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A compositional breakage equation for wheat milling

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ABSTRACT

The compositional breakage equation is derived, in which the distributions of botanical components following milling of wheat are defined in terms of compositional breakage functions and concentration functions. The forms of the underlying functions are determined using experimental data for Outer Pericarp, Intermediate Layer, Aleurone and Starchy Endosperm generated from spectroscopic analysis of milled fractions of a hard and a soft wheat milled under Sharp-to-Sharp (S–S) and Dull-to-Dull (D–D) dispositions. For the hard Mallacca wheat, the Outer Pericarp, Intermediate Layer and Aleurone compositions mostly varied with particle size in similar ways, consistent with these layers fusing together as "bran" and breaking together, although with possibly a subtle difference around the production of very fine particles under D–D milling. By contrast, for the soft Consort wheat, Outer Pericarp, Intermediate Layer and Aleurone were distributed in broken particles very differently, particularly under D–D milling, suggesting a different breakage mechanism associated with differences in the mechanical properties and adhesion of the bran layers. These new insights into the nature of wheat breakage and the contributions of the component tissues could have implications for wheat breeding and flour mill operation.

1. Introduction

In the 1950s Broadbent and Callcott introduced breakage matrices to relate input and output particle size distributions during grinding operations (Broadbent and Callcott, 1956a, 1956b, 1957). They used square matrices in which the input and output particle size distributions covered the same size ranges, and applied this approach to model coal grinding. Campbell and Webb (2001) applied the breakage matrix approach to roller milling of wheat, extending the approach to use non-square matrices covering different size ranges for the input and output particle size distributions, thus improving the applicability and accuracy of the approach.

A complete understanding of milling requires the ability to predict the size distribution of broken particles and also the composition of particles of different sizes. Fistes and Tanovic (2006) demonstrated that compositional breakage matrices could also be constructed that, combined with breakage matrices for predicting output particle size, allowed the composition of those output particles also to be predicted. They also employed roller milling of wheat as the system with which to demonstrate the value of predictions for composition as well as size; the key feature of roller milling of wheat is that the bran tends to stay as large particles and the endosperm as small particles, hence facilitating separation of bran and endosperm by sifting.

Subsequent work by Campbell and co-workers focussed on the continuous form of the breakage equation and of breakage functions, rather than the discrete forms that underpin the construction of breakage matrices; continuous functions are more generally applicable and more readily interpretable, thus yielding greater predictive power and greater mechanistic insights regarding wheat breakage. This body of work has allowed the effects on the output particle size distribution of roll gap, roll disposition, wheat kernel

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hardness, moisture content and shape to be quantified (Campbell and Webb, 2001; Campbell et al., 2001, 2007, 2012; Fang and Campbell, 2003a,b; Fuh et al., 2014). The objectives of the current work are to demonstrate that continuous breakage functions can also be defined in relation to particle composition, for use alongside breakage functions that predict particle size distribution, and to generate experimental data to begin to identify the form and significance of those functions and the new insights they reveal. The current work thus represents the continuous equivalent of the discrete compositional breakage matrices introduced by Fistes and Tanovic (2006).

2. Theory

The breakage equation for roller milling of wheat in its cumulative form is

$$P_2(x) = \int_0^\infty B(x, D)\rho_1(D)dD \tag{1}$$

where D is the input particle size, x is the output particle size, $P_2(x)$ is the proportion by mass of output material smaller than size x, $B(x, D)$ is the breakage function and $\rho_1(D)$ is the probability density function describing the input particle size distribution (Campbell et al., 2007). The logic of the breakage equation is that the total mass of particles smaller than a given size x arises from contributions from all the inlet particles. The contribution from inlet particles initially of size D depends on how many of those particles there are (which is quantified by $\rho_1(D)$) and on how those particles break (which is quantified by the breakage function, $B(x, D)$. The total mass is found by integrating all of these contributions over the range of inlet particle sizes.

Applying equivalent logic, the composition of particles can also be described and related to the particle size distribution. Choomjaihan (2009) derives the relationships by proposing that the entire wheat kernel, and its milled fractions, can be considered to be made up of four main components: Pericarp (including testa and nucellar tissue), Aleurone, Starchy Endosperm and Germ. The sum of the proportions of these four components is unity:

$$X_{pe} + X_{al} + X_{en} + X_{ge} = 1 \tag{2}$$

where X_{pe} is the proportion of the whole wheat that is Pericarp, X_{al} is the proportion of the whole wheat that is Aleurone, X_{en} is the proportion of the whole wheat that is Endosperm, and X_{ge} is the proportion of the whole wheat that is Germ. Typically X_{pe} would be about 8%, X_{al} about 7%, X_{en} about 82% and X_{ge} about 3% (Pomeranz, 1988).

On breakage, particles are formed that individually may contain Pericarp, Aleurone, Endosperm and Germ in different proportions. In general, the particles in a size range, say from 100 to 200 μm, will have a proportion of each component that will be different from particles in a different size range, say 2000–2100 μm; the smaller particles are likely to contain more Endosperm material, the larger particles more bran material (*i.e.* Pericarp and Aleurone).

Consider the total proportion of outlet particles smaller than size x, given by $P_2(x)$. These particles, as a whole, are made up of a proportion of Pericarp, a proportion of Aleurone, a proportion of Endosperm, and a proportion of Germ. The total amount of particles smaller than size x is made up of the total Pericarp that is in particles smaller than size x, plus the total Aleurone that is in particles smaller than x, plus the total Endosperm that is in particles smaller than x, plus the total Germ that is in particles smaller than x. Mathematically:

$$\begin{aligned} P_2(x) &= \frac{\text{total mass of particles smaller than } x}{\text{total mass}} \\ &= \sum_i X_i \cdot Y_i(x) \\ &= X_{pe} \cdot Y_{pe}(x) + X_{al} \cdot Y_{al}(x) + X_{en} \cdot Y_{en}(x) + X_{ge} \cdot Y_{ge}(x) \end{aligned} \tag{3}$$

where $Y_{pe}(x)$ is the proportion (by mass) of the total Pericarp that is in particles smaller than x, and so on for $Y_{al}(x)$, $Y_{en}(x)$ and $Y_{ge}(x)$. Fig. 1 illustrates how the distributions of the four components sum to give the total particle size distribution. Fig. 2 illustrates the distributions in their non-cumulative forms. (Note that in Figs. 1 and 2, the proportions of the four components are unrealistic, having been set at 20%, 10%, 67% and 3% arbitrarily, just to separate out the lines in order to illustrate the point. The shapes of the curves are also arbitrary, contrived to show Endosperm predominantly breaking into small particles, Pericarp and Aleurone staying in larger particles, and Germ forming a narrow peak within the mid-range particles.)

For example, consider the more realistic situation that in the whole wheat, $X_{pe} = 0.08$, $X_{al} = 0.07$, $X_{en} = 0.82$, $X_{ge} = 0.03$. The wheat is milled, forming particles ranging in size from 0 up to 4000 μm, with most of the particles at the smaller end of the range. Consider just those particles that are smaller than 500 μm. Imagine that 40% of the total Pericarp has ended up in those particles; the other 60% is in particles that have remained larger than 500 μm. However, the Aleurone has not broken so readily, so only 30% of the total Aleurone has ended up in the particles smaller than 500 μm; 70% of the Aleurone has stayed in the larger particles. The Endosperm has broken easily; 80% of the Endosperm is now in small particles, with only 20% in large particles. Meanwhile, the Germ is evenly split; half of the Germ material is in particles that are smaller than 500 μm. Thus:

$$Y_{pe}(500) = 0.40, Y_{al}(500) = 0.30, Y_{en}(500) = 0.80, Y_{ge}(500) = 0.50$$

Then, the total proportion of particles smaller than 500 μm is given by

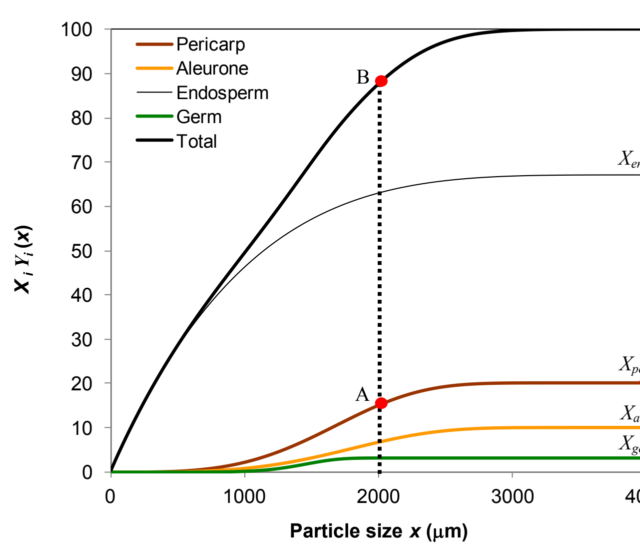

Fig. 1. Contrived example that shows how the cumulative PSD is comprised of the cumulative distributions of the four botanical components in particles of different sizes. Adapted from Choomjaihan (2009).