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Quantitative Instrumental Assessment of Cooked Rice Stickiness

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Abstract

Stickiness is a major textural characteristic of cooked rice and an important criterion in cultivars classification. Many reports on instrumental evaluation cooked rice stickiness are based on variants of the texture profile analysis (TPA), a method that has fundamental methodological flaws and creates logical inconsistencies. Notable among these is that cooked rice tested as a flat cylindrical specimen having a larger diameter is always harder and stickier than when tested as a narrower specimen. Recent novel improvements have been the use of a universal testing machine (UTM) to record the force and calculate the work needed to separate a pre-compressed *pair of individual cooked rice kernels*, or to separate a *single* pre-compressed cooked kernel from the flat surface to which it is attached, while accounting, in both cases, for the contact areas. It is proposed to modernize an older manual method to measure the attractive force between two uncompressed cooked rice kernels directly with a tensiometer by replacing it with a UTM and expressing the result in term of a *cohesion index*, the dimensionless ratio between the *net separation force* and *an individual cooked kernel's weight*. Rough calculations based on published data indicate that cooked rice of cultivars known to be sticky would have an index on the order of 15 while those known as non-sticky about 3 only, where the actual values will depend on the cooking procedure and the dry rice's history. Also proposed is a similar *adhesion index* to characterize the attractive interaction of cooked rice with any surface of interest.

Keywords Rice · Stickiness · Texture profile analysis (TPA) · Cohesion · Adhesion

Introduction

Cooked rice texture in general and stickiness in particular have been of great interest to consumers and hence to geneticists, growers, and processors. Thus, the technical literature on the subject has numerous reports on what affects cooked rice stickiness, notably its variety (cultivar) which determines its starch compositions and molecular structure, e.g., [1–8], and how it is influenced by processing and storage of the dry grains, and preparation method, primarily the amount of water and temperature, e.g., [7, 9–15].

There are also many reports on how rice "stickiness" has been evaluated sensorily and/or instrumentally, e.g., [2, 8–10, 14–24].

Many of the described instrumental methods to quantify rice stickiness can be considered variants of the instrumental texture profile analysis, also known by its acronym TPA. The concept of instrumental texture profiling and human mastication imitation by a testing machine was proposed in the pioneering works of Alina S. Szczesniak and her collaborators at the MIT and later at the General Foods Corporation, leading to the development and construction of the GF Texturometer [25]. Malcolm C. Bourne [26] has popularized the concept by obtaining a "texture profile" from two successive compression-decompression cycles replacing the "bites" and performing the test with a universal testing machine (UTM), then new to food research. His TPA version, initially known as the "Instron TPA" named after the testing machine he used, has been probably the most commonly used in foods texture evaluation [27] cooked rice texture included, e.g., [3, 5, 10, 16, 17, 21, 23].

Wherever the mechanical properties of solid materials are evaluated, and regardless of the tested materials kind and whether it is tested in tension or compression, almost all commercial UTMs used operate with their crosshead moving up and down, or vice versa, at a constant speed set by the user. When the specimen's initial height or length and the crosshead's momentary position and speed are known, the output of the machine sensors, commonly a load cell, is translated into and recorded or plotted as a force (force units) vs. time (time units) relationship that can be easily transformed into a raw force (force units) vs. deformation (length units) curve–

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see below. In the common instrumental TPA method, a food specimen mostly in the form of a relatively flat cylindrical specimen and occasionally a cube or of other rectangular shape is compressed twice in succession to a preset very large deformation (50–80%) and the force recorded–see below. From this recorded curve, and the enclosed areas under it in the compression strokes and above it in the decompression strokes, one derives the instrumental TPA's parameters, expressed in terms such as "hardness," "cohesiveness," or "adhesiveness." The specimen preparation, the test execution, and the data retrieval and processing are all fairly simple and fast, contributing to the method's attractiveness. That the experimenter can report and do statistical analysis on 5–7 parameters obtained simultaneously with a single test seems to be an added bonus, at least to some.

Its great popularity in food research notwithstanding, the instrumental TPA's method and the concept on which it is based have several serious fundamental methodological and logical flaws, each a sufficient reason for their long overdue abandonment [28, 29]. Regrettably, these shortcomings, some also noticed and discusses by others [27], have been largely ignored in the food literature and only recently started to receive some attention, see [30–33].

In what follows, conceptual issues with the instrumental TPA method will be raised again, with emphasis on their implications in cooked rice stickiness (and texture) evaluation. The main objectives are to highlight issues with published methods to assess the stickiness of cooked rice instrumentally, and to explore the possibility of replacing them with a technique more in line with the principles of mechanical testing as practiced in engineering, material science and related disciplines.

Stickiness: Definition and Related Terms

The term "stickiness" has very different meanings in different fields. In the context of cooked rice texture, "stickiness" according to the Oxford English Dictionary (OED) is "the fact of being made of or covered in a substance that sticks to things that touch it," and "[to] stick" is "to fix something to something else, usually with a sticky substance." According to the Merriam-Webster Dictionary, the adjective "sticky" (from which "stickiness" is derived) is defined as "a. adhesive b. (1): viscous, gluey (2): coated with a sticky substance." Disregarding the tautologies in some of these definitions, the essence of "stickiness" is the property of bodies to spontaneously adhere, attach, or be glued to other bodies including of their own kind–see below.

Cohesion, Adhesion, and Friction

Soil Mechanics and Powder Technology are two disciplines that deal extensively with interactions between particulates, their physical manifestations, and manners of their quantification. In these two disciplines, the phenomenon/property of particulates sticking to other particulates of their own kind is referred to as *cohesion*, while interacting with particulates of other kinds or surfaces such as a container's or equipment's wall is called *adhesion*. In quantitative terms, *cohesion* is defined as the yield shear stress under zero consolidation stress and expressed in stress units, i.e., as force per unit area.

Friction is a form of adhesion, which is manifested in impeding *sliding*. It is expressed in term of a dimensionless angle or a coefficient of friction derived from it–see below.

Stickiness in Foods and Non-food Materials

The phenomenon or property of stickiness is a central topic in several technological disciplines, notably those dealing with natural and synthetic adhesives or glues, where it is mostly evaluated and quantified by *peeling tests*.

A review of foods' stickiness and its assessment, and of attempts to relate it to glass transition, can be found in [9]. In cereal products, stickiness is especially of concern in pasta and dough [36]. However, unlike cooked rice kernels, the mass of wheat flour dough is highly stretchable, and therefore its stickiness and deformability ought to be considered simultaneously (ibid). In contrast, the *stiffness* and *strength* of individual cooked rice kernels by far exceed the attraction between them and between them and metal, wood, or plastic surfaces with which they might be in contact. Thus unless glued or bonded in other ways to both sides of the stretching device, the individual cooked rice grain itself is unlikely to break in tension. This is true for both testing machines operating in a tensile mode as in the Instrumental texture profile analysis (TPA)—see below—and the surfaces of the human tongue and/or the spoon, fork, or chopsticks during cooked rice consumption. Also, the *stiffness* of individual cooked rice kernels is high enough to resist gravity, so they do not stretch to any visible extent under their own weight. The same is true of their *strength* and therefore they do not break under their own weight in tension, as wheat dough might. Notice that in Mechanics and Material Science, *stiffness* refers to a material's *resistance to deformation.* It is manifested in the slope of the pre-failure stress-strain relationship and expressed as a *modulus* having stress dimensions and units. *Strength* refers to a material's ability to resist *failure* or *rupture* and is expressed as the *stress at failure*. *Toughness* refers to the amount of absorbed energy prior to failure. It is determined as the area under the pre-failure stress-strain curve and expressed in *work per unit volume units*. These three mechanical properties can differ dramatically for compression, tension, and shear. In fact, more often than not, a uniaxially compressed or stretched specimen actually fails in shear. *Hardness* of engineering materials usually refers to their resistance to penetration (e.g., Brinell, Vickers), or to scratching (Mohs scale). Also notice that these material properties bear little relation to those described by the TPA vocabulary. They have different dimensions and units and are all, at least in principle, independent of the tested specimen's shape and size. The serious implications of these discrepancies are discussed in more detail elsewhere [28, 34] so here they will be only addressed in the context of instrumental assessment of cooked rice texture particularly its stickiness.

Graphical Representation

The attraction between two adhered individual cooked rice kernels is manifested in the force needed to separate them. This cohesive force can be stronger or weaker than the attractive force that attaches the cooked kernels to an external surfaces with which they might be in contact, as shown schematically in Fig. 1. The figure represents two idealized scenarios of perfect horizontal contact with no shearing or peeling, and where the particles' weight (the gravitational force) is negligible relative to either and both the adhesive and cohesive attractions. Although the figure shows only two particles in a perfect geometrical array, the principle applies to cooked rice *lumps*, i.e., to kernels held together by the inter-grain cohesive forces. In that case, however, gravitation may well play a role, determining the *size* of a cooked kernels lump that can hang freely from the upper plate of a testing machine before breaking under its own weight.

Friction is a qualitatively different phenomenon as shown schematically in Fig. 2. Ignoring the issue of static vs. dynamic friction, the angle θ at which an individual cooked grain or a lump of grains start to slide only depends on the nature of the surfaces in contact, which may include lubrication. In other words, the coefficient of friction, μ, defined as $\mu = \mathrm{Tan}\theta$, is by definition independent of the grain's or lump's weight and hence its mass. But because a mechanically stable lump's size is determined by the cohesive forces between the individual cooked grains, a manifestation of its "stickiness," the sliding behavior of cooked rice can at least in principle provide an empirical measure of its *adhesiveness* to cutlery (e.g., metal or plastic) as well as to chopsticks (e.g., wood, metal or plastic).

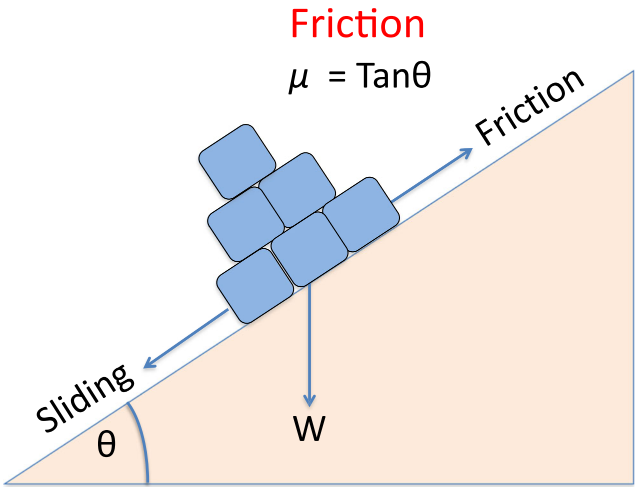
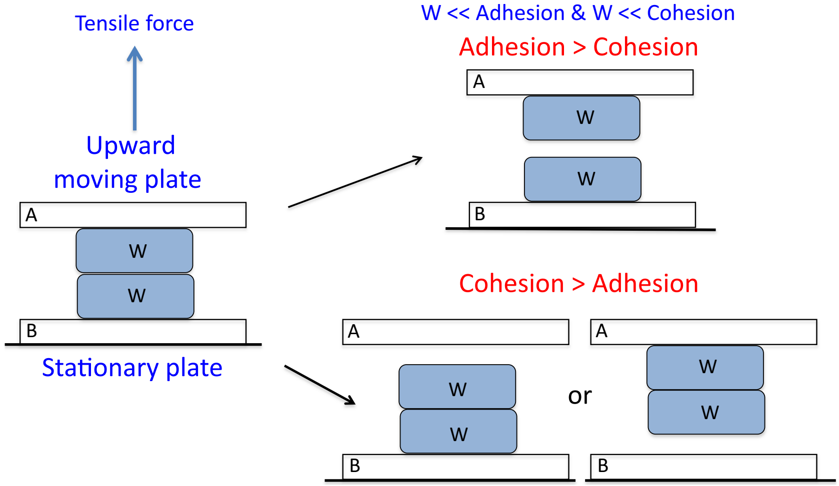


Fig. 2 Angle and coefficient of friction cooked rice kernels lump (schematic)

Fundamental Issues with the Instrumental Texture Profile Analysis

Historically, as already mentioned, the concept of instrumental texture profiling, from which the current TPA method originate, was an attempt to imitate the *reciprocating human mastication pattern*. Only later was it presented as a mechanical testing method of foods performed with the more commonly available universal testing machines, which operate *in linear motion at a constant speed*. According to this later and by far more popular version, which has been also implemented in cooked rice texture evaluation, a flat cylindrical specimen of arbitrary dimensions is compressed once or twice to only about 50% of its initial height at a constant displacement rate (constant crosshead velocity) and the force recorded. Once the

Fig. 1 Individual cooked rice kernels attractive forces: adhesion and cohesion (schematic)



preset degree of compression is reached, the crosshead is withdrawn, frequently at an arbitrary speed, see below, and decompression ensues. At a certain point, the diminishing compressive force, which continues to be recorded, becomes negative (tensile) marking an area under the abscissa (x-axis), which has been associated with the foods adhesiveness and cohesiveness in different ways. Because of their *plasticity*, cooked rice kernels especially when compressed in bulk do not exhibit gross failure, some works only report on the first bite, i.e., the first compression—decompression cycle only—see below.

Figure 3-left—shows, schematically, a typically recorded *force-time* relationship of cooked rice ("first bite" in the TPA terminology). Notice the absence of gross failure or fracture, which would have been marked by a significant almost instantaneous (vertical) force drop as in fruit flesh testing for example. The area under the time axis, frequently mislabeled "deformation," marked A in the figure, is called "adhesiveness" in the TPA vocabulary. It is considered a measure of the cooked rice's attraction to the flat plates between which the specimen has been compressed and hence, presumably, also to its "stickiness."

As already stated, the instrumental TPA in all its versions has several very serious methodological and logical flaws [28, 29], each serious enough to undermine its validity as a mechanical testing method, including for cooked rice stickiness evaluation. The list of major problems with the instrumental TPA includes but is by no means limited to the following:

a. All the TPA parameters' magnitudes inherently depend on the specimen's geometry, i.e., shape, dimensions, and also on the test conditions. Therefore, they cannot be considered meaningful material properties as understood by material scientists. For example, if the method is taken seriously, the same cooked rice tested as a wider cylindrical specimen having the same height is both stickier and harder than when tested as narrower specimen, which is absurd of course.
b. The TPA's first bite's force-time relationship shown schematically in Fig. 3- left—is not the same as the actual force-deformation (displacement) relationship which is shown in Fig. 3- right [34].
c. The arbitrarily preset *compression ratio*, which has nothing to do with the tested specimen's texture, significantly affects the measured "hardness," as well the area under the curve which is used to determine its "cohesiveness" as shown schematically in Fig. 4—right.
d. The arbitrarily set *crosshead's return speed*, which too has nothing to do with cooked rice texture, dramatically affects the area under the curve, is used to determine its "cohesiveness" as shown schematically in Fig. 4—left.
e. The recorded "negative area," marked A in Fig. 3, depends not only on the specimen's diameter and preset compression ratio, but also on the *material and finish of the deforming plates* and hence cannot be attributed solely to the cooked rice.

Each of these issues alone, as already stated, is sufficient to invalidate the notion that the instrumental TPA parameters really represent intensive material properties as understood in Material Science and related disciplines. Therefore, it is surprising that the method has survived for so long in food research and continues to proliferate. The meaninglessness of the TPA parameters is not only due the arbitrary specimen's geometry, preset compression ratio, and the crosshead upward and downward speeds. Unlike well-defined mechanical properties such as *strength*, *stiffness*, *toughness*, and *strain at failure*, the instrumental TPA parameters' magnitudes *inherently depend* on the arbitrary test conditions. Therefore, establishing standard specimen geometry and testing protocol, as some suggest, cannot resolve the issues with the instrumental TPA method. The same applies to the idea that the method can be saved by "improvement," whatever this term means in this context. This is because any chosen specimen geometry and set compression ratio, for example, will inevitably affect the interrelationships between the supposedly independent

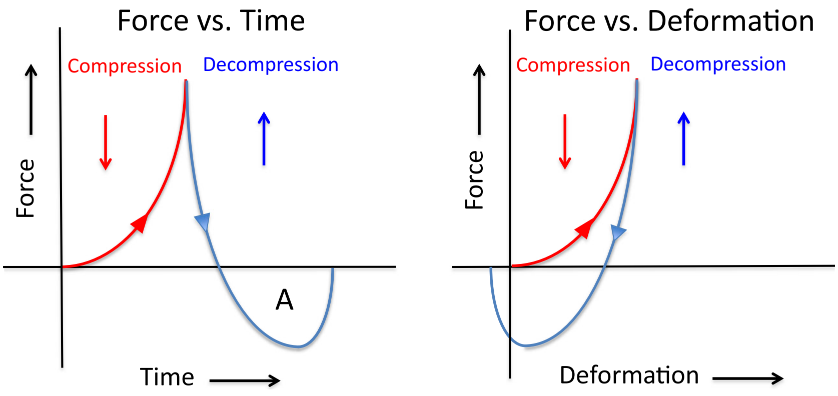


Fig. 3 The difference between the force-time (left) and force-displacement (right) curves in a compression-decompression test cycle

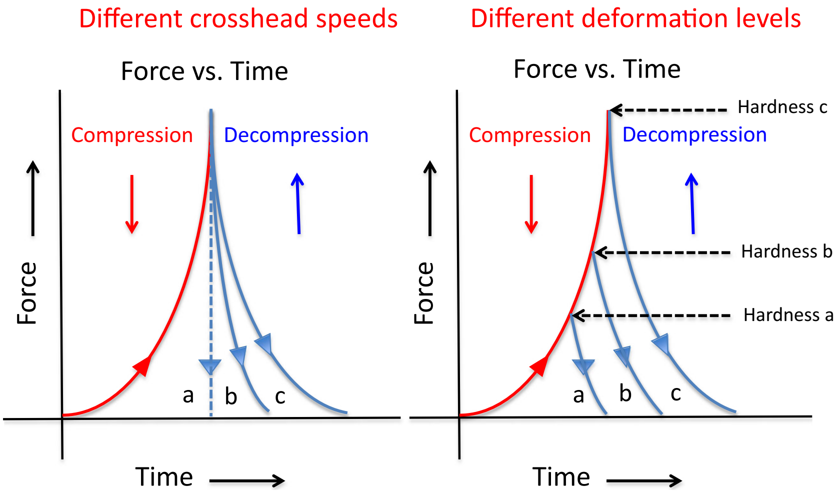


Fig. 4 Left—Effect of the crosshead's return speed on the shape of and area under the instrumental TPA's first bite curve. Right—Effect of the preset deformation level on the shape of and area under the instrumental TPA's first bite curve. Notice that a different area under a curve implies different TPA's "cohesiveness!"

material properties of the tested food. The chosen "standard" or "improved" test conditions will also affect the relation between the very same properties in different foods, or in our case in different rice varieties and/or under different cooking conditions. For example, unless the textural differences are huge, in which case almost every conceivable method will be able to detect them, it is quite possible, at least theoretically, that if the preset deformation is 50%, cooked rice A will be found "harder" than cooked rice B, and the opposite if the preset deformation is preset to 75%.

Testing a Single and a Pair of Attached Cooked Rice Kernels

Yang et al. [14] and Yu et al. [24] have recently reported notable advances in cooked rice stickiness evaluation. The first group devised a compression/pull method to measure the adhesiveness of a *compressed individual cooked rice kernel* and a formula to account for the contact area. With this method, the "stickiness" is expressed in terms of force per unit area (pressure) units, which eliminates the specimen diameter issue that plagues the traditional TPA. The second group devised a test whereby the compression/pull protocol was applied to *two individual cooked rice kernels placed in a cross position*. These researchers used the array's raw force vs. the machine gap plot to identify the maximum pull force, and treated the curve's "negative area" as the adhesion work in absolute energy unit. The paper also reports estimates of the contact stresses between the compressed cooked grains. However, the calculation was based on the Hertz theory, which had been originally developed for rigid elastic spheres. Whether the Hertz formula is applicable to soft plastic–cooked rice grains is unclear, but the approach of treating rice stickiness as a contact stresses problem is promising. Also important in these two recent works is that the attractive force between an individual cooked rice grain and a surface, or between two individual cooked rice grains, could be measured with a common load cell that comes with a commercial universal testing machine. Although the role of the pre-compression level used to cement the grain or grains was monitored and studies in both works, whether and how it represents conditions during cooked rice consumption is somewhat unclear. The same can be asked about whether and how the stickiness so generated is also perceived as such by humans.

Direct Measurement of the Attractive Force between Two Uncompressed Cooked Rice Grains

An alternative approach to the methods to assess the stickiness of cooked rice pre-compressed in bulk or as individual kernels was described years ago [18] but hardly received any attention in the rice research community. The idea was to measure the force between two individual uncompressed cooked grains brought into contact *directly*. The experimental array is shown schematically in Fig. 5. In the actual experiments, the cooked kernel at the bottom was held in place with a miniature vice-like device especially designed and built for the purpose, while the suspended upper kernel was held by a bent double-forked skewer device made of very thin stainless steel wire that had a loop at the top. The array was connected to the moving arm of a manual surface tensiometer through a suspended thread. After the two individual cooked grains were manually brought into contact in a *parallel position*—other orientations were also tried—the top part of the array was pulled apart with the tensiometer dial handle and the pulling force, F_{pull}, recorded. The tensiometer was then zeroed again with the upper part containing the separated top cooked rice kernel hanging freely to compensate for its dead weight. The net attractive force, $F_{\mathrm{attraction}}$, was calculated as:

$$F_{\mathrm{attraction}} = F_{\mathrm{pull}} - W \qquad (1)$$

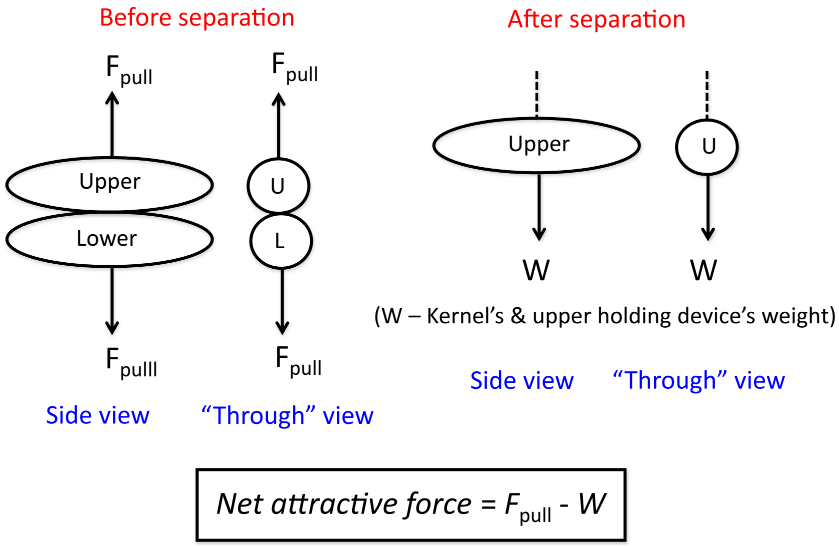


Fig. 5 Direct measurement of the attractive force between two individual cooked rice grains (schematic). After [18]

where W is the dead weight of the suspended part which included the cooked rice kernel, the holding "skewer," and the thread. The test was repeated 10 times with pairs taken from different cultivars or same cultivars under different cooking conditions.

Naturally, the reproducibility of such a test's results is quite low, primarily because of the contact area's non-uniformity and the size and shape variability among the individual kernels. Thus, not surprisingly, when expressed in terms of their *coefficient of variance* (COV) defined (in %) as:

$$\mathrm{COV}(\%) = \frac{\text{standard deviation} \times 100}{\text{mean}} \tag{2}$$

the net force measurements' scatter was mostly in the range of 20–50% and in two cases as high as 71 and 78%. Nevertheless, the differences between the rice cultivars known to be sticky or non-sticky were on the order of *two or more folds*, i.e., the differences between the cultivars were by far larger than those between the single kernel pairs. This indicated that the *method*, despite its crudeness, was sensitive enough to unambiguously distinguish between the sticky and non-sticky cultivars. Moreover, the method was also sufficiently sensitive to monitor the effect of the cooking water to dry rice ratio on the attractive force between the cooked kernels of the same cultivar (ibid).

The major finding of that work were that the attractive force between rice kernels, cooked with water to dry rice ratios from 0.75:1 to 1.9:1, was on the order of 1200–1700 dyne (12–17 mN) in known sticky cultivars and 200–400 dyne (2–4 mN) in the non-sticky ones (mN = millinewton).

The primarily manual procedure was dictated by logistic considerations and conditions that existed in our and other laboratories over 30 years ago. Today, such attractive force measurements can be made with modern computer-interfaced testing equipment having highly sensitive electronic sensors that can be used to record and process the results. At least in principle, such instrument even those ubiquitous in food research laboratories can also be used to record and analyze the effects of the pulling rate and of slight but controlled pre-compression of the two grains on the attractive force between them. The testing instrument can also be supplemented with a camera, which could be used to quantify the contact area if it is indeed worthy of investigation. A fast-setting glue might facilitate the grip formation, especially in the upper part, and would speed up the test. This in turn would enable the investigator to increase the number of measurements for statistical analysis.

But regardless of what equipment and experimental procedure will be eventually adapted, it is imperative that the currently used TPA–based methods to determine cooked rice stickiness be replaced by direct measurement of the grain-to-grain attractive force. Despite its conceptual simplicity and the expected large scatter in its results, the direct inter-grain force determination is probably the only way to produce stickiness measures that are free of serious artifacts and inherent methodological flaws.

Adhesion

In principle, the procedure of direct measurement of the net attractive force between two cooked rice grains in contact can be also used to measure the attractive force between a single cooked rice grain and any surface of interest such as that of the already mentioned cutlery, e.g., metal, plastic. All that will be needed is to replace the bottom kernel with a flat (or curved) surface made of the material in question. In contrast with the TPA-based procedures, the stickiness/adhesiveness so measured will not be treated as a "universal material property" but as quantifying a specific interaction with a particular surface.

Dimensionless Cohesion and Adhesion Indices

The net attractive force between two cooked rice kernels in contact [14, 18, 24] is the most meaningful and probably also the most sensitive measure of their cohesion. Certainly, it is consistent with the classification of rice to sticky and non-sticky cultivars. However, being expressed in force units, this measure is inherently size dependent and therefore cannot serve as a bona fide quantifier of an intensive textural property [29]. It is suggested that this issue can be resolved by normalization, i.e., by expressing the separation force in terms of a dimensionless *cohesion index* defined as the ratio between the attractive force and the kernel weight both having the same force units, i.e.,

$$\text{Cohesion index} = \frac{\text{Net separation force}}{\text{An individual kernel weight}} \tag{3}$$

The mass of an individual dry rice kernel is known to vary widely, but commonly in the range of 15–40 mg. Depending on the cooking method and the amount of water used, a wet cooked grain's mass can be assumed to be roughly two and a half to three times its dry mass, i.e., in the range of about 40–120 mg. Thus for a representative mass on the order of 80 mg, this translates to weight (gravitational force) on the order of 0.8 mN or 80 dyne, i.e., approximately 1 mN or 100 dyne. Since weighing a sample having a counted number of cooked rice kernels, in order to estimate their representative (mean) weight, is a trivial matter and commonly done in dry grains physical characterization, e.g., [12, 17, 35], determination of the actual cooked kernel's weight need not be an issue. With the above rough estimates of the grain's weight, and the extreme experimental data of 200–400 and 1200–1700 dyne net separation force reported in [18], one would expect that the magnitude of the dimensionless cohesion index of non-sticky cultivars would be on the order of 2–4 and that of clearly sticky cultivars on the order of 12–17. Notice that the cohesion index by definition is insensitive to the cohesion's specific causes, e.g., to whether it is mainly a manifestation of chemical attractive forces, the contact area and geometry, or a combination of both. Nevertheless, it is not unreasonable to expect that the maximum size of a cooked rice *lump* will primarily depend the cohesion index regardless of the particular combination of the factors that determine it. Naturally, if the dimensionless cohesion index concept and method of its determination would be one day accepted, new experimental data would provide more accurate and reliable estimates of the index's magnitude. With this index, one would be able to compare of how the cohesiveness of different rice cultivars is affected by storage history and preparation method, for example, using the same scale.

The principle and method of determination can be extended to cooked rice adhesiveness to any particular surface or object, in which case the *adhesion index* would be calculated as:

$$\text{Adhesion index} = \frac{\text{Net separation force}}{\text{An individual kernel weight}} \tag{4}$$

where the net separation force refers to a lifted individual cooked kernel initially in contact with the surface of interest.

Concluding Remarks

Despite the great interest in the stickiness of rice cultivars and in what affects it, there is still no generally accepted method of its quantification. Partly, this is due to the nature of rice stickiness the intensity of which, however defined, inherently depends on the dry rice's history, fraction of broken kernels, and how it is prepared. But as shown in this review, there are also methodological issues with many of the extant methods of rice stickiness evaluation, especially those that can be considered offshoots of the instrumental TPA method. These, in the author's opinion, should have been abandoned long ago, and replaced by direct measurement of the kernel-kernel attractive force, and expressing the result in terms of a dimensionless ratio between this force and the individual cooked kernel's weight. This ratio, which might be dubbed *cohesion index*, has been estimated using published data on cultivars known a priori to be sticky and non-sticky, and found to be on the order of 15 in the first kind and only 3 in the second kind, a difference on the order of fivefolds. In other words, this index has a range large enough to serve as a sensitive stickiness measure for rice cultivars classification and rating. In principle, the cohesion index can also be used to quantify the effect of the water to dry rice ratio and the water temperature and cooking duration on the cooked rice stickiness. Also, at least theoretically, the index could be used to quantify the stickiness of broken kernels individually and the effect of their presence and concentration on the stickiness of the entire lot. The same can be said on quantifying the effect of pressing the cooked rice kernels together in a manner similar to that reported by Yang et al. [14]. Since different cultivars might be affected differently by the preparation method's particulars, the classification and rating of intermediate varieties with respect to their stickiness would be probably helped by *cluster analysis*, which can be easily and quickly done with modern mathematical software. Hopefully, these hypotheses will be confirmed in the future experimental studies.

In addition to the above, since the cohesion index can be viewed as the number of cooked grains that can be held suspended vertically by a single grain, how the index's magnitude might be related to the formation of lumps, their size, and strength will also be an interesting topic for future investigation. Since the proposed cohesion index determination is independent of that of the cooked rice's other mechanical/textural properties, one can investigate if and how it might be related to the stiffness and ductility of the grains in various cultivars.

All the above can also be pertinent to stickiness assessment in other cooked grainy foods such as barley, bulgur, buckwheat, and even certain pastas (including couscous), provided that their attractive inter-particle forces are within the testing machine's sensitivity range.

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