Food Matrices and the Matrix Effect in the Kitchen

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Introduction

Chemically speaking, dishes are mainly composed of water, proteins and amino acids, lipids (mainly triglycerides) and saccharides (mono-, oligo- or poly-saccharides), but they also contain many compounds (polyphenols, minerals, vitamins, etc.) that are minor in terms of proportions but can be important in terms of sensory appreciation, nutrition or toxicology (Belitz et al., 2009). These compounds are not always homogeneously dispersed in the dishes, or in a free molecular state; in most cases, they are entrapped in a “matrix” that can take different forms. These might be solid deposits or liquid droplets, a liquid phase (water or oil), or glassy or rubbery domains, and they are also sometimes adsorbed on various interfaces separating phases such as gas, liquids and solids (Aguilera, 2013; This, 2016).

The breakdown of food during consumption can release some of these compounds in saliva as dissolved molecular or ionic species, or volatilized in the gas phase inside the mouth and the nose. This release is not the same as it would be if the pure compounds were sprinkled over the surface of a finished dish. Moreover, during digestion, not all food compounds become available as individual nutrients; thus, they are unavailable to be carried to the cells of our bodies. Two key related concepts, expressed in the terms “food matrix” (FM) and the “matrix effect” (ME), are questions that we discuss in this chapter.

What Is a Food Matrix?

Dictionaries define a matrix as “something where other things are embedded”. The term “matrix” is used in several scientific disciplines to describe those parts of a whole that provide a specific functionality (scaffolding, stability, strength, diffusivity, etc.). In cell biology, for example, the intracellular cytoplasmic matrix corresponds to a gel-like structure in the interior of cells, based on filaments, microtubules and proteins, that restricts the mobility of molecules in the cytoplasm. Thus, the FM may be viewed as a part of the microstructure of foods, usually corresponding to a spatial domain that contains, interacts with and/or gives particular functionalities to a specific constituent of the food (e.g., a nutrient, odorant molecules, beneficial bacteria, etc.) (Aguilera, 2018).

The organization of chemical compounds in dishes at the various scales (macroscopic, microscopic, mesoscopic, nanoscopic and molecular) determines their physical and biological (sensorial, nutritional, etc.) properties (Aguilera, 2005; This, 2009; Heertje, 2014). For example, both the structural (physical) organization and the chemical composition dictate the textural responses of foods (Stanley, 1987) and their effects on the human body.

The term “matrix effect” has appeared in the food science and technology literature to denote that compounds in dishes and in other formulated products behave differently in isolated form (e.g., in solution) than when forming part of food structures. A first deduction from this definition is that the FM is component-specific, i.e., that different components in the same food may “see” or interact with different matrices. A second deduction is that the FM is scale-sensitive, i.e., interactions of food components may take place at various scales in the same food, hence involving different matrices.

For example, the matrix in bread responsible for the textural properties of the porous crumb consists of the protein-starch walls (a few hundred micrometres in thickness) surrounding the air cells. Starch granules undergo gelatinization during baking while constrained by the continuous gluten matrix (at a scale of 10–100 micrometres); then, at the nanoscale, the hydrated and swollen (or partially swollen) starch granules are the matrix on which α-amylases act during digestion to release glucose or oligosaccharides from amylase.
can be classified in order of the number of phases (themselves ranked in alphabetical order) and in order of “complexity” of operators as ranked using the free energy ($\sigma$, $\gamma$, $\delta$, $\phi$). Here, we use the microscopic scale to describe the main characteristics of some food systems from the food science and technology literature.

**Solid and Liquid Matrices (S)**

Solids and solutions (aqueous solutions W, or “oils” O) are among the simplest food systems; chemical interactions between the molecules of a solid, or between solutes and the solvent (in this case, the matrix), change the release of compounds as compared with pure preparations of these compounds (Ammari and Schroen, 2018).

For example, the matrix of wine corresponds to the aqueous + ethanol phase, which contains organic acids, phenolic compounds (including tannins), glycerol, minor quantities of proteins and saccharides, and odorant compounds (Villamor and Ross, 2013). Most of these chemical species, through their interactions, influence the flavour of wine (Jones et al., 2008). One could assume that solutions are simple systems, but this is not true, as even a dilute solution of sucrose in water contains “aggregates” of sucrose (Kaufman and Dorman, 2008). When solutions contain bigger molecules, more complex interactions take place, and this determines the release of such nutrients as vitamin C and bioactive compounds (carotenoids, flavonoids and other polyphenols) from fruit juices, in particular when crushed or homogenized (fruit “smoothies” contain a lot of fibres, i.e., cellulose or hemicellulose molecules) (Caswell, 2009).

**Emulsions (L₁/L₂) and Suspension (S/L) Matrices**

The next systems after solids and solutions (S) in terms of complexity are emulsions and suspensions. Emulsions are described by DSF formulas such as O/W (oil-in-water), as in mayonnaise, W/O (water in oil) or even W/W (water in water) in some particular Ramsden solutions (Nicolai and Murray, 2017). More generally, a liquid L₁ is randomly dispersed in another liquid L₂, hence the formula L₁/L₂. The concept of the matrix in emulsions, particularly in O/W emulsions, has various interpretations depending on the scale. At the macroscopic scale, the matrix is the continuous phase (L₂) that contains the dispersed phase (L₁), the latter including the interface layer and the interior of the droplets. This viewpoint has been important in studying the (meta)stability of emulsions (e.g., by controlling the make-up of the interfacial layer and the viscosity of the continuous phase). However, at the microscopic and nanoscopic levels, the architecture of the interfacial layer itself is also denominated as a “matrix” and plays a key role in particle-to-particle interactions and protection of the droplet contents against oxidation while allowing entrapment of odorants, for example. Finally, the case of Ramsden emulsions (sometimes wrongly called “Pickering emulsions”), i.e., emulsions stabilized by solid particles that adsorb onto the interface between the two phases, has to be considered, because at this level, the DSF formula is different, which shows that DSF, including the reference scale, could be usefully used for the definition of the FM (Ramsden and Oxon, 1904; Rayner et al., 2014).

**Gel Matrices (X/D3(S), XxD3(S))**

As shown in other chapters in this handbook, gel matrices are important food structures that can hold large amounts of various liquids (e.g., >80%), often within a three-dimensional network, providing a semi-solid material with a specific soft texture behaviour. The network of many food gel matrices is fine-stranded (gelatine and pectin gels) or particulate (protein aggregates), gel matrices possibly holding small elements dispersed in their interior as well as particles (filled gels), oil droplets (emulsion gels) and air bubbles (aerated gels) (Banerjee and Bhattacharya, 2012). Gels can be prepared from a single biopolymer (e.g., gelatin, agar-agar, alginate and some carrageenans), from mixtures of gelling agents (e.g., egg proteins in the white of a soft-boiled egg) and as part of many dishes (aspics, desserts) and confectionery products (e.g., jelly beans). In particular, confectionery gels have quite a complex FM that results from interactions of high-sugar components (sucrose and glucose syrup) and gelling precursors such as starch, gelatin or pectin (Burey et al., 2009). However, as can be seen in the chapter on gels in this book, plant and animal tissues are also gels, owing most of their mechanical properties to the connective tissues (collagen) or to the membrane and cell wall surrounding and binding the gelled cell contents (Vincent, 2008). Most of the time, the use of the word “matrix” in fruit and vegetable studies refers to the entrapment inside cell walls of microstructural elements relevant to foods (e.g., starch granules, protein bodies, etc.) and organelles containing nutrients and functional molecules (e.g., chloroplasts, chromoplasts, etc.). In turn, the cell wall (around 100 nm in thickness) consists of a matrix comprised of cellulose, hemicelluloses, pectins and some structural proteins (Cosgrove, 2005).

**Porous Matrices**

Several foods are porous materials consisting of a continuous matrix, which may be a solid (uncooked meringue) or a gel (bread, marshmallows, etc.), enclosing open or closed gas cells (bubbles or gas channels). Porous matrices may be formed by fermentation and baking, extrusion, aeration or gasification, gas release from chemical reactions, or freeze-drying. In addition, several fruits are naturally porous (most notably apples, which have around 25% porosity). The dispersion of a gas phase within a food matrix not only affects its texture (making the final product lighter) but also changes the appearance, consistency, colour and mouth-feel. Foamed liquid matrices may be used as scaffolds and folded in with sweet or salty fillers, as in soufflés. The texture of porous solid foods and liquid foams largely depends on the properties of the matrix surrounding the dispersed gas phase (Corriadini and Peleg, 2008).

**More Complex Matrices**

In food, there are often more than only two phases, and this leads to more complex matrices (associated with a specific DSF formula). For example, dense matrices are usually low-moisture, glassy, semi-crystalline or crystalline structures. They are found particularly in sugar-based confections and categorized as amorphous (ungrained caramel), glassy (hard candy), crystalline
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Food matrices and matrix effects (rock candy) or partially crystalline (fondants) (Ergun and Hartel, 2009). Food powders produced by spray-drying (e.g., skim milk or instant coffee), milling (flours of cereals or legumes, ground dry spices) and starch flour also belong to the category of amorphous complex matrices. Glassy matrices drastically reduce the mobility of small solutes such as volatile odorants, which become trapped during spray- and freeze-drying (e.g., in instant coffee), or may be produced so as to encapsulate probiotic bacteria, bioactive compounds or flavourings.

FM and Cooking

There are several reasons why chefs and cooks should be aware of FM and the ME. The following is a limited list.

Texture

Let’s take an egg as an example. Although the composition of an egg does not change during heating in hot water, a soft-boiled egg has a texture quite different from that of a hard-boiled egg. We can say that the matrix changes from soft gelatinous (the white) and liquid (the yolk) to a full gel consistency (the white) and a crumbly solid (the yolk).

In the case of baked products, most of the desirable textural properties are ascribed to a matrix formed by a stiff gluten-starch network that occludes a gas phase in different proportions.

Flavour Release

Of course, the release of specific compounds important for flavour (including odour, taste, trigeminal sensation, etc.) is linked to the breakdown of food during oral processing, which comprises biting, mastication, comminution, mixing and lubrication, bolus formation, and swallowing. During mastication, solid and soft food matrices become reduced in size to an extent depending on their physical properties and the chewing behaviour of individuals. Most odorant, taste and trigeminal compounds are detected sensorially or active biologically only when they are released from the FM (Guichard and Salles, 2016). Matrix hydration and breakdown in the oral cavity favour the diffusion and mass transfer of molecules into the saliva and through the gas phase to olfactory or trigeminal receptors in the nose. The nature, amount and interactions of different components liberated from the FM greatly influence odorant and trigeminal perception (e.g., sensations of warmth, coldness, tickling, pain, etc.).

Nutrition

In recent decades, nutritional sciences have become concerned not only about the kind and amounts of nutrients required for good health but also with the fraction of a given nutrient that is actually available to be utilized by our body. Molecular gastronomy also came to consider such questions (This, 2013). The “compound release” (fraction released for a particular physiological process following mastication, digestion and perhaps fermentation in the lower intestine), bioaccessibility of nutrients (fraction released during digestion) and bioavailability (fraction being actually absorbed) are directly related to the FM. Bioconversion and bioefficacy have to do with biochemical transformations of food components once released from the matrix, and their specific physiological and health responses in the body. Bioavailability, rather than the amount of food compounds ingested, has become the criterion to assess the potential nutritional benefits derived from bioactive compounds in foods and to sustain their health claims.

Food Analysis

Quite often, foods are analysed in laboratories for the presence of minor components whose effects on our health could be positive (e.g., micronutrients) or negative (toxic compounds, allergens, pollutants and even pathogenic microorganisms). Laboratory techniques are designed to recover and make available for quantification most of (if not all) the molecules or entities under scrutiny. In the laboratory, drastic size reduction methods (mechanical grinding, ultrasonic disruption) are used to break down the FM, and a variety of solvents and enrichment procedures are used to isolate molecular species (and microorganisms).

These procedures and conditions are quite different from those experienced by foods in the oral cavity and during transit in the gastrointestinal system. There is now ample evidence that many molecules in foods are not released from the food matrix during digestion, and hence are not absorbed into the body. As a matter of fact, we eliminate around 130 grams of wet faeces and 1.4 litres of urine per day, which mainly contain unabsorbed material coming from foods (Rose et al., 2015). For example, intact almond cells surviving mastication and digestion have been found in faeces, and thus, their reported caloric content (based on composition) may be greatly overestimated. In the case of pasta products, extensive size reduction eliminates the encapsulating effect of the protein matrix on starch granules, with a concomitant overestimation of the glycaemic index. ME provided by intact cells or complex matrices may thus be relevant to bioaccessibility and bioavailability studies.

Conclusions

The concept of FMs is now extensively used by food and nutritional scientists to try to explain why some compounds from foods behave differently in a food than in isolated or pure form (e.g., in a solution). Several types of matrices can be recognized in foods that are also referred to in other disciplines: liquids, emulsions, cellular tissues, polymer networks, etc. It follows from this viewpoint that the FM is component-specific and scale-sensitive. Analytical procedures to assess the bioaccessibility of nutrients should preserve the MEs; otherwise, the results will only represent the total amount present in a sample.

REFERENCES

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