Example problems to accompany:

“Relationships between food physical properties and oral processing outcomes”

January 20, 2026
Your name:

Instructions

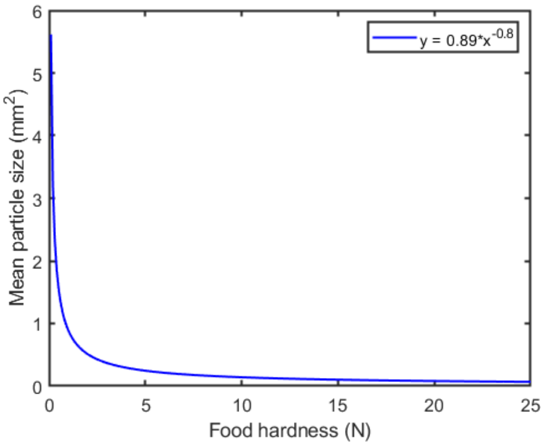
This handout contains example problems and short answer questions to build skills and understanding related to how the physical properties of solid foods affect outcomes during oral processing. All students should complete problems 1 and 2, and respond to the short answer questions. Graduate students should also complete problem 3. *For this example, solutions are provided in the grey boxes.*

Problem setup

Food scientists ran an experiment where human beings chewed different types of food and expectorated (spit out) the boluses at the moment they felt the food was ready to swallow. The boluses were collected and the mean (average) particle size of the small pieces of food was measured. It was found that the hardness of the food was related to the average particle size in the bolus according to the following relationship:

$$d = 0.89 * h^{-0.80}$$

Where:
d = average particle size (mm)
h = food hardness (N)



§ Power law relationship between mean particle size and food hardness. [1]

[1] Chen, J., Khandelwal, N., Liu, Z., Funami, T. 2013. “Influences of food hardness on the particle size distribution of food boluses.” Archives of Oral Biology. 58:293-298. https://doi.org/10.1016/j.archoralbio.2012.10.014

Question 1) Say that walnuts have a hardness of 12 N. Please calculate the mean particle size that would be expected for chewed walnuts:

$d = 0.89 * (12)^{-0.8}$
$\boxed{d = 0.12\, mm^2}$

Question 2) Say that you were a food product developer working on a food product that should break down during oral processing into particles with mean size < 0.5 mm. What would be the lowest hardness value for this product that would still lead to the desired mean particle size?

$0.5 = 0.89 * h^{-0.8}$
$0.5/0.89 = h^{-0.8}$
$0.5618 = h^{-0.8}$
$0.5618^{(1/-0.8)} = h$
$\boxed{h = 2.06\, N}$

Question 3) For some foods (like almonds) there is limited breakdown of particles after they are swallowed and diffusion of digestion fluids into the particles is slow. This makes the percentage of nutrients that are released during digestion (such as fatty acids in the case of almonds) dependent on the surface area to volume ratio of the particles that are swallowed. Say the percent bioaccessibility is directly proportional to the surface area to volume ratio: $\%Bio = c * SA/V$

Where:
$\%Bio$ = percent bioaccessibility (%)
c = a constant of proportionality
SA = surface area of the food particle (m^2)
V = volume of the food particle (m^3)

A food company would like to predict which of two potential products will lead to higher percent bioaccessibility of a nutrient of interest. The hardness of the first product is twice as high as the second product, and so it is expected that oral processing will result in different particle sizes. However, the constant of proportionality of the second product (the c value) is three times as high as the constant for the first product. Please calculate the ratio of bioaccessibility from product 1 as compared to product 2 ($find: \%Bio_1/\%Bio_2$). Assume that both products break down into spherical food particles ($SA = \pi d^2$, $V = \pi d^3/6$) with the same relationship between hardness and particle size (diameter) given in the problem setup.

Find: $\frac{\%Bio_1}{\%Bio_2}$, *percent bioaccessibilty from product 1 relative to product 2*

Given:
$\%Bio = c * SA/V$, *percent bioaccessiblity*
$SA = \pi d^2$, *surface area of the particle*
$V = \pi d^3/6$, *volume of the particle*
$d = 0.89 * (h)^{-0.8}$, *relation between hardness* (h) *and particle size*
$h_1 = 2h_2$, *hardness of product 1 is twice that of product 2*
$c_2 = 3c_1$, *constant of proportionality of product 2 is three times higher than product 1*

Calculation:

$\frac{\%Bio_1}{\%Bio_2} = \frac{c_1 * SA_1/V_1}{c_2 * SA_2/V_2}$, *set up the ratio for product 1 to product 2*

$\frac{\%Bio_1}{\%Bio_2} = \frac{1}{3}\frac{SA_1/V_1}{SA_2/V_2}$, *since* $c_1/c_2 = 1/3$

$\frac{SA}{V} = \frac{\pi d^2}{\pi d^3/6} = \frac{d^2}{d^3/6} = \frac{\frac{d^2}{1}}{\frac{d^3}{6}} = \frac{d^2}{1}\frac{6}{d^3} = 6/d$, *simplify surface area to volume formula*

$\frac{\%Bio_1}{\%Bio_2} = \frac{1}{3}\frac{6/d_1}{6/d_2} = \frac{1}{3}\frac{\frac{6}{d_1}}{\frac{6}{d_2}} = \frac{1}{3}\frac{6}{d_1}\frac{d_2}{6} = \frac{1}{3}\frac{d_2}{d_1}$, *sub in surface area to volume formula*

$\frac{\%Bio_1}{\%Bio_2} = \frac{1}{3}\frac{0.89h_2^{-0.8}}{0.89h_1^{-0.8}} = \frac{1}{3}\frac{h_2^{-0.8}}{h_1^{-0.8}} = \frac{1}{3}\left(\frac{h_2}{h_1}\right)^{-0.8}$, *sub in the equation for particle size*

$\frac{\%Bio_1}{\%Bio_2} = \frac{1}{3}\left(\frac{1}{2}\right)^{-0.8}$, *since* $h_2/h_1 = 1/2$

$\boxed{\frac{\%Bio_1}{\%Bio_2} = 0.58}$

This analysis predicts that the bioaccessibility from product 1 will be 58% of that of product 2.

Short answer questions:

1. Please explain the major steps in food oral processing in your own words.

   Oral processing refers to everything that happens between a food being placed into the mouth and when it is swallowed. The major steps are chewing (mastication), mixture with saliva, bolus formation, and swallowing.

2. What is the difference between the hardness and the elastic modulus of a food particle? (*hint: one of these properties is dependent on the size of the particle, the other is not*)

   Hardness is defined as the force that is needed to crush a piece of the food. It takes more force to crush a bigger piece of food than a smaller piece (even if they are both from the same type of food) which makes hardness an extensive or extrinsic property. Elastic modulus also indicates how much a food particle resists deformation, but it is normalized per unit of sample surface area. This property is given by the slope of the stress vs strain curve for that food and so it has units of stress (since strain is unitless), such as N/m^2 *or* Pa *and is an intensive or intrinsic property that does not depend on how big of a piece of food is tested.*

3. Please explain the difference between the elastic modulus of a food particle and the fracture toughness of the food particle?

   Elastic modulus is the resistance to deformation whereas fracture toughness is the resistance to crack extension (or fracture). Elastic modulus has units of N/m^2 *or* Pa *whereas toughness has units of* N/m *or* J/m^2.

4. If we wanted to predict the change in surface area for food particles during chewing by molar teeth, would the displacement-limited index or the stress-limited index be more appropriate?

   The displacement-limited index was developed for the situation of a food particle during chewing by molars.

5. Taking a look at Figure 1 (the relationship between food particle hardness and particle size of the food after chewing), what are some reasons it has this shape? In other words, why do you think the human participants in the study that developed this graph chewed harder foods into smaller particles?

   I hypothesize that harder foods like candy or almonds need to be smaller in order to swallow safely and comfortably. According to the Lillford model of oral processing (the "swallowing box") food needs to be sufficiently lubricated and broken down structurally in order for swallowing. I hypothesize that a lot of foods with high hardness also have low moisture content and strong structures, and so they take longer to prepare into a bolus, needing more time for saliva to lubricate them and teeth to break down the particles.