Developing the Next Generation of Functional Foods

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"What happens to your food after you eat it?" Although broadly stated, this question drives the current research in the Food Engineering Lab at UC Davis. Our goal is to quantitatively describe food breakdown, transport, and absorption processes during digestion in order to optimize food quality and functionality.

Food digestion as an engineering process

Imagine this process: Food material is broken down in a crusher and mixed with liquids. Pumping transports the material to a reactor, where shear and hydrodynamic forces continue the breakdown. Acids and enzymes are added as part of a control system to optimize hydrolysis. Sieving allows smaller particles to be pumped out of the reactor into another reactor, where additional enzymes are added to continue hydrolysis. The material goes through a filtration step, where nutrient molecules are removed from the system for use elsewhere. The remaining material is pumped to a fermenter, where it is inoculated with primarily anaerobic bacteria. The material undergoes a final filtration step, where fermentation byproducts and water are removed, and any remaining material is disposed of as waste.

This process may sound like what is found in a typical food or chemical plant. However, the above process actually describes food digestion. Each time we consume food, our body acts like a food processing plant to deconstruct the food into its constituent nutrients and energy for use by the body. Food digestion is a complex process that involves size reduction, hydrolysis reactions, mixing, control systems, pumping, sieving, filtration, and fermentation, all of which are similar to the unit operations found in process engineering.

In a food processing plant, the inputs and the process parameters can all be modified to achieve the desired output, in this case the food product being manufactured. However, in human digestion, typically only the input can be modified (i.e., the food being consumed), and the process is expected to achieve the desired output. In this case, the desired output may be a quantity or rate of nutrient absorption or breakdown, resulting in certain health benefits. To achieve this output, it is crucial to develop an engineering understanding of the digestive process, so that we can modify the process input (new food products) to accurately produce the desired output (health benefits).

How to study food digestion?

Food digestion can be studied using *in vivo* (human or animal) systems, *in vitro* (laboratory) models, or *in silico* (mathematical) models. While *in vivo* systems offer the benefit of "real-life" conditions, they are costly and resource intensive, and they can be ethically controversial. In addition, the types of samples that can be collected from *in vivo* systems are limited. In contrast, *in vitro* and *in silico* models offer promising alternatives for studying specific facets of food digestion, and they allow for a mechanistic understanding of individual processes.

In the Food Engineering Lab at UC Davis, we have developed a dynamic, mechanical gastric digestion model, the Human Gastric Simulator (HGS). The HGS simulates the biochemical conditions in the human stomach by addition of acid and enzymes into its stomach cavity, as well as the physical contractions of the stomach wall by pressing curved rollers along the cavity. This dynamic in vitro model can represent both the physical and biochemical breakdown of food during gastric digestion. We use the HGS, as well as other *in vitro* systems, coupled with *in vivo* and *in silico* studies, to obtain an integrated engineering understanding of the digestion process.

The Human Gastric Simulator (HGS) developed at UC Davis. The HGS is set up here to show digestion of carrot particles (orange) in the stomach cavity (blue). The rollers simulate the muscular contractions of the stomach that aid in physical breakdown of foods.

Translating results into functional food development

Many mechanisms and breakdown pathways influence food digestion. Using *in vitro* models, we have been able to isolate certain factors to better understand the process. For example, we have investigated the influence of different cooking processes (such as boiling, steaming, and frying) on the mass transport processes and structural breakdown of sweet potatoes during gastric digestion. In these studies, we isolated the biochemical breakdown using a simple *in vitro* digestion system in which samples were incubated with simulated gastrointestinal fluids without physical breakdown. We were able to model the diffusion of gastric acid and water into the food matrices and then relate these processes to macro-structural and micro-structural changes. Ultimately, we are working to link these fundamental transport processes with outcomes such as nutrient release and absorption rates.

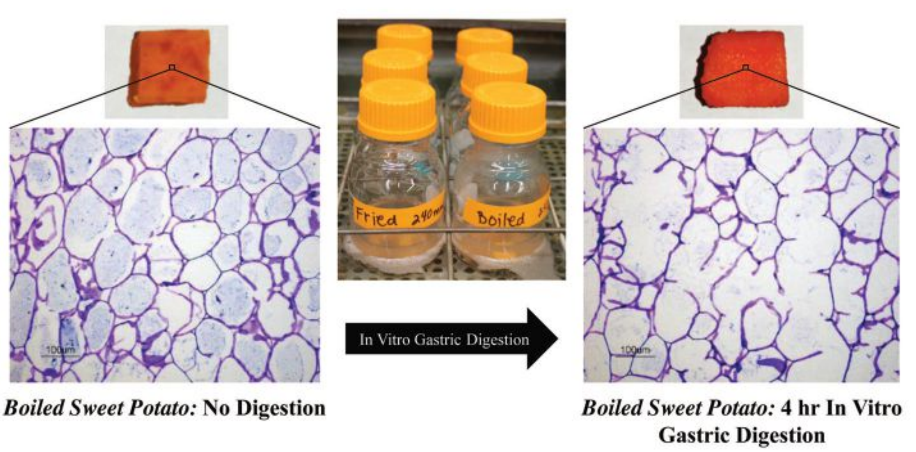
Similar studies can be used to link industrial food processing parameters to digestive processes. We are currently working to determine the influence of pilot-scale processing parameters on the stability and availability of nutrients in fruit and vegetable juices. These studies will help us understand the relationships between processing parameters and their influence on food functionality.

In addition to the physical and chemical breakdown of foods leading to nutrient release, there are also complex flow and mixing processes that occur during digestion. These processes influence the specific biochemical conditions encountered by ingested food (e.g., addition of acid secretions), as well as the shear stresses and collisions experienced by food particles, which influence their breakdown. We are working to characterize the mixing and particle transport that occur during digestion using several non-invasive imaging techniques, such as magnetic resonance imaging (MRI), positron emission particle tracking (PEPT), and particle imaging velocimetry (PIV). These imaging techniques allow a more complete description of the flow and mixing processes during digestion, so that food materials may be modified to induce certain flow or mixing patterns.

Doctoral student Yamile Mennah-Govela (*left*) and research intern Clair Floyd (*right*) pasteurize juice in the California Processing Tomato Industry Pilot Plant at UC Davis to understand the influence of processing parameters on juice quality and functionality.

Future directions

As knowledge is gained on the mechanisms and processes of digestion, it will be crucial to develop experimental and computational models that incorporate the initial properties of the food (e.g., structure and composition) as well as the engineering properties of the system (e.g., mass transport processes, breakdown processes, rate kinetics of hydrolysis, flow and mixing patterns). As part of this holistic approach, processes that occur across all length scales should be considered, from molecular interactions to cell wall breakdown to macrostructural degradation. Once these multi-scale, integrated models are developed, they can be used to solidify the relationship between processing of foods prior to consumption and the behavior of foods during digestion. This information can be used by the food industry to create the next generation of functional foods that deliver optimized benefits to the consumer.



Example of the microstructural changes that occur during four hours of *in vitro* gastric digestion of boiled sweet potatoes.

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