawakita models (Heckel, 1961; Walker, 1923) in a suitable stress domain. Heckel model, developed initially for metallic powders, is the most popular to model the compression. It makes it possible to measure the mean yield pressure (Py), given by the inverse value of the curve slope in the relation between $Ln\ (1/n)$ and P (where n and P are respectively the porosity of the granular material bed and the uniaxial pressure) (Heckel, 1961). Py gives information about the mechanical properties of the particles constituting the granular material bed. High values of Py are associated with brittle materials and, lower values are representative of a plastic material (Benabbas et al., 2021; Hooper et al., 2016; Özalp et al., 2020). The presence of a Py threshold value marking the transition between the plastic and brittle behavior remains very controversial (Hooper et al., 2016; Sonnergaard, 1999). In the pharmaceutical industry, Py is used to evaluate the mechanical behavior of particles during tablets compression. In this area, the study of the variation of the Py value as a function of the compression velocity during uniaxial compression, allows to determine a parameter called the strain rate sensitivity (SRS) whose value enables to discriminate between brittle and plastic granular materials. The deformation of plastic materials is more sensitive to the compression velocity which results in greater variations in the measured Py value, compared to brittle materials. Thus, the SRS will be higher for plastic materials than for brittle ones (Katz & Buckner, 2013; Kim et al., 1998).

This study aims to develop a physical test for the characterization of the crispiness or crunchiness of food granular samples, based on the use of uniaxial compression tests and the modeling of stress/strain curves using Heckel model. This allows to obtain, for food granular samples, Py values whose relative intensity with respect to

reference materials (microcrystalline cellulose as a plastic model [Benabbas et al., 2020] and sucrose as a brittle granular material model [Duncan-Hewitt & Weatherly, 1990]) could allow to discriminate crispy or crunchy food products (brittle) from non-crispy or non-crunchy (plastic) ones. Heckel modeling applied at two compression velocities also allows to determine the SRS value, so as to identify the material dependence on its compression velocity. The proposed work focused on determining these two parameters (Py and SRS) as relevant indicator of the crispiness/crunchiness of food granular samples (sucrose, gari, grinded corn flakes), and their ability to highlight the plasticizing effect of water. These results were supported by 3D imaging obtained by x-ray microtomography (XMT). XMT is a non-destructive method that provides a 3D image for the inner and the outer structure of the sample by measuring the attenuation of x-rays beam passing through it at different angular orientations (Landis & Keane, 2010). Following scanning of the object, a backprojection algorithm (Feldkamp et al., 1984) combines radiographic projections in order to obtain two-dimensional sections of the sample, which thereafter allows to reconstruct the sample in three dimensions. The final image is composed of voxels having different gray levels corresponding to different density values (Withers et al., 2021). XMT seems to be a good non-destructive alternative for the classical granulometric analysis methods such as SEM, laser diffraction and sieving. Nevertheless, and contrary to XMT, these last methods cannot be applied on cohesive compacts. XMT allows to identify the mechanical behavior (brittle vs. plastic) of granular materials, by following up the evolution of the particle size distributions before and after compression based on the equivalent volume sphere diameter (ESDv) (Boudina et al., 2021). Finally, the results were compared with those obtained from acoustic and sensory evaluation, which served as reference methods to determine the crispiness or crunchiness of food products.

2 | MATERIALS AND METHODS

2.1 | Materials

Four granular samples were used in this work. Powders of extra pure sucrose (E. MERCK AB, Stockolm), and microcrystalline cellulose (microcrystalline cellulose VIVAPUR® 102, JRS Pharma), known to have a brittle and plastic behavior respectively, were used as reference materials. Gari obtained from Benin local production (Escobar et al., 2021) and commercial corn flakes cereals (U, Rungis cedex. France) were used as food granular materials. Gari was chosen for its crispy attribute sought for certain consumption modes. Corn flakes, previously manually grinded into coarse powder, was expected to have a significantly higher crispiness.

2.2 | Methods

2.2.1 | Granular materials properties

Except sucrose powder, powder samples were sieved so as to remove the small particles for sakes of homogeneous particle size distribution between the different granular materials. Sieving was carried out using a sieve shaker Retsch AS 200 Control. The sieving time was set to 10 min for each powder with an amplitude of 60%. The limits for the sieving diameters were determined according to the particle size characteristics of the native powders. Microcrystalline cellulose was sieved between 150 and 300 μm, gari up than 300 μm and corn flakes between 300 and 710 μm. Particle size distribution is then obtained by laser diffraction method and gives the following values of (d_{50} – span = $[d_{90} - d_{10}]/d_{50}$) for the different granular materials: sucrose (378–1.63 μm); microcrystalline cellulose (224–0.73 μm); grinded corn flakes (499–0.9 μm) and gari (508–0.83 μm).

Tapped porosity (Table 1) was measured on each granular material according to the standard of European Pharmacopeia (Ph. Eur 10 ed.) in order to determine the minimal porosity which can be reached after 2500 taps (Schüssele & Bauer-Brandl, 2003). The tapped volume obtained was used to calculate the tapped porosity which constitutes the threshold from which any decrease in porosity under the effect of a compression is no longer linked to particle rearrangement but to their deformation. The determination of this tapped porosity constitutes a first guide to validate the choice of the range of application of Heckel equation.

True density (ρ^*) (Table 1) of all granular samples was measured in triplicate using helium pycnometer (Multi Volume 1305, Micromeretics). It is evaluated after the powder was manually micronized with a

TABLE 1 Results of water contents, true densities, and tapped porosities for studied granular samples.

		Water content (db) (%) ± SD	True density (g cm^{-3}) ± SD	Tapped porosity ± SD
Native granular materials	Sucrose	0.1 ± 0.0	1.58 ± 0.03	0.38 ± 0.00
	Microcrystalline cellulose	4.6 ± 0.3	1.56 ± 0.02	0.73 ± 0.00
	Gari	12.6 ± 0.3	1.40 ± 0.17	0.61 ± 0.00
	Grinded corn flakes	3.4 ± 0.3	1.47 ± 0.09	0.59 ± 0.08
Modified granular materials	Dried gari	0 ± 0.0	1.47 ± 0.09	0.60 ± 0.02
	Humidified grinded corn flakes	8.9 ± 0.0	1.45 ± 0.06	0.53 ± 0.03

mortar and a pestle in order to remove any occluded porosity that may be present.

2.2.2 | Modification of the water content of the granular samples

Dry basis water content (w) of granular samples was measured in a moisture analyzer (Sartorius MA37). Table 1 depicts the water content values corresponding to the studied granular samples. The values vary in a fairly wide range of water content. The lowest being for sucrose (0.1%) and the highest for gari (12.6%). This high value for gari is in line with the maximum standard required for gari according to the Codex Alimentarius (CODEX STAN 151-1989), which recommends a maximum water content of 12%. Microcrystalline cellulose has an intermediate value of 4.6%. The latter is in line with the monography of European Pharmacopeia 10th Edition which sets a maximum value of 5%. Considering the plasticizing effect of water and its impact on crispiness, specific water content for gari and grinded corn flakes was set to evaluate the sensitivity of some parameters resulting from the analysis of the compression cycle to the water content.

A fraction of the batch of grinded corn flakes which had an initial water content of 3.4% was humidified by introducing the sample into a vessel (during 26 h) in which the relative humidity (RH) was maintained at 75% with a NaCl saturated solution (Pro Analysis, Merck KGaA). Water content values of 8.9% were obtained for the grinded corn flakes at the end of the process.

Conversely, a fraction of the batch of gari which had an initial water content of 12.6% was totally dried (in order to obtain the dried gari sample) in a ventilated oven for 96 h at 75°C until constant mass was attained. During the drying period, several samples with different water contents (2%, 4%, 5.5%, 7.6%, 8.9%, and 11.7%) were collected to obtain gari with water contents between the initial gari ($w = 12.6\%$) and the dried gari ($w = 0\%$). Samples with higher water contents (20%, 23.8%, and 25%) were obtained by wetting the native gari using different amounts of water.

2.2.3 | Study of the behavior of granular samples during compression

Experimental setup

Uniaxial compression tests were used to evaluate the mechanical properties in an attempt to correlate the results to the crispiness of food granular materials. The granular material compression is performed using a compression simulator Styl'One Evolution (Medelpharm, France, 0.01–50 kN) equipped with force sensors using 11.28 mm flat round punches. The granular material mass introduced into the die varied between 400 and 600 mg, depending on the granular material density, so as to obtain a height of 3.5 mm for the elaborated compacts. The evolution of the granular bed deformation and densification as a function of the normalized applied stress was evaluated.

Compression cycle setting (V-shape cycle) was chosen in order to obtain a constant displacement velocity during compression. The punch displacement in the die was collected using Analis® (Medelpharm, France) software.

Heckel modeling analysis (Py and SRS index)

For Heckel modeling (Heckel, 1961), three compacts of the studied materials were used. Heckel mean yield pressure (Py) is given as the reciprocal value of the slope of the curve obtained according to the following equation:

$$Ln\left(\frac{1}{1-\frac{m}{\rho_s^* V}}\right) = KP + A \tag{1}$$

In the equation, $1-\frac{m}{\rho_s^* V}$ is the porosity (n) of the compressed granular material bed, ρ_s^* is the material true density (g cm^{-3}), V is the compact volume (cm^{-3}) which decreases during compression, and m (g) is the introduced granular material mass. P (Pa) is the compaction pressure; K is the slope of the linear part of the plot (with the best R^2 fit) and A is the Y-axis intercept with the linear part of the Heckel plot.

In the literature, a significant attention has been paid to the analysis of the Heckel data, especially to identify the appropriate linear part of the Heckel plot to calculate the Py (Katz & Buckner, 2013; Rue & Rees, 1978; York, 1979). As each granular material responds differently to the applied stress during compression, the choice of the linear part of the Heckel plot to calculate the Py, was based on a specific porosity range corresponding to porosity values lower than that obtained for the close random packing ($n = 36\%$). For polydispersed and non-spherical media such as most granular materials, we can assume that this state is reached for porosities lower than those obtained under 2500 vibrations (tapped porosity, Table 1). Thus, for a better safety marging, Py was calculated on the linear part of the Heckel plot starting from 25% of porosity. The lower value of the porosity range on which Py is calculated on the Heckel plot is 15%. This value is the limit from which the Heckel plot can lose its linearity because the porosity variation is related to the deformation of a medium which is no longer made of discrete particles but of a continuous compact. So as to normalize Py calculation, it is thus calculated on a 25%–15% porosity range whatever the product (Figure 1). In this part of the plot, the decrease in porosity is only due to deformation/breakage of the particles. The first rearrangement phase is excluded.

The Py of the Heckel model was used to calculate the SRS (Roberts & Rowe, 1985) in order to compare the mechanical properties of materials. The SRS was calculated following Equation (2) where Py_1 and Py_2 are obtained from two uniaxial compression tests characterized with opposite punch velocities of 0.033 mm/s (Py_1) and 300 mm/s (Py_2).

$$\text{SRS}\,(\%) = \frac{Py_2 - Py_1}{Py_2} \times 100 \tag{2}$$

In pharmaceutical powder compression, the SRS allows to identify plastic versus brittle materials by identifying a time-dependent/non-

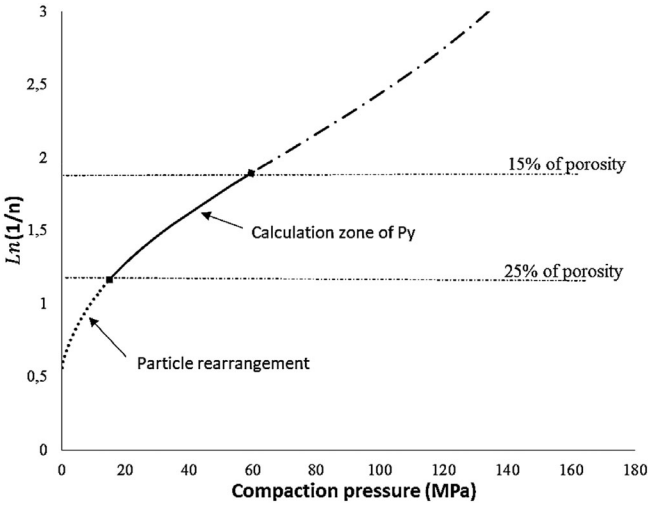

FIGURE 1 Schematic diagram representing the different compression phases and the modeled part of the Heckel-plot for the calculation of the Py.

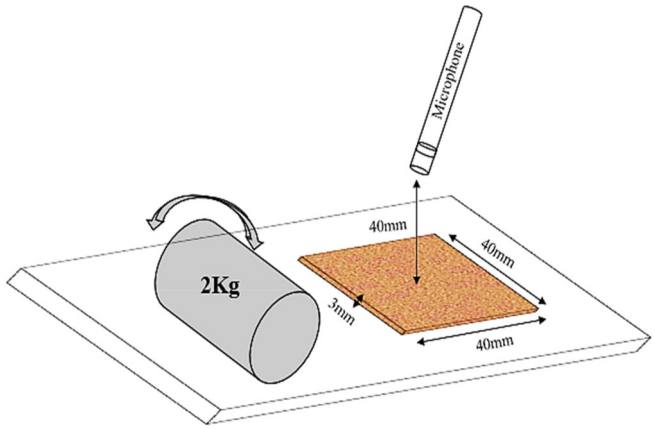

FIGURE 2 Schematic diagram of instrumental acoustic setup.

dependent behavior, when a stress is applied. This ratio has been developed using a compression simulator that can reach two opposite punch velocities. With the V-shape cycle used in this study, the lowest and highest velocities achievable were 1 mm s^{-1} (Py_1) and 500 mm s^{-1} (Py_2), respectively.

2.2.4 | Sorption isotherms

Water vapor sorption kinetics were performed at 25°C using a controlled atmosphere micro-balance (IGASORP-CT, Hiden Isochema), which enables recording the water vapor uptake of the materials as a function of time for 10 successive RH steps (10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 93%). Approximately 15 mg of material was deposited in the sample compartment. After the cycle, the sample undergoes a treatment at 70°C 0% RH for 24 hours, then is placed in a ventilated oven at 103°C for the determination of its dry mass. Water vapor sorption isotherms were established from the equilibrium moisture contents at each RH step. Tests are performed in duplicate.

2.2.5 | Sensory analysis

In order to identify the relevance of the method based on the determination of the Py as an objective physical indicator for the crispiness perception, a sensory analysis was conducted to validate this method. This was carried out in the sensory analysis laboratory of QualiSud UMR (CIRAD) with a room capacity of 16 boxes equipped with adaptable light. Three coded samples of gari with different water contents (0%, 6%, and 12%) were served to 11 panelists and chosen for the descriptive sensory evaluation. The panelists were trained according to the ISO 8586 (2012) standard. The crispiness defined as a high level of fracturability, is the only descriptor of relevance selected considering the purpose of our study. It was evaluated on a scale of 11 points from 0 to 10 (0: not crispy/10: very crispy). The protocol consisted in introducing a small tea spoon (≈3 g) of each sample into the mouth, and evaluating the crispiness after 1–2 chews. The average and the standard deviation were used to express each crispiness score. Considering the normality of distribution, ANOVA test at significance level of 0.05 was carried out in order to assess a significant difference between the obtained results. The experimental design, which establishes the code and the order during evaluation for each served sample was carried out using XSLSTAT® (2021).

2.2.6 | Acoustic measurements

To complete the results of the sensory analysis and mechanical measurements, an acoustic evaluation of crispiness was also carried out by recording the sound generated by the sample fracture while undergoing a mechanical solicitation. The granular material was placed on a rigid support (Figure 2) to ensure its stability during measurements. In order to guarantee repeatability, the mass (3 g), position and dimensions ($40 \times 40 \times 3$ mm^3) of the granular material bed were kept constant in each test. A microphone (Bruel & Kjaer, Type 4188-A-021) with a dynamic range of 15.8–146 dB was placed at 40 mm from the center of the sample. The granular material sample placed on the support is mechanically stressed thanks to a 2 kg cylindrical load of 30 mm diameter which was rolled on the granular material. The sound thus emitted was captured through the microphone, and allowed to plot the acoustic module (dB) as a function of time (s) using Stable Micro System–Exponent software. The mean and the standard deviations were calculated in quadruplicate for each sample.

2.2.7 | X-ray microcomputed tomography analysis

For XMT evaluation, native and compacted granular materials (at 200 MPa) of raw gari and grinded corn flakes were analyzed. The

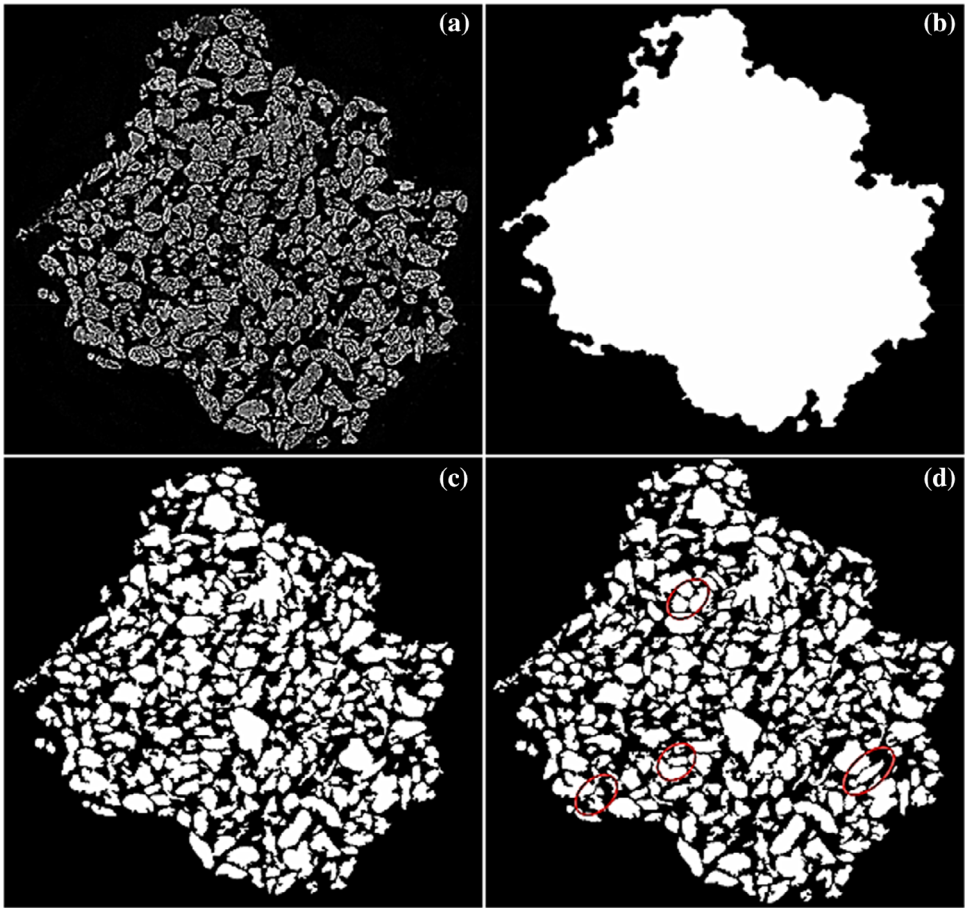

FIGURE 3 Image analysis steps applied on the gari. Raw image in gray levels (a); 2D representation of the volume of interest (VOI) (b); Binarized image inside VOI (c); Binarized image after the application of the watershed separation algorithm (d).

aim of this section is to apply the methodology developed in a previous work (Boudina et al., 2021) to quantify the evolution of the volume equivalent sphere diameters (ESDv) before and after compression. ESDv is the diameter of the sphere that would have the same volume as the discrete 3D object. It has actually been shown that ESDv remains constant before and after compression for plastic materials, whereas it decreases concerning brittle ones.

XMT imaging was carried out with a SkyScan 1272 (Bruker) high-resolution scanner. A known mass (m) of a sample previously introduced in a polystyrene sample holder was scanned at a pixel size of 4 μm. The current (U, eV), the intensity (I, μA) of the x-ray beam as well as the nature and thickness of filters, which vary according to the sample density variation were selected to obtain a 30% signal transmission in the denser part of the sample. The x-ray power source ($P = U\ I$) was kept constant at 10 W. The scanned orbit of 180° with a rotation step of 0.2° was chosen and adapted to the magnification.

Bruker's NRecon® software was used to reconstruct the scan projections into 2D images using Feldkamp algorithm. Gaussian smoothing, ring artifact reduction and beam hardening correction were applied. Volume rendered 3D images were generated using an RGBA transfer function in SkyScan CTVox® software. Image analysis was performed using SkyScan CTAn® software.

Two image segmentations were successively carried out on the raw image (Figure 3a): the first one to define the sample volume of interest (VOI) (Figure 3b) and the second one to define the object volume (granular material volume) within this VOI (Figure 3c). To avoid subjective segmentation, gray level threshold was set by successive iterations in order to respect a volume object (V) equal to:

$$V = \frac{m}{\rho_s^*} \tag{3}$$

where m (g), is the mass of the object subjected to acquisition and ρ_s^* is the true density of the material (g cm^{-3}) measured by a helium pycnometer (Table 1).

A 3D watershed separation algorithm was applied with defined tolerance to separate particles which may have stuck together (Figure 3d).

ESDv was calculated, on the compacts generated at 200 MPa with a punch velocity of 1 and 500 mm s^{-1}, from the 3D images for all individual binarized 3D objects within the VOI. The results are expressed in volume percentage. A granulometric decile (d_{50}) is calculated from the obtained distributions.

3 | RESULTS AND DISCUSSION

3.1 | Granular material properties

Table 1 presents the true density and the tapped porosity values for all the granular samples. True density values are similar and in the

order of magnitude of what is usually found for this type of granular materials of organic nature. Logically, adding or removing water changes the true density values by increasing it for the dried gari and decreasing it for the humidified grinded corn flakes. The values of the tapped densities allow to calculate tapped porosities which correspond to the lowest porosities that can be obtained under the effect of rearrangement due to vibrations. Thus, porosity domains above these values can be excluded for the calculation of the Py.

3.2 | Calculation of indicators correlated to the crispiness: Py and SRS

Table 2 summarizes, for two different compression velocities, the range of pressure used for the calculation of the Py from the Heckel plot. The pressure range allowing to achieve compact porosities between 25% and 15% differs according to the material. Grinded corn flakes and dried gari require higher stresses to achieve the low porosity values, which indicates a higher resistance to re-arrangement and/or deformation at the particle scale for these two materials.

Figure 4a shows the values of the yield pressure (Py) of the Heckel model for the two uniaxial solicitation velocities for each studied sample. Microcrystalline cellulose considered as a reference for plastic materials, shows low Py values which are close to that reported in the literature (Benabbas et al., 2020; Roberts & Rowe, 1987). The Py values of gari and humidified grinded corn flakes (not significantly different cf. ANOVA results Table 2) which is lower than that of microcrystalline cellulose, suggest that these materials can be classified as plastic materials that deform easily and largely under stress. Conversely, dried gari and grinded corn flakes show high Py values close to that found with sucrose. Based on the literature, which attributes brittle behavior for sucrose (Duncan-Hewitt & Weatherly, 1990), dried gari and grinded corn flakes can thus be considered as brittle materials, in which the original particles undergo a fragmentation and generate smaller particles. These results are in line with initial expectations, providing that humidified grinded corn flakes and gari should exhibit more plastic behavior than raw grinded corn flakes and dried gari. Taking into account the only difference between the two samples, which is the water content, the obtained results could underline the fact that the yield pressure (Py) is particularly sensitive to the plasticizing properties of water.

As shown in Figure 4a, the increase in the compression velocity has a low impact on the Py values. Nevertheless, it can be pointed out that the Py values are always higher when the compression velocity increases. These small differences impact the SRS values calculated on each material.

Figure 4b shows the SRS results obtained for the studied samples. Low and statistically similar (cf. Table 2) SRS values of 8.2%, 8%, and 7% are obtained for sucrose, grinded corn flakes, and dried gari respectively. These three samples are also characterized by higher Py values, which suggests that the consolidation of these samples results largely from brittle failure, and that compression velocity has only a low impact on the mechanisms of deformation which is in relation with brittle materials. Humidified grinded corn flakes, gari, and microcrystalline cellulose have the highest SRS values (28.4%, 22%, and 12%, respectively), indicating that these materials are more sensitive to compression velocity which is more typical of plastic deformation. In these studies, the chosen velocities were adapted according to the simulator capacities. Despite this, the SRS value obtained for plastic samples remain higher than that of sucrose and the two other brittle materials.

From the discussed results, Py and SRS seem to be good indicators to describe the mechanical properties of particles (plastic deformation or brittle failure), and therefore the food granular materials crispiness which is associated to the brittle behavior of particles. Gari and grinded corn flakes show two opposite mechanical behaviors. The brittle behavior of the grinded corn flakes indicates that it can be considered as a crispy product. When considering grinded corn flakes versus humidified grinded corn flakes, it can be shown that the plasticizing effect of water impact the crispiness of the product inducing a decrease in Py and an increase in SRS values. On the other hand, gari which shows a plastic deformation (due to 12.6% of water

TABLE 2 Heckel model and SRS results.

		Compression at minimum velocity (1 mm s^{-1})			Compression at maximum velocity (500 mm s^{-1})			
		Pressure range (MPa)		Py (MPa) ± SD	Pressure range (MPa)		Py (MPa) ± SD	SRS values (%) ± SD
		−	+		−	+		
Native granular materials	Sucrose	21	71	100 ± 1[a]	18	80	109 ± 2[a]	8.2 ± 0.5[a]
	Microcrystalline cellulose	42	73	61 ± 1[b]	52	90	70 ± 1[b]	12.0 ± 0.6[b]
	Gari	24	40	32 ± 0[c]	34	59	41 ± 0[c]	22.0 ± 0.8[c]
	Grinded corn flakes	58	109	109 ± 1[d]	57	118	118 ± 2[d]	8.0 ± 2.0[a]
Modified granular materials	Dried gari	59	109	98 ± 3[a]	66	126	107 ± 1[a]	7.0 ± 1.3[a]
	Humidified grinded corn flakes	24	40	31 ± 1[c]	34	58	43 ± 2[c]	28.0 ± 1.1[d]

Note: Standard deviations were calculated from triplicates for each sample. In each column, values with a different letter are significantly different ($P < .05$) according to single factor analysis of variance (ANOVA).

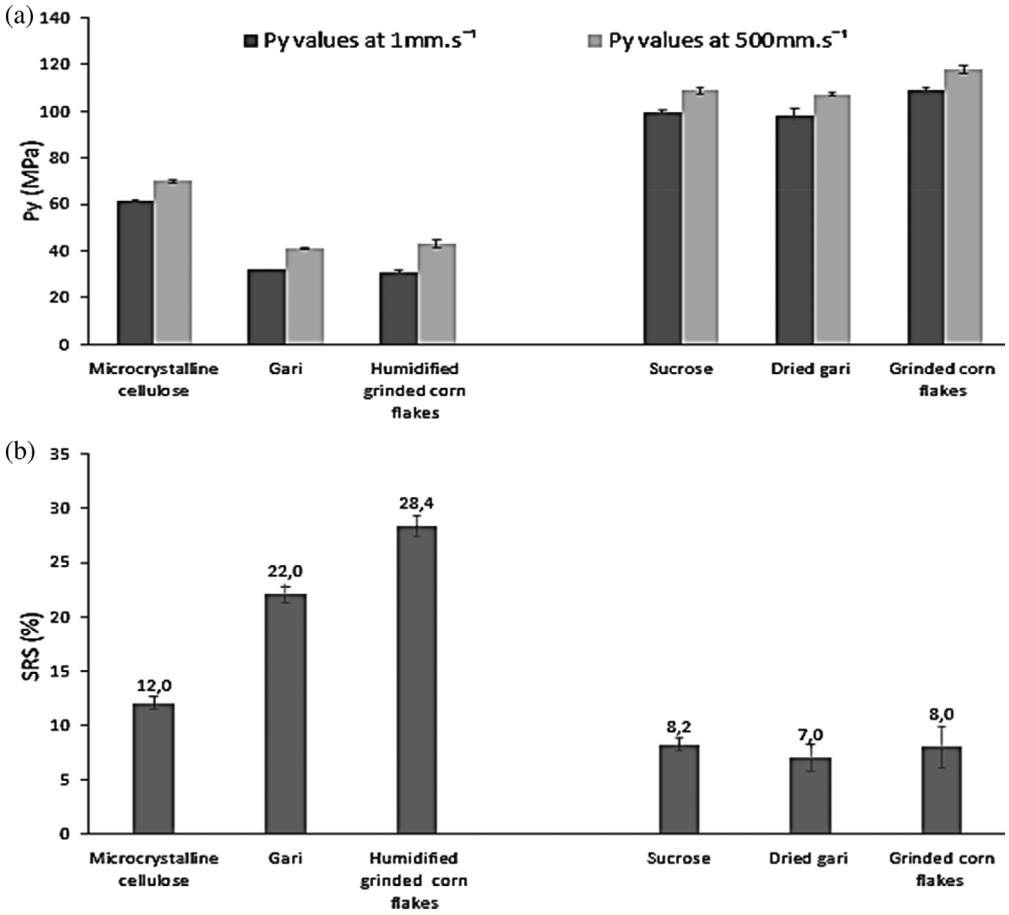

FIGURE 4 Py values for two different compression velocities (1 and 500 mm s^{-1}) (a) and strain rate sensitivity (SRS) values (b) of the studied granular materials.

content) cannot be crispy at least in its native form. To support these findings, the next section will focus on the study of the influence of water content of gari on its crispy properties.

3.3 | Influence of water content on mechanical, acoustic and sensory measurements

3.3.1 | Mechanical measurements: Py values of gari

Figure 5 depicts the evolution of the Py value for gari as function of its water content, for the two uniaxial solicitation velocities. As previously shown in Figure 4a, Py values are higher when punch velocity increases. The influence of the water content on Py is the same for the two tested solicitation velocities as shown on the curve. It can be decomposed into two parts: a first part for water content values between 0% and around 10%–12% where a sharp decrease in Py is observed, and a second part, for water content higher than 12% where the decrease in Py drop is less pronounced. Table 3 underlines, through ANOVA analysis, the significative difference between Py values depending on the water contents. The influence of water content can be explained, at the molecular scale, as the result of the plasticizing effect of water on starch which is the main component of gari. This effect is due to the decrease of the glass transition temperature of starch with higher water content, which increases the free volume

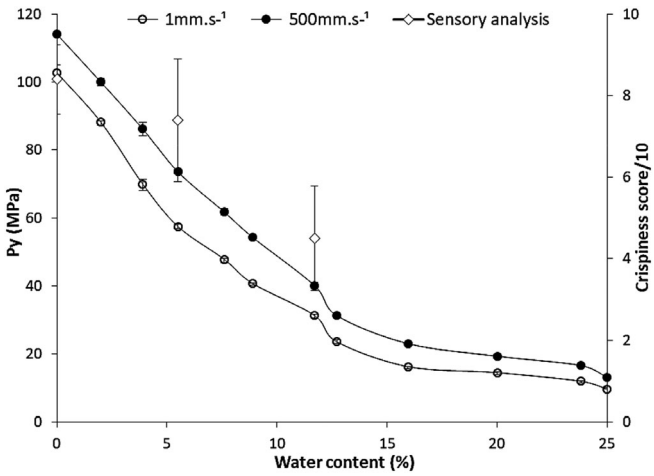

FIGURE 5 Influence of the water content on Py values and sensory evaluation of the crispiness of gari.

allowing a larger mobility of the starch macromolecules (Mizuno et al., 1998; Perdomo et al., 2009; Van Nieuwenhuijzen et al., 2010).

Taking into account the discontinuity of gari as a result of its granular nature, the evolution of Py as a function of water content can also be explained by a phenomena occurring at the mesoscopic scale, that is, at the scale of the grains surface. Water sorption isotherms of gari are shown in Figure 6. The sorption isotherm allows to

TABLE 3 Impact of water content on Py and sensory score value.

Water contents (db)	0%	6%	12%
Py (1 mm s^{-1}) (MPa) ± SD	103 ± 2[a]	57 ± 1[b]	31 ± 0[c]
Py (500 mm s^{-1}) (MPa) ± SD	114 ± 1[a]	74 ± 1[b]	40 ± 1[c]
Sensory score ± SD	8.4 ± 0.8[a]	7. 4 ± 1.5[b]	4.5 ± 1.3[c]
Acoustic values (dB) ± SD	68.6 ± 0.1[a]	65.9 ± 0.4[b]	64.4 ± 0.1[c]

Note: Standard deviations were calculated from triplicates for each sample. In each line, values with a different letter are significantly different ($P < .05$) according to single factor analysis of variance (ANOVA).

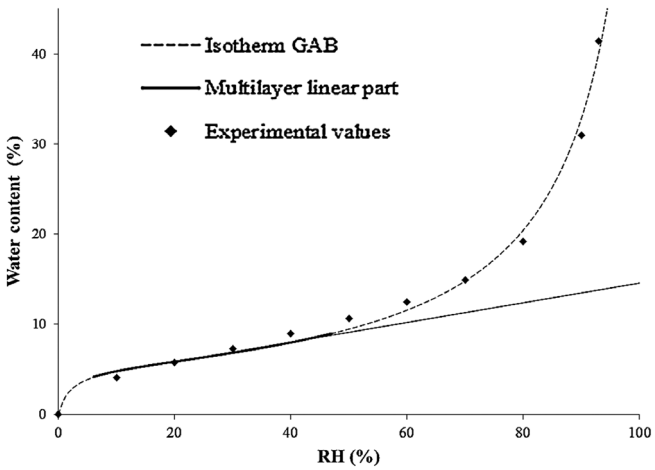

FIGURE 6 Sorption isotherm of gari.

distinguish bound and free water, the latter corresponding to the establishment of capillary meniscus at the mesoscopic scale. The use of GAB equation ($R^2 = 0.99$) (Van den Berg, 1984) to model the isotherm makes it possible to observe that between 0% and around 10% of water content, water is bound in a physical state corresponding to monomolecular or multimolecular layers. This can explain the slope change between Py and water content in Figure 5. Above 10% of water content, free water appears. In the case of microporous solids, such as gari, free water first appears within the open porosity of the sample as a result of capillary condensation phenomena. It is only afterwards, and probably at slightly higher contents, that capillary menisci appear between gari grains at the mesoscopic scale. It is therefore possible to draw a parallel between the state of the water in the granular matrix and the influence of the water content on the mechanical strength value. The moment where water is adsorbed as a monolayer or multilayer corresponds to the phase where the Py values decrease rapidly (Figure 5). The plasticizing effect of water reaches its peak when the multilayers are saturated, at around 10% of water content, and when free water starts to appear. After this point, the increase in water content is more reflective of the inter-granular voids that make up the generated granular material bed. In this pendular state, the effect of the increase of water content on the Py value is therefore less pronounced.

The realization of sorption isotherms confirms that Py is a sufficiently sensitive parameter to detect the effect of a slight increment in the water content effect on the plastic or brittle character, and thus on the crispiness qualities of a food granular material.

3.3.2 | Sensory analysis

In order to validate the Py as an indicator of crispiness attributes, the results were confronted to the results obtained through the sensory panel analysis considered as reference method for determining the crispiness attributes of food products, and which can be used to correlate the objective crispness measurements (Antonova et al., 2004).

Table 3 summarizes the scores of sensory analysis and Py measurements for gari samples with different water contents: 0%, 6%, and 12%. These results are also depicted in Figure 5. ANOVA test carried out on the crispiness scores of the three samples with different water contents gives a P-value $= 3.84 \times 10^{-7}$, which is lower than the significance level of .05. This means that the crispiness score differs significantly between the three samples. It can be highlighted that the dried gari (water content = 0%) is characterized by the highest sensory score (higher crispiness) and Py value. The decrease of these two values is linked to the increase of the water content.

This analysis coupled with the reference method confirms the interest of the determination of the Heckel parameter which emerges as a relevant indicator to describe the crispiness.

3.3.3 | Acoustic measurements

The acoustic measurements were carried out on the same three samples of gari as in the sensory analysis and mechanical estimation of Py, in order to validate these results with another instrumental method (results are shown in Figure 7). ANOVA test results gives a P-value of 3.02×10^{-8} with a significance level of .05 which means that the samples are significantly different in terms of the acoustic measurements. Average values of 68.6 ± 0.1, 65.9 ± 0.4 and 64.4 ± 0.1 dB were measured on samples with 0%, 6%, and 12% of water contents respectively, which indicates that the samples with less water content produce a higher acoustic module. As shown previously with the sensory analysis and mechanical characterization of Py, the increase in water content is associated with a significant decrease in the acoustic module (Table 3).

A correlation analysis conducted between the above studied parameters (Py values, sensory and acoustic parameters) showed that they are highly and positively correlated (correlation coefficients between 0.90 and 0.99).

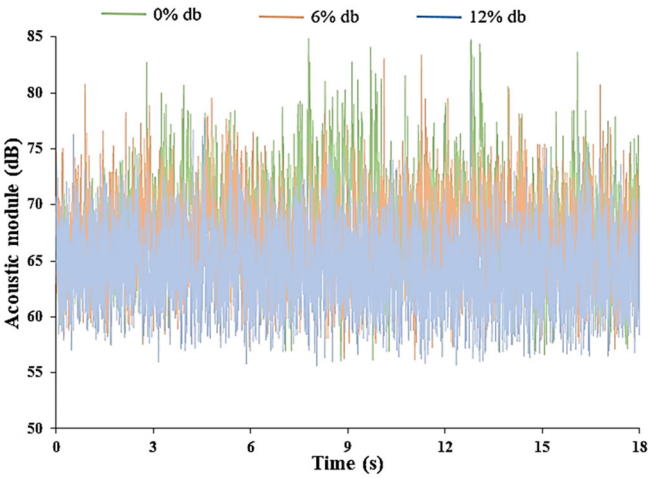

FIGURE 7 Acoustic measurements results of the three samples of gari with different water contents.

3.4 | X-ray computed tomography analysis

The determination of the Py value on gari and grinded corn flakes allows to classify them, relatively to their aptitude to crispiness, in two groups: crispy brittle granular sample for grinded corn flakes and a non-crispy plastic for gari. In order to verify if these results reflect a morphological change associated with the particle breakage for the granular materials with the highest Py value, we used an image analysis methodology described previously (Boudina et al., 2021) in order to compare the morphometric data values on these food granular samples before and after compression.

The approach relies on following the evolution of the particle size distribution during compression based on the ESDv. The distributions are established for the gari and grinded corn flakes before and after compaction at 200 MPa (1 and 500 mm s^{-1} of punch velocity).

Figure 8 depicts the evolution of the ESDv during compression for (Figure 8a) grinded corn flakes and (Figure 8b) gari. Concerning grinded corn flakes, there is a decrease in the d_{50} value measured before (485 ± 19 μm) and after compression of 18% (398 ± 17 μm) and 22% (379 ± 2 μm) when punch velocity is set respectively at 1 or 500 mm/s. This result is likely to be related to the brittle behavior of this material which generates smaller particles. Another interesting

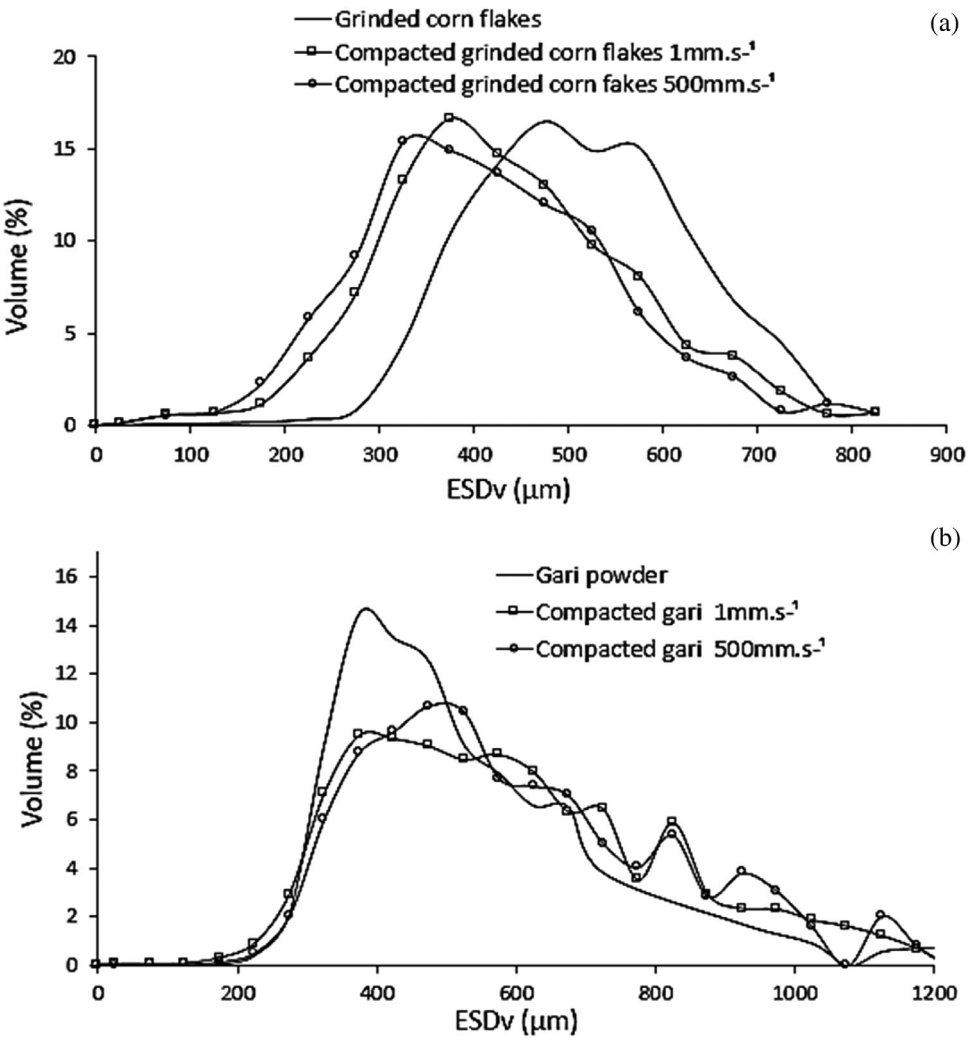

FIGURE 8 Evolution of the equivalent volume sphere diameter (ESDv) during compression of grinded corn flakes (a), gari (b).

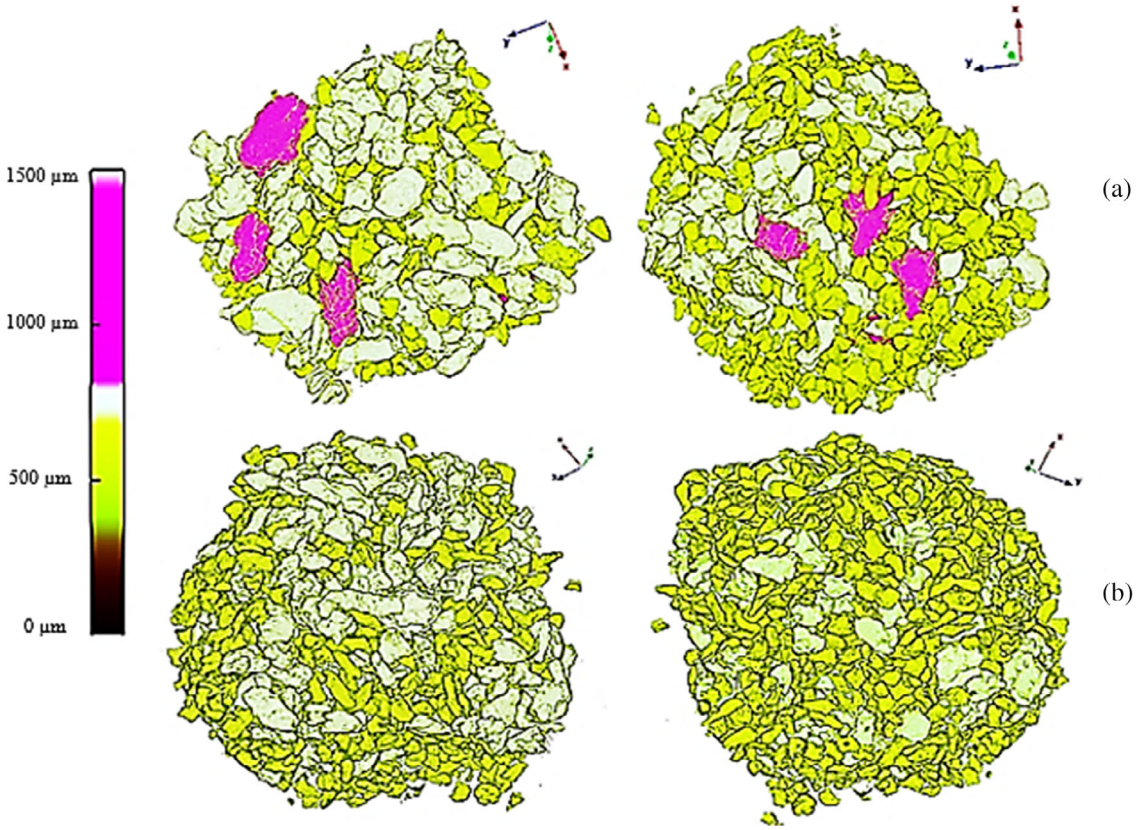

FIGURE 9 Agglomeration/coalescence phenomenon of the compacted gari 500 mm s^{-1} (a), absence of this phenomenon with the uncompacted gari (b).

finding is the negligible difference (4.7%) in the median diameter measured on granular material compacted at 1 or 500 mm/s. This result is in line with the above-mentioned findings concerning SRS measurements where brittle materials are shown to be not very sensitive to the compression velocity.

An increase in the d_{50} value of gari can be highlighted. Instead of being stable due to the plastic deformation, which is supposed not to change the particle volume, gari particles seem to increase in size after compaction comparatively to native ones (16% and 20% for 1 and 500 mm/s punch velocity respectively). This result may be due to coalescence/agglomeration phenomenon of particles that stick together to generate bigger ones. In these cases, the watershed separation algorithm is not capable of separating initial individual particles as shown in Figure 9 where it can be highlighted that bigger particles (pink) results from the association of smaller ones. This coalescence of the plastic particles has already been reported previously (Boudina et al., 2021) and constitutes the limit of the use of the XMT in the monitoring of the ESDv and d_{50} value during compression. It is in any case possible to observe that for the granular samples with the lowest Py (gari), there is no observable particle fragmentation, contrary to the brittle material (grinded corn flakes) with high Py that undergoes a decrease in their d_{50} during compression. These results obtained with x-ray tomography confirm the interest of using Py as a parameter to determine the particle mechanical behavior associated to the crispiness of a food granular material.

4 | CONCLUSION

The aim of this study is to propose a new method for evaluating the crispiness of food granular materials. This method is based on the determination of the yield pressure (Py) obtained from the modeling of the compression curves using the Heckel model. Granular materials of the study were chosen for their known crispiness attribute. They could be categorized into two distinct groups according to their Py value, in which the crispiest granular materials showed high Py values indicating a brittle behavior. The compression rate defined in this study through the SRS calculated based on the Py values of two opposite punch velocities, shows less impact on the brittle materials compared to the plastic ones, which indicates that the latter are more sensitive to the compression velocity. The results provided by this parameter, prove the interest of Py in defining the mechanical properties of food granular materials and ultimately their crispiness.

As shown by the results concerning the plasticizing effect of water, Py seems to be a sufficiently precise parameter to highlight relatively small differences in crispiness associated with small increments in water content. These results were corroborated by the two reference methods: sensory panel analysis, and the determination of the acoustic modules. The decrease in Py value as the water content of the granular material increases is associated with a decrease in the crispiness score generated by the sensory analysis panel and a decrease in the acoustic modulus. Finally, the tomographic image

analysis showed that particles with the highest Py values break up under compression.

It seems therefore that this physical method for crispiness evaluation, through the Py measurement, is reliable for reporting the crispiness attributes of a food granular materials. It can even significantly distinguish differences in crispiness due to the plasticizing effect of water. Compared to other crispiness determination methods used in the literature, it also has many advantages such as objectivity, less time consumption and low cost compared to sensory analysis. Also, ease of implementation and reproducibility compared to acoustic methods can be claimed. Considering the above-mentioned advantages and after further statistical evaluation, this method can contribute to provide a new approach that can be adopted and added to the available reference methods allowing the determination of food products crispiness.

AUTHOR CONTRIBUTIONS

Imen Boudina: Conceptualization, methodology, software, data curation, formal analysis, investigation, funding acquisition, writing–original draft, visualization, writing–review & editing. Michèle Delalonde: conceptualization, methodology, validation, writing–review & editing, visualization. Laurène Koegel: Data curation, software, formal analysis. Isabelle Maraval: Validation, methodology, data curation. Nelly Forestier-Chiron: Methodology, validation, data curation. Romain Domingo: Methodology, validation, data curation, software. Julien Ricci: Methodology, validation, data curation. Tahmer Sharkawi: Conceptualization, investigation, methodology, validation, writing–review & editing, visualization, supervision, resources, project administration. Eric Rondet: Conceptualization, methodology, validation, visualization, writing–review & editing, supervision, resources, project administration.

ACKNOWLEDGMENTS

This work was supported by the Algerian Ministry of High Education and Scientific Research through the funding of the PhD of Imen Boudina.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interests.

DATA AVAILABILITY STATEMENT

Research data are not shared.

ORCID

Imen Boudina https://orcid.org/0009-0006-2734-3259
Eric Rondet https://orcid.org/0000-0002-8635-3696

REFERENCES

Andreani, P., de Moraes, J. O., Murta, B. H., Link, J. V., Tribuzi, G., Laurindo, J. B., Paul, L., & Carciofi, B. A. (2020). Spectrum crispness sensory scale correlation with instrumental acoustic high-sampling rate and mechanical analyses. *Food Research International*, *129*, 108886. https://doi.org/10.1016/j.foodres.2019.108886

Antonova, I., Mallikarjunan, P., & Duncan, S. E. (2004). Sensory assessment of crispness in a breaded fried food held under a heat lamp. *Foodservice Research International*, *14*(3), 189–200. https://doi.org/10.1111/j.1745-4506.2004.tb00189.x

Benabbas, R., Sanchez-Ballester, N. M., Aubert, A., Sharkawi, T., Bataille, B., & Soulairol, I. (2021). Performance evaluation of a novel biosourced co-processed excipient in direct compression and drug release. *Polymers*, *13*(6), 988. https://doi.org/10.3390/polym13060988

Benabbas, R., Sanchez-Ballester, N. M., Bataille, B., Leclercq, L., Sharkawi, T., & Soulairol, I. (2020). Structure-properties relationship in the evaluation of alginic acid functionality for tableting. *AAPS PharmSciTech*, *21*(3), 1–11. https://doi.org/10.1208/s12249-020-1633-3

Bhandari, B. (2013). Introduction to food powders. In B. Bhandari, N. Bansal, M. Zhang, & P. Schuck (Eds.), *Handbook of food powders* (pp. 1–25). Woodhead Publishing.

Boudina, I., Rondet, E., Nezamabadi, S., & Sharkawi, T. (2021). Insight into tableted pellets by combining X-ray micro-computed tomography and experimental compaction. *Powder Technology*, *397*, 117083. https://doi.org/10.1016/j.powtec.2021.117083

Bourne, M. (2002). Texture, viscosity, and food. In *Food texture and viscosity: Concept and measurement*. Academic Press.

Çarşanba, E., Duerrschmid, K., & Schleining, G. (2018). Assessment of acoustic-mechanical measurements for crispness of wafer products. *Journal of Food Engineering*, *229*, 93–101. https://doi.org/10.1016/j.jfoodeng.2017.11.006

Chaunier, L., Courcoux, P., Della Valle, G., & Lourdin, D. (2005). Physical and sensory evaluation of cornflakes crispness. *Journal of Texture Studies*, *36*(1), 93–118. https://doi.org/10.1111/j.1745-4603.2005.00007.x

Chauvin, M. A., Younce, F., Ross, C., & Swanson, B. (2008). Standard scales for crispness, crackliness and crunchiness in dry and wet foods: Relationship with acoustical determinations. *Journal of Texture Studies*, *39*(4), 345–368. https://doi.org/10.1111/j.1745-4603.2008.00147.x

Chen, J., Karlsson, C., & Povey, M. (2005). Acoustic envelope detector for crispness assessment of biscuits. *Journal of Texture Studies*, *36*(2), 139–156. https://doi.org/10.1111/j.1745-4603.2005.00008.x

Dias-Faceto, L. S., Salvador, A., & Conti-Silva, A. C. (2020). Acoustic settings combination as a sensory crispness indicator of dry crispy food. *Journal of Texture Studies*, *51*(2), 232–241. https://doi.org/10.1111/jtxs.12485

Diaz, J. M. R., Suuronen, J. P., Deegan, K. C., Serimaa, R., Tuorila, H., & Jouppila, K. (2015). Physical and sensory characteristics of corn-based extruded snacks containing amaranth, quinoa and kañiwa flour. *LWT-Food Science and Technology*, *64*(2), 1047–1056. https://doi.org/10.1016/j.lwt.2015.07.011

Duncan-Hewitt, W. C., & Weatherly, G. C. (1990). Modeling the uniaxial compaction of pharmaceutical powders using the mechanical properties of single crystals. II: Brittle materials. *Journal of Pharmaceutical Sciences*, *79*(3), 273–278. https://doi.org/10.1002/jps.2600790319

Escobar, A., Rondet, E., Dahdouh, L., Ricci, J., Akissoé, N., Dufour, D., Tran, T., Cuq, B., & Delalonde, M. (2021). Identification of critical versus robust processing unit operations determining the physical and biochemical properties of cassava-based semolina (gari). *International Journal of Food Science & Technology*, *56*(3), 1311–1321. https://doi.org/10.1111/ijfs.14857

Feldkamp, L. A., Davis, L. C., & Kress, J. W. (1984). Practical cone-beam algorithm. *Journal of the Optical Society of America A*, *1*(6), 612–619. https://doi.org/10.1364/josaa.1.000612

Gilbert, L., Savary, G., Grisel, M., & Picard, C. (2013). Predicting sensory texture properties of cosmetic emulsions by physical measurements. *Chemometrics and Intelligent Laboratory Systems*, *124*, 21–31. https://doi.org/10.1016/j.chemolab.2013.03.002

Gouyo, T., Rondet, É., Mestres, C., Hofleitner, C., & Bohuon, P. (2021). Microstructure analysis of crust during deep-fat or hot-air frying to understand French fry texture. *Journal of Food Engineering*, *298*, 110484. https://doi.org/10.1016/j.jfoodeng.2021.110484

Hanada, M. (2020). Food-texture dimensions expressed by Japanese onomatopoeic words. *Journal of Texture Studies*, *51*(3), 398–411. https://doi.org/10.1111/jtxs.12499

Heckel, R. W. (1961). Density-pressure relationships in powder compression. *Transactions of the Metallurgical Society of AIME*, *221*, 671–675.

Hooper, D., Clarke, F., Mitchell, J., & Snowden, M. (2016). A modern approach to the Heckel equation: The effect of compaction pressure on the yield pressure of ibuprofen and its sodium salt. *Journal of Nanomedicine and Nanotechnology*, *7*(381), 2. https://doi.org/10.4172/2157-7439.1000381

Jakubczyk, E., Gondek, E., & Tryzno, E. (2017). Application of novel acoustic measurement techniques for texture analysis of co-extruded snacks. *LWT*, *75*, 582–589. https://doi.org/10.1016/j.lwt.2016.10.013

Katz, J. M., & Buckner, I. S. (2013). Characterization of strain rate sensitivity in pharmaceutical materials using indentation creep analysis. *International Journal of Pharmaceutics*, *442*(1–2), 13–19. https://doi.org/10.1016/j.ijpharm.2012.09.006

Kilcast, D. (2004). Texture in food. In *Solid foods* (Vol. 2). Woodhead Publishing.

Kim, H., Venkatesh, G., & Fassihi, R. (1998). Compactibility characterization of granular pectin for tableting operation using a compaction simulator. *International Journal of Pharmaceutics*, *161*(2), 149–159. https://doi.org/10.1016/S0378-5173(97)00337-2

Landis, E. N., & Keane, D. T. (2010). X-ray microtomography. *Materials Characterization*, *61*(12), 1305–1316. https://doi.org/10.1016/j.matchar.2010.09.012

Lawless, H. T., & Heymann, H. (1999). Texture evaluation. In *Texture evaluation sensory evaluation of food* (pp. 379–405). Springer. https://doi.org/10.1007/978-1-4419-7452-5_11

Li, Q. E. (2010). Investigating the glassy to rubbery transition of polydextrose and corn flakes using automatic water vapor sorption instruments, DSC, and texture analysis (MS Thesis). Available from University of Illinois Library. http://hdl.handle.net/2142/16711.

Luyten, H., Plijter, J., & Van Vliet, T. (2004). Crispy/crunchy crusts of cellular solid foods: A literature review with discussion. *Journal of Texture Studies*, *35*(5), 445–492.

Mizuno, A., Mitsuiki, M., & Motoki, M. (1998). Effect of crystallinity on the glass transition temperature of starch. *Journal of Agricultural and Food Chemistry*, *46*(1), 98–103. https://doi.org/10.1021/jf970612b

Özalp, Y., Onayo, M. M., & Jiwa, N. (2020). Evaluation of lactose-based direct tableting Agents' compressibility behavior using a compaction simulator. *Turkish Journal of Pharmaceutical Sciences*, *17*(4), 367–371. https://doi.org/10.4274/tjps.galenos.2019.94840

Perdomo, J., Cova, A., Sandoval, A. J., García, L., Laredo, E., & Müller, A. J. (2009). Glass transition temperatures and water sorption isotherms of cassava starch. *Carbohydrate Polymers*, *76*(2), 305–313. https://doi.org/10.1016/j.carbpol.2008.10.023

Primo-Martín, C., & Van Vliet, T. (2009). Sensory crispness of crispy rolls: Effect of formulation, storage conditions, and water distribution in the crust. *Journal of Food Science*, *74*(8), S377–S383. https://doi.org/10.1111/j.1750-3841.2009.01318.x

Raleng, A., Singh, A., Chavan, P., Attkan, A., & Singh, B. (2019). Standardization of deep-frying process and their effects on storage stability of pineapple pomace powder-incorporated rice-based extruded product. *Journal of Food Processing and Preservation*, *43*(7), e13950. https://doi.org/10.1111/jfpp.13950

Roberts, R. J., & Rowe, R. C. (1985). The effect of punch velocity on the compaction of a variety of materials. *The Journal of Pharmacy and Pharmacology*, *37*(6), 377–384. https://doi.org/10.1111/j.2042-7158.1985.tb03019.x

Roberts, R. J., & Rowe, R. C. (1987). The compaction of pharmaceutical and other model materials–a pragmatic approach. *Chemical Engineering Science*, *42*(4), 903–911. https://doi.org/10.1016/0009-2509(87)80048-9

Roudot, A. C. (2004). Terminology in food quality management. In G. J. McNulty (Ed.), *Paper presented at the 5th international conference on quality–reliability–maintenance*. Professional Engineering Publishing Limited, Bury St Edmunds.

Rue, P. J., & Rees, J. E. (1978). Limitations of the Heckel relation for predicting powder compaction mechanisms. *Journal of Pharmacy and Pharmacology*, *30*(1), 642–643. https://doi.org/10.1111/j.2042-7158.1978.tb13347.x

Salvador, A., Varela, P., Sanz, T., & Fiszman, S. (2009). Understanding potato chips crispy texture by simultaneous fracture and acoustic measurements, and sensory analysis. *LWT-Food Science and Technology*, *42*(3), 763–767. https://doi.org/10.1016/j.lwt.2008.09.016

Sauvageot, F., & Blond, G. (1991). Effect of water activity on crispness of breakfast cereals. *Journal of Texture Studies*, *22*(4), 423–442. https://doi.org/10.1111/j.1745-4603.1991.tb00502.x

Schüssele, A., & Bauer-Brandl, A. (2003). Note on the measurement of flowability according to the European pharmacopoeia. *International Journal of Pharmaceutics*, *257*(1), 301–304. https://doi.org/10.1016/S0378-5173(03)00142-X

Silva-Espinoza, M. A., del Mar Camacho, M., & Martínez-Navarrete, N. (2020). Use of different biopolymers as carriers for purposes of obtaining a freeze-dried orange snack. *LWT*, *127*, 109415. https://doi.org/10.1016/j.lwt.2020.109415

Silva-Espinoza, M. A., Salvador, A., Camacho, M. d. M., & Martínez-Navarrete, N. (2021). Impact of freeze-drying conditions on the sensory perception of a freeze-dried orange snack. *Journal of the Science of Food and Agriculture*, *101*, 4585–4590. https://doi.org/10.1002/jsfa.11101

Sonnergaard, J. M. (1999). A critical evaluation of the Heckel equation. *International Journal of Pharmaceutics*, *193*(1), 63–71. https://doi.org/10.1016/S0378-5173(99)00319-1

Tunick, M. H., Onwulata, C. I., Thomas, A. E., Phillips, J. G., Mukhopadhyay, S., Sheen, S., Liu, C., Latona, N., Primentel, M., & Cooke, P. H. (2013). Critical evaluation of crispy and crunchy textures: A review. *International Journal of Food Properties*, *16*(5), 949–963. https://doi.org/10.1080/10942912.2011.573116

Van Den Berg, C. (1984). Description of water activity of foods for engineering purposes by means of the GAB model of sorption. *Engineering Science in the Food Industry*, *1*, 311–321.

Van Nieuwenhuijzen, N., Tromp, R., Mitchell, J., Primo-Martín, C., Hamer, R., & Van Vliet, T. (2010). Relations between sensorial crispness and molecular mobility of model bread crust and its main components as measured by PTA, DSC and NMR. *Food Research International*, *43*(1), 342–349. https://doi.org/10.1016/j.foodres.2009.10.015

Walker, E. (1923). The properties of powders. Part VI. The compressibility of powders. *Transactions of the Faraday Society*, *19*, 73–82.

Withers, P. J., Bouman, C., Carmignato, S., Cnudde, V., Grimaldi, D., Hagen, C. K., Maire, E., Manley, M., Plessis, A. D., & Stock, S. R. (2021). X-ray computed tomography. *Nature Reviews Methods Primers*, *1*(1), 18. https://doi.org/10.1038/s43586-021-00015-4

York, P. (1979). A consideration of experimental variables in the analysis of powder compaction behaviour. *The Journal of Pharmacy and Pharmacology*, *31*(4), 244–246. https://doi.org/10.1111/j.2042-7158.1979.tb13487.x

Zhang, C., Zhang, H., Wang, L., & Qian, H. (2014). Physical, functional, and sensory characteristics of cereal extrudates. *International Journal of Food Properties*, *17*(9), 1921–1933. https://doi.org/10.1080/10942912.2013.767831

How to cite this article: Boudina, I., Delalonde, M., Koegel, L., Maraval, I., Forestier-Chiron, N., Domingo, R., Ricci, J., Sharkawi, T., & Rondet, E. (2023). Mechanical approach for the evaluation of the crispiness of food granular products. *Journal of Texture Studies*, 1–13. https://doi.org/10.1111/jtxs.12764