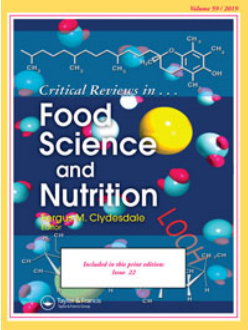

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REVIEW

The food matrix: implications in processing, nutrition and health

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ABSTRACT

The concept of food matrix has received much attention lately in reference to its effects on food processing, nutrition and health. However, the term matrix is used vaguely by food and nutrition scientists, often as synonymous of the food itself or its microstructure. This review analyses the concept of food matrix and proposes a classification for the major types of matrices found in foods. The food matrix may be viewed as a physical domain that contains and/or interacts with specific constituents of a food (e.g., a nutrient) providing functionalities and behaviors which are different from those exhibited by the components in isolation or a free state. The effect of the food matrix (FM-effect) is discussed in reference to food processing, oral processing and flavor perception, satiation and satiety, and digestion in the gastrointestinal tract. The FM-effect has also implications in nutrition, food allergies and food intolerances, and in the quality and relevance of results of analytical techniques. The role of the food matrix in the design of healthy foods is also discussed.

KEYWORDS
Matrix effects; microstructure; bioavailability; nutrition; fermentation; healthy foods

Introduction

Foods are commonly associated with nutrients such as protein, fats and carbohydrates, and some minor components (salt, a few vitamins, sodium, calcium and iron, additives, etc.) that appear in nutrition labels. Less known is that in a product these nutrients are neither homogeneously dispersed nor in a free form, but as part of complex microstructures (McClements 2007; Aguilera 2013). Evidence accumulating in the last 40 years has given a great importance to the structure of foods and its relation with desirable physical, sensorial, and nutritional properties, and derived health implications. Food microstructure identifies organizational and architectural arrangements of discernible elements at different length scales, and reveals structural interactions that may explain specific properties and functionalities of a food (Raeuber and Nikolaus 1980; Heertje 1993; Aguilera 2005). For example, food scientists recognized early on that the microstructural organization rather than the chemical composition dictated the textural responses of major foods (Stanley 1987). The subject of food microstructure is covered in several journals, and the book by Morris and Groves (2013), among others.

The term "food matrix" has appeared in the food technology and nutrition literature to denote that chemical compounds in foods behave differently in isolated form (e.g., in solution) than when forming part of food structures. For example, sucrose dispersed in the aqueous phase within the network of a 2% Ca alginate gel exhibits a mass diffusivity which is 86% that as a solute in pure water (Aguilera and Stanley, 1999:238). Special reference in these articles is made to nutrients and bioactive compounds that deliver health benefits beyond their basic nutritional value. The food matrix has been described as the complex assembly of nutrients and non-nutrients interacting physically and chemically, that influences the release, mass transfer, accessibility, digestibility, and stability of many food compounds (Crowe 2013). The food matrix affects directly the processes of digestion and absorption of food compounds in the gastrointestinal tract (GIT). It is also relevant in the microbial fermentation of some unabsorbed compounds and the absorption of resulting metabolites in the colon. After absorption in GIT and prior to entering the systemic circulation, some compounds released from the food matrix undergo biotransformations in the intestinal epithelium and the liver before reaching the sites of action in body tissues or being excreted in the urine (Motilva, Serra and Rubio 2015).

In recent decades, nutrition science became 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. Table 1 summarizes some of concepts that are used to describe the physiological fate of nutrients, bioactive compounds and metabolites, as they move from digestion into to the sites of their specific metabolic actions in the body.

The bioaccessibility of nutrients (fraction released during digestion) and the bioavailability (fraction being actually absorbed) are directly related to the food matrix.

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Table 1. Terminology used in food matrix studies and associated with nutritional/health effects.

Term	Accepted definition	Selected references
Bioaccessibility	Fraction of an ingested compound (nutrient, bioactive) which is released or liberated from the food matrix in the GI tract.	Carbonell-Capella et al. 2014; Galán and Drago 2014; Parada and Aguilera 2007.
Bioavailability	Fraction of a given compound or its metabolite that reaches the systemic circulation.	Motilva, Serra, and Rubio 2015; Carbonell-Capella et al. 2014; Parada and Aguilera 2007.
Bioconversion	Fraction of a bioavailable nutrient that is converted to its active form from an absorbed precursor (e.g., retinol from provitamin A).	Lietz 2013; van Lieshout, West, and van Breemen 2003; Castenmiller and West 1998.
Bioactivity	Specific effect of a compound in the body. It includes tissue uptake and the consequent physiological response (e.g., antioxidant, anti-inflammatory, etc.).	Carbonell-Capella et al. 2014; Honest, Zhang, and Zhang 2011; Lavecchia et al. 2011
Bioefficacy (or bioefficiency)	Fraction of an ingested nutrient converted to the active form after biotransformation in the body that produces desirable (or undesirable) human health outcomes in target populations.	Lietz 2013; Rein et al. 2013; Holst and Williamson 2008; van Lieshout, West, and van Breemen 2003.

Bioconversion, bioactivity 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 nutrient ingested, has become the criterion to assess the potential nutritional benefits derived from nutrients and bioactive compounds in foods, and to sustain their health claims (Holst and Williamson 2008; Rein et al. 2013; Pressman, Clemens, and Haye 2017).

The importance of relating the food matrix, nutrition and health is better appreciated in Figure 1 that is based on a search of abstracts in the databases Food Science and Technology Abstracts (FSTA) and Medline (both accessed on March 6, 2018), containing both terms, "food matrix" and "bioavailability". The total number of matches and the date of first entry in each database were 249 and 385, and 1986 and 1989, respectively. As shown in Figure 1, while in the period prior to 2006 the average number of abstracts per year was below five, in the last five years (2013–2017) the yearly number of abstracts including both terms multiplied by a factor of ten. Carotenoids, polyphenols, vitamins, iron and calcium represent the majority of nutrients referred to in these publications. Inspection of the text of several of the articles involved revealed that the term "food matrix" was used ambiguously. In many cases, "matrix" appeared in the title of the article but was not defined and only sparingly

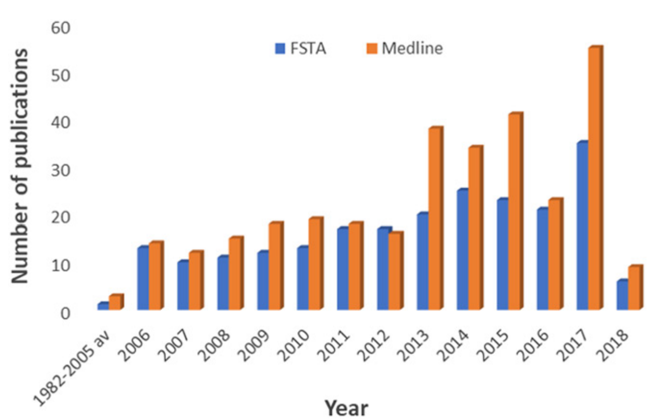


Figure 1. Number of abstracts containing the terms *food matrix* and *bioavailability* in publications listed in the databases Food Science and Technology Abstracts (FSTA) and Medline. (Accessed on March 6, 2018).

referred to later in the contents. Commonly, matrix was used to represent "a physical part of a food" or simply as synonymous of the whole food.

This review deals with aspects of food processing, digestion, nutrition and health related to the food matrix, rather than on specific nutrient-matrix interactions that have been reviewed elsewhere (Parada and Aguilera 2007; Lietz 2013; Sensoy 2014; Pressman, Clemens, and Haye 2017; Fardet et al. 2018). The aim is to put forward the concept of food matrix, propose a classification of food matrices and their properties, and discuss the use of the term in different contexts. This will facilitate the identification and mechanisms of interactions between the food matrix and food constituents, in addition to the potential implications of these interrelations in food quality, nutrition and health.

The concept of food matrix

Most dictionaries define 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, the cytoplasmic matrix corresponds to a gel-like structure in the interior of cells where filaments, microtubules and proteins exert their biological roles, and molecules have a restricted mobility (Gershon, Porter, and Trus 1985). Some cells may also possess an exocellular matrix in the form of a scaffold of proteins and polysaccharides which allows for morphogenesis and differentiation (Frantz, Stewart, and Weaver 2010). In pharmacology, several types of liquid and solid matrices are used to contain, protect and deliver drugs (Patel et al. 2011). In polymer science, composites (which are close to several food structures) consist of a matrix or continuous phase in which structural elements (usually fibers or particles) are dispersed to enhance the mechanical performance of the material (Wang, Zheng, and Zheng 2011).

It is quite common in the food science and nutrition literature that "matrix" is referred to as the actual food which contains a nutrient or a mixture of them, either naturally or purposely included. Galán and Drago (2014) added enteral formulas to conventional foods (referred to as matrices) in order to seek new flavors and textures, and assessed the bioavailability of minerals. Flach et al. (2017) reviewed the shelf-life, survival in the gut, and clinical efficacy of probiotics in "matrices" that in fact, were commercial food products (fermented milks/yogurts, cheese, sausages, etc.). Often the food matrix is confounded with the microstructure itself, and viewed as the structural organization of all food components at multiple spatial length scales (Capuano, Oliviero, and van Boekel 2017; Guo et al. 2017). Sometimes, the term matrix is used instead of phase, as in the study of microbial inactivation within fat droplets in an emulsion (van Boekel 2009).

In fact, the food matrix is a part of the microstructure of foods, usually corresponding to a physical and spatial domain, that contains, interacts directly and/or gives a particular functionality to a constituent (e.g., a nutrient) or element of the food (e.g., starch granules, microorganisms). A first deduction from this concept is that the food matrix is component-specific, i.e., different components (or structural elements) in the same food may "see" or interact with different matrices. For instance, during heating of milk or cream, whey proteins undergo denaturation in the aqueous plasma, while the solid fraction of milk fat melts inside the fat globules (Kulozik 2008). In the same plant tissue, the bioaccessibility of carotenoids depends on their liberation from intracellular organelles (chromoplasts and chloroplasts), while the derived nutritional effects of dietary fiber are mostly related to the degradation of the external cells walls (Dhingra et al. 2012; Raikos 2017). A second inference is that the matrix of a food is scale-sensitive i.e., interactions 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 are the protein-starch walls surrounding the air cells, and the relevant scale is on the order of a few hundred microns (Liu and Scanlon 2003). Starch granules undergoing gelatinization during baking may be regarded as inclusions in the continuous gluten matrix at a scale of approximately 10 μm (Maeda et al. 2013). At the nanoscale, gelatinized starch granules are the matrix onto which α-amylases exert their action during digestion to release glucose molecules (Dhital et al. 2017). As mentioned before, carotenoids in many yellow-, orange-, and red-colored plant tissues, are deposited inside cells (50–80 μm in size) in substructures of chromoplasts (a few μm in size) as crystalloids and small globular units dissolved in lipids (Schweiggert et al. 2012). Figure 2 presents a scheme summarizing the role of the food matrix in bioaccessibility and bioavailability, as well as the concepts of scale sensitivity and constituent specificity.

A classification of food matrices

What follows is an attempt to classify food matrices into basic types and describe their main characteristics. This classification is based on cases taken from the food science and nutrition literature and on the use of the term matrix in related sciences. Evidently, some overlapping exists among the proposed types of matrices due to the complexity of structures present in foods.

Liquid matrices

Blood is a good example of a fluid having living cells and other biological elements contained in a liquid matrix. Biologists recognize as the matrix of blood either the plasma (liquid after removal of blood cells) or the serum (liquid remaining after clotting) (Yu et al. 2011). In milk, the aqueous liquid matrix is also either called plasma (milk excluding fat globules) or serum (plasma less casein micelles but including the soluble proteins) (Walstra, Wouters, and Geurts 2006). The matrix of wine corresponds to the aqueous/ethanol phase containing polyphenolic compounds, polymeric pigments (tannins), minor quantities of proteins and carbohydrates, and the aroma compounds (Villamor and Ross 2013). Most fruit juices are good sources of vitamin C and bioactives (carotenoids, flavonoids and other phenolic compounds), but contain abundant sugars, hence, they have a high caloric content (e.g., 60–80 kcal/150 mL). However, the liquid matrix permits the addition of crushed

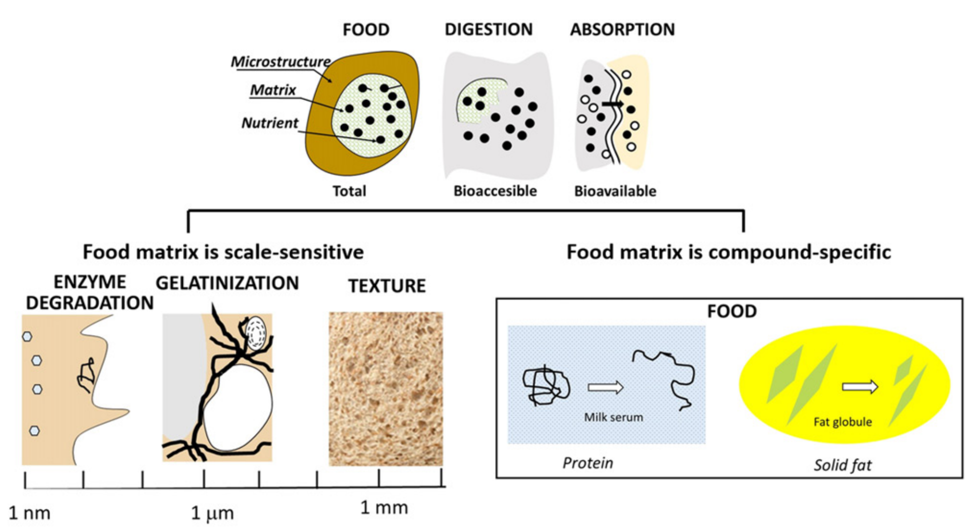


Figure 2. Simplified scheme summarizing the role of the food matrix in bioaccessibility and bioavailability, and the concepts of scale-sensitivity in bread (bottom left) and compound-specificity in milk (bottom right).

or homogenized fruit (smoothies), thus increasing the amount of fiber (Caswell 2009).

Emulsion matrices

The concept of matrix in liquid emulsions, particularly in oil-in-water (O/W) emulsions, has two interpretations depending on the scale. At the macroscale, the matrix is the continuous phase which contains the dispersed phase formed by the interface layer and the interior of the droplets. This viewpoint has been important in studying the stability of emulsions (e.g., by controlling the make-up of the interfacial layer and the viscosity of the continuous phase) and in the development of rheological models based on phase volume and droplet size (Rao 2007; Dickinson 2008). At the sub-micron level, the architecture of the interface itself is also denominated "matrix" and plays a key role in particle-to-particle interactions and the protection of the droplets' content (Dickinson 2009). For example, oxidation of lipids in O/W emulsions having very small droplets may be lessened by locating specific types of proteins and other hydrocolloids at the interphase (Chen, McClements, and Decker 2013). The retention of aroma compounds in emulsions depend on the type and composition of the aqueous matrix along with their specific interactions with proteins adsorbed at the interface of fat droplets (Seuvre, Espinosa-Díaz, and Voilley 2000). Several emulsion-based delivery systems (e.g., nanoemulsions, multilayer emulsions, solid lipid particles, filled hydrogel particles, etc.) have been proposed as matrices for lipids and bioactives to induce satiety, delay digestion, increase the bioavailability of lipids, and the targeting of lipophilic bioactive components in the gut (McClements and Li 2010).

Gel matrices

Gels are important food structures that can hold large amounts of water (e.g., $>80\%$) within a biopolymer network, providing a semi-solid texture and a viscoelastic behavior. The polymer network of food gel matrices can be fine-stranded (gelatin, pectin gels) or particulate (protein aggregates). Gel matrices may hold small elements dispersed in their interior: particles (filled gels), oil droplets (emulsion gels), and air bubbles (aerated gels) (Banerjee and Bhattacharya 2012). Although gels prepared with a single biopolymer (e.g., gelatin or agar) are common in desserts and confectionery, the major role of gel matrices is as texture provider in multicomponent foods such as processed meats (frankfurters), dairy products (yoghurt and cheeses), and fruit preserves and jams.

Cellular matrices

Plant tissues are hierarchical composites owing most of their mechanical properties to the thick walls surrounding the cell contents and binding the cells together (Vincent 2008). The cell walls provide tensile strength and protection against mechanical stresses, and allow cells to develop an internal turgor pressure. Most of the time the use of the word matrix in fruits and vegetables studies refers to the entrapment inside cell walls of microstructural elements relevant in foods (e.g., starch granules, protein bodies, etc.) and organelles containing nutrients and functional molecules (e.g., chloroplasts, chromoplasts, etc.). The cell wall (around 100 nm in thickness) consists of a hydrated matrix of glucuronoxylans, xyloglucans, pectins, and some structural proteins, reinforced with cellulose microfibrils (Cosgrove 2005). Cell walls have been associated to the edible quality of fruits and vegetables as well as to the digestibility of plant materials (Barrett, Beaulieu, and Shewfelt 2010; Ogawa et al. 2018).

Network exocellular matrices

Exopolysaccharides (EPS) secreted by microorganisms, mainly *Lactobacillus* species, impart rheological properties to some fluid food matrices, e.g., increased viscosity, improved texture and reduced syneresis. EPS are classified as homopolysaccharides and heteropolysaccharides, and are either secreted into the medium by bacteria or anchored as a capsule around them. In fermented dairy products such as yoghurt, kefir, and fermented cream, secreted EPS interact with whey proteins and casein micelles increasing the viscosity and binding water (Duboc and Mollet 2001; Patel and Prajapati 2013). Furthermore, it has been reported that EPS can positively affect gut health by providing protection against chronic gastritis by adhering to the gut mucosa. It has also been claimed that EPS have therapeutic properties such as antitumor, anti-mutagenic, anticancer and cholesterol-lowering effects as well as immuno-stimulatory activity (Patel and Prajapati 2013; Singh and Saini 2017).

Fibrous extracellular matrices

Collagen is the most abundant extracellular matrix protein in animal tissues. In biophysics, fibrous extracellular matrices of collagen and elastin provide integrity to biological tissue (are a cellular "glue") and the capacity to withstand stresses without a permanent plastic deformation or rupture (Muiznieks and Keeley 2013). Meat basically consists of long muscle fibers surrounded by layers of connective tissue, and interspersed by adipose tissue (marbling). The fibrous connective tissue in meat forms a continuous extracellular matrix composed mostly of collagen. This extracellular matrix plays a definite role in the texture of meat as collagen crosslinks become stronger with animal aging, with the concomitant increase in the mechanical properties of the matrix and the progressive toughening of meat (Nishimura 2010). Cooking meat to a tender texture is a balance between promoting the shrinkage and solubilization of the collagen matrix into gelatin (a process starting at around 60 °C) and slowing down the denaturation of myofibrillar proteins in meat fibers, leading to toughening and drip loss, that takes place between 52.5 and 60 °C (Zielbauer et al. 2016). This is the basis of *sous vide* cooking of meats and the reason for holding them for several hours below 70 °C. Collagen is digested and absorbed partly as dipeptides that have shown some physiological activity (Koyama 2016).

Viscoelastic matrices

There are a few food materials that recover their original shape after continuous cycling under large deformations. Hydrated wheat gluten is an important viscoelastic matrix in foods which imparts unique properties to baked products. The viscoelastic properties of wheat dough are primarily due to the interaction between two types of proteins: glutenins and gliadins. In a dough, the high-molecular weight glutenins provide the elastic properties while gliadins act as a plasticizer, and are responsible for the viscous properties. Gluten in baked and pasta products is referred to as a protein network and a matrix that holds starch filler particles (Jekle and Becker 2015; Kontogiorgos 2011). The formation of a viscoelastic protein network is crucial for gas retention during dough proofing, and in the final setting into a porous structure in baked products like bread and cakes. In chewing gum, another elastic network, the rubber-like gum base forms a continuous matrix where sugars (or sweeteners), glycerol and flavorings are dispersed in a discontinuous aqueous phase (Potineni and Peterson 2008).

Dense matrices

Dense matrices are usually low-moisture, glassy, semi-crystalline or crystalline structures. These types of matrices are frequently used in pharmacology to contain drugs (Baghel, Cathcart, and O'Reilly 2016). They are also found in foods, particularly in sugar-based confections, and categorized into amorphous (ungrained caramel), glassy (hard candy), crystalline (rock candy) or partially crystalline (fondants) (Ergun and Hartel 2009). Food powders produced by spray-drying (e.g., skim milk, instant coffee), milling (flours of cereals or legumes, ground dry spices), and starch flour, also belong to this category (Bhandari et al. 2013). Amorphous or glassy matrices are formed during processing by the fast removal of water from a solution and/or by rapid cooling (Roos 1998). Matrices of spray dried powders are mostly in the glassy state and result in different particle morphologies depending on the composition of the feed and processing conditions (Nandiyanto and Okuyama 2011). Given that small solutes such as volatile aroma molecules exhibit a reduced diffusivity in glassy matrices (e.g., on the order of 10^{-14} m^2 s^{-1}), they are trapped during spray- and freeze-drying (e.g., in instant coffee), or encapsulated as flavors. Triacylglycerol molecules crystallize into densely packed microcrystals which become arranged hierarchically into clusters and eventually form fat crystal networks that may span in size from the nanoscale to a few hundred micrometers (Tang and Marangoni 2006). These "crystalline matrices" may occlude in their interior liquid fat and water providing the desirable plasticity and sensorial properties of fatty foods such as margarine and low-calorie fat spreads (Heertje 2014).

Matrices of porous materials

Several foods are porous materials consisting of a continuous matrix which may be solid (bread), viscoelastic (marshmallows) or liquid (whipped egg white), that encloses a dispersed phase in the form of open or closed gas cells (bubbles). Porous matrices may be formed by fermentation and baking, extrusion, aeration, gas release from chemical reactions and freeze-drying (Niranjan and Silva 2008). Dispersing a gas phase within a food matrix not only affects its texture and firmness (making the final product lighter), but also changes the appearance, color 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 foods largely depends on the properties of the matrix surrounding the dispersed gas phase (Corriadini and Peleg 2008). Some porous extracellular matrices of fruits and vegetables can be infiltrated with solutions of sugar, salts, acids, flavorings or vitamins to modify their texture, flavor, shelf life and nutritional properties (Gómez Galindo and Yusof 2014).

Artificial matrices

Some food matrices are specially built to contain, protect and control the delivery of compounds (flavors, bitter peptides, nutrients, bioactive molecules) and microorganisms. Often a distinction is made between encapsulation and entrapment of a bioactive substance or microorganism. Usually, encapsulation refers to building a thin protective shell around the object to be protected. Entrapment means trapping the compound of interest within or throughout a matrix, e.g., in a gel or an amorphous carbohydrate phase (Pegg and Shahidi 2007)[TQ1]. The subject of encapsulation and delivery systems in foods, including the technologies used for their fabrication are covered elsewhere (Madene et al. 2006; Lakkis 2016). Encapsulation of beneficial bacteria and bioactives to modulate their delivery and action in the GIT is an area of active matrix design (McClements et al. 2009). Matrix materials are selected according to their physicochemical properties (e.g., proteins that can form complexes with bioactive molecules) and the ability to induce a determined release mechanism and kinetics (Crowe 2013). Several adjuncts (skim milk, whey proteins, etc.) may be added to the formulation to provide protection to microorganisms preserved by freeze-drying and spray drying. Matrices for microbial encapsulation that involve a freezing step may include cryo-protectants to prevent damage to cell membranes (Alonso 2016). Table 2 summarizes the proposed classification of food matrices, presents the main relevant features, and gives some examples.

The food matrix effect (FM-effect)

Most of the recent interest in the food matrix derives from its particular interactions with food components that modify their properties compared to those exhibited when they are in the free form (e.g., in solution). Differences among food matrices are largely responsible for the nutritional performance and health potential of products that have similar chemical composition (Fardet 2014; Capuano,

Table 2. Classification of food matrices.

Type of matrix	Examples	Relevance	Selected references
Liquid (aqueous)	Plasma and serum in fluid milk; aqueous/ethanolic medium plus small components in wine; aqueous phase in fruit juices.	Hold elements (caseins, fat globules) for structuring dairy products; participate in aroma release and taste perception.	Villamor and Ross 2013; Aguilera 2006; Walstra, Wouters, and Geurts 2006; Seuvre, Espinosa-Díaz, and Voilley 2000.
Liquid (emulsions)	Continuous phase in O/W emulsions (mayonnaise, salad dressings, etc.).	Influence rheological properties and stability); act as carrier of bioactives; interface may restrain digestion of lipids.	Chen, McClements, and Decker 2013; Dickinson 2008, 2009; Wilde and Chu 2011.
Gels	3-D networks formed by proteins and polysaccharides (yoghurt and desserts; processed meats, etc.).	Provide structure to soft and moist textures; enclose fat droplets; modulate flavor intensity and prolonged perception.	Banerjee and Bhattacharya 2012; Corredig, Sharafbafi, and Kristo 2011; Wilson and Brown 1997.
Cellular	Natural structure of most fresh fruits and vegetables consumed as foods.	Cell walls contribute to texture and turgor, encase nutrients, affect bioaccessibility during digestion and provide dietary fiber.	Ogawa et al. 2018; Grundy, Lapsley, and Ellis 2016; Mandalari et al. 2008; Aguilera and Stanley 1999.
Network exocellular	Exopolysaccharides in fermented dairy products (yoghurt) and in some fermented vegetables.	Increase viscosity; claimed to provide beneficial nutritional and health attributes.	Singh and Saini 2017; Patel and Prajapati 2013; Duboc and Mollet 2001
Fibrous extracellular	Collagen network in connective tissue surrounding and binding muscle fibers in meats.	Influence the toughness of cooked meats by persisting in binding together muscle fibers after cooking.	Tornberg 2013; Nishimura 2010
Viscoelastic	3-D network of proteins filled with starch developed in wheat dough (baked and pasta products).	Contain the expansion of gas bubbles in baked during baking and restrict gelatinization/digestion of starch in pasta.	Jekle and Becker 2015; Kontogiorgos 2011.
Dense	Compact and brittle structures of flours, dry powders, milk chocolate, etc.	Usually amorphous or semi-crystalline structures providing stability and convenience in use as ingredients.	Hutchings et al. 2011; Nandiyanto and Okuyama 2011.
Porous	Low-density foods products. Extruded snacks, aero-chocolate, instant coffee powder, etc.	Provide a light texture, and changes in the appearance and mouth-feel. Ease of rehydration and reconstitution.	Saguy and Marabi 2009; Niranjan and Silva 2008.
Artificial	Flavors, bioactives or microorganisms encapsulated in gels or within solid walls.	Contain, protect and allow control of the delivery of compounds or microorganisms by selecting the encapsulating formulation.	Martin et al. 2015; McClements et al. 2009; Pegg and Shahidi 2007

Oliviero, and van Boekel 2017). This phenomenon has been generically called the "food matrix effect" (FM-effect) (Lecerf and Legrand 2015; Zou et al. 2015; Givens 2017). The term FM-effect started to be used in the late 1990s by nutrition scientists who found that the bioavailability of carotenoids in blood plasma was five times higher when consumed as supplements dissolved in oil than when eaten from raw carrots (Castenmiller and West 1998). Researchers attributed the difference to the complexing of carotene with proteins in chloroplasts, and the entrapment within plant cell structures that made them unavailable after digestion. Polyphenols with a high antioxidant activity *in vitro*, exhibited a poor bioaccessibility when consumed from fruits and vegetables that was attributed to a "plant effect" (Dufour et al. 2018). Furthermore, it was found that nutrients and bioactives released from the food matrix in the small intestine could undergo several interactions with other food components or become biotransformed into beneficial metabolites by the gut microbiota before being absorbed (Holst and Williamson 2008; Palafox-Carlos, Ayala-Zavala, and González-Aguilar 2011; Rein et al. 2013). FM-effects that have been found to exist beyond those related to nutrition are briefly reviewed below.

Food processing

Main aims of food processing are to prolong the shelf life of foods, and add value to diets by providing safety, convenience, variety, and nutrition. Several unit operations and processes involving heat, mass and momentum transfer have been applied for centuries to different materials to achieve these purposes, with concomitant changes in the physical, chemical, biochemical, microbiological, organoleptic and nutritional properties of foods (Fellows 2009; Clark, Jung, and Lamsal 2014; Weaver et al. 2014). Food processing may have beneficial effects such as the improvement of taste, texture and microbiological safety, and increases in digestibility and the bioavailability of some nutrients (Capuano et al. 2018). Severe heating may have deleterious consequences in terms of loss of nutrients, aggregation of proteins, polymerization of oxidized lipids, and the formation of some toxic compounds (Hoffman and Gerber 2015; Capuano et al. 2018).

In the last few decades and with the aid of microscopy tools and materials science concepts, the implications of food processing at the microstructural level started to be unveiled, leading to the view that processing (including cooking) was a controlled effort to preserve, destroy, transform and create edible structures (Aguilera and Stanley 1989; Aguilera 2013). This approach led to structure-property relationships that extended to texture, flavor, shelf-life, product design and nutrition (Aguilera 2005).

Since matrices are part of food structures, they are also subject to some major changes during processing, particularly in their physical state (e.g., due to phase and state transitions), chemical condition (e.g., due to thermal reactions and solubilization), and the state of aggregation or dispersion (e.g., particulated, gelled, emulsified), among others (Bhandari and Roos 2012). The effect of processing on nutrition has been a preoccupation for a long time of food technologists and nutritionists alike (Harris and von Loesecke 1960). However, the relationship between processing and the food matrix, and the resulting implications in quality, digestion, nutrition and health are a subject of recent interest (Parada and Aguilera 2007; Sensoy 2014). Many food components (e.g., sucrose, oil, wheat flour) are released from their original matrices in plant tissues and converted into useful ingredients that are later combined and processed into products. Casein and fat globules in milk become "activated" through heating, shearing and enzymatic treatments to originate the matrices of emulsions (butter), gels (yogurt, soft cheeses), foams (whipped cream) and powders (dried milk), among others (Aguilera 2006). Details of the science and technology behind the formation of dairy matrices can be found in Corredig, Sharafbafi, and Kristo (2011) and Kulozik (2008). Cellular matrices found in plant foods and muscle tissue undergo major transformations during processing and cooking. Cooking of grains, tubers and legumes produces a softer texture and increases the digestibility as the intercellular cement holding the matrix together becomes solubilized, and the starch granules are hydrated and gelatinized (Singh, Dartois, and Kaur 2010; Aguilera and Stanley 1999). In meats, the collagen matrix binding muscle fibers is disrupted and partly solubilized by heating which contributes to the tenderness of the tissue (Tornberg 2013). Destruction of cellular matrices by processing allows the liberation several functional components (e.g., carotenoids, polyphenols and glucosinolates) and vitamins, improving their bioaccessibility. Disruption of the food matrix allows the release of carotenoids and their solubilization within mixed micelles prior to intestinal absorption (Raikos 2017). Homogenization of fruit flesh into juice improves the bioavailability and antioxidant capacity of functional bioactives (Quirós-Sauceda et al. 2017). In the case of lycopene, food processing allows for the transformation of the naturally occurring *all trans*-isomers to *cis*-isomers that are more bioavailable and bioactive (Honest, Zhang, and Zhang 2011).

Fermentation

Processing by natural fermentations takes place in a wide variety of food sources: milk and dairy products, cereal doughs, grape musts, meats, cereals and grains, vegetables and seafoods (e.g., fish sauces). Microbial fermentation induces favorable changes in natural food matrices by creating new textures, flavors and metabolites. Less is known about the role of germination and fermentation on the food matrix and their effects on nutrition. Germination (sprouting) of cereals and legumes partly hydrolyze cell walls and the different storage constituents of the grains with the improvement in the contents of certain essential amino acids, total sugars, B-group vitamins, and minerals, as well as a decrease of some anti-nutritional factors. The digestibility of proteins and starch are improved due to their partial hydrolysis during sprouting (Lorenz and D'Appolonia 2009). From a microstructural viewpoint, the action of enzymes released by microorganisms on cell walls not only makes these structures more permeable during cooking and digestion but also liberates some of the nutrients locked inside plant cells. The subject of natural food fermentations is receiving much attention due to the beneficial health contributions of fermentative microorganisms as probiotics, producers of bioactive metabolites and in improving the bioaccessibility of nutrients (Marco et al. 2017). However, these beneficial effects are sometimes offset by the potential formation of toxic biogenic amines, already detected in wine and dairy products (Bourdichon et al. 2012; Spano et al. 2010). Given the consumers' trend towards the consumption of "natural" and minimally processed foods as well as the demand for probiotic foods, the study of food fermentations in new and lesser known food matrices becomes imperative. Applications of metagenomics (the analysis of DNA from microbial communities) are likely to produce advances in the use of microbial genetic resources, the understanding of the activities of beneficial microbes in food fermentations, and to ensure process control, quality and safety of products (de Filippis, Parente, and Ercolini 2017).

Oral processing and flavor perception

Oral processing involves biting, mastication, comminution, mixing and lubrication, bolus formation and swallowing. During mastication, solid and soft food matrices become reduced in size depending on their physical properties and the chewing behavior of individuals, e.g., chewing force, salivation volume and time to swallowing (Bourne 2002). The average particle size and broadness of the size distribution curve before swallowing the bolus varies considerably among individuals and depend on the type of matrix and state of the filler, as shown for peanuts dispersed in hard and soft matrices (Hutchings et al. 2011). Disintegration of the food matrix in the mouth leads to interactions between some of the released food components, and the proteins and enzymes present in saliva. Polyphenols released in the mouth react with proline-rich salivary proteins forming insoluble complexes responsible for the perception of astringency of various food products, e.g., chocolate, coffee, tea, beer and wine (Gallo et al. 2013). During chewing, some starch is hydrolyzed into glucose and dextrins by salivary α-amylase but the degree of hydrolysis ranges considerably depending on the food type and the physical state of starch.

Most flavors (tastants and aromas) need to be released from the food matrix to be perceived during oral processing and the post swallowing steps (Salles et al. 2011; Guichard and Salles 2016). Matrix hydration and breakdown in the oral cavity favors the diffusion and mass transfer of molecules into the saliva and the transport of volatiles into the gas phase and receptors in the nose (de Roos 2006; Voilley and Souchon 2006). The nature, amount and interactions of different components present in the food such as proteins, lipids and carbohydrates greatly influence aroma release and perception (Paravisini and Guichard 2016). In the case of proteins, molecular interactions take the form of ionic bonding, hydrogen bonding, and hydrophobic bonding. The presence of lipids influences partitioning of aroma compounds between the oil and the aqueous phase and, consequently, their presence in the gas phase. Polysaccharides cause a reduction in aroma release by increasing the viscosity of the liquid matrix and/or direct molecular interactions with flavor compounds (Voilley and Souchon 2006). Increasing the mechanical strength of the matrices resulted in longer chewing times, lower intensity but a more prolonged flavor perception (Wilson and Brown 1997).

Aroma compounds in wine may interact with several components dispersed in the wine matrix, among them, yeast walls, bentonite, polyphenolic compounds (specifically tannins), proteins, carbohydrates as well as ethanol (Voilley and Lubbers 1998; Villamor and Ross 2013; Baker and Ross 2014). In processed meats, salt replacers may substitute sodium chloride in the matrices without affecting flavor when products have a complex flavor profile, e.g., they contain spices and smoke (Gaudette and Pietrasik 2017). Studies in salsa demonstrated that pungency caused by capsaicinoids depended on the complexity of the matrix, i.e., the intensity was larger in model salsas containing extra oil and starch than real ones (Schneider, Seuß-Baum, and Schlich 2014). The sensory quality of milk was largely influenced by casein micelles and fat globules dispersed in the aqueous matrix (Schiano, Harwood, and Drake 2017). New sensory methodologies are advancing the understanding of flavor release and flavor-matrix interactions in real foods, among them, the kinetic analysis of flavor release using time-intensity curves (Frank et al. 2012).

Satiation/satiety

Satiation (end of eating) and satiety (time between eating periods of hunger) are key factors in appetite control, hence, on the reduction in food intake during and between meals, so different strategies are being used to induce both sensations. Management of FM-effects involves not only the selection of food components with intrinsic satiating properties (e.g., proteins and fiber) but also rheological and structural properties of the food. In general, solid foods have stronger effects on satiety than liquid food matrices of equal caloric value (Chambers, McCrickerd, and Yeomans 2015). Structured dairy products, such as yoghurt and cheese produce a higher satiety than fluid milk (Turgeon and Rioux 2011). In the stomach, increased gastric volume induces both sensations by activating stretch receptors in the smooth muscles, and delaying gastric emptying (van Kleef et al. 2012). Several studies report that gums and gelling food fiber giving a high viscosity matrix elicit a satiation response by delaying gastric emptying or retarding the action of digestive enzymes (Fiszman and Varela 2013). These examples suggest that satiation and satiety could be managed in a food by providing the same nutrients but structured as different matrices (Campbell, Wagoner, and Foegeding 2017).

Food matrices in the GIT

Food digestion is completed in the gut. During digestion, the swallowed bolus undergoes mixing, shearing and transporting as well as acid and enzymatic transformations before the major food components (proteins, lipids, soluble and insoluble carbohydrates) become available as absorbable units (Boland 2016). The effect of microstructure and food matrices on digestion and nutritional properties of foods was reviewed by Turgeon and Rioux (2011). Significant advances have been made in the understanding and modelling of the breakdown of foods in the mouth and the rheological dynamics of food digestion in the stomach (Ferrua, Xue, and Singh, 2014; Lentle and Janssen 2014). As known from the early 1950's, the digestion of solid matrices in the stomach depends largely on their breakdown into small particles, the particle size and surface area, and the nature of these surfaces (Yurkstas and Manly 1950; Lentle and Janssen 2014). The gut microbiota plays a major role in nutrition and health by digesting complex indigestible polysaccharides, and biotransforming unabsorbed compounds such as some polyphenols and bile salts (Oriach et al. 2016; Ercolini and Fogliano 2018). Thus, several foods have been used as delivery carriers for prebiotics and probiotic bacteria, assuring their survival and activity in the host (Espírito Santo et al. 2011). Moreover, specialized bacteria have the ability to degrade fragments of matrices occluding undigested starch granules and remnants of plant cell walls (Flint et al. 2012). An audacious proposition has been to design food matrices with a low bioavailability so that unabsorbed compounds can be utilized to feed beneficial bacteria in the colon (Ercolini and Fogliano 2018).

Three classes of foods have attracted much attention in recent times in regards to their unique degradation patterns during digestion, and the concomitant nutritional and health consequences: milk and dairy products, almonds and other whole nuts, and pasta products. For this reason they deserve a special discussion in relation to the characteristics of their matrices that may explain the particular behaviors.

Milk and dairy products

The digestion of milk proteins by humans has not been suitably studied *in vivo*, but it is well known that gastric emptying of casein takes much longer than for whey proteins, and that both proteins are extensively degraded to peptides when entering the small intestine (Ross et al. 2013). Some of the formed peptides interact with small fat globules in homogenized, pasteurized milk retarding complete protein digestion (Tunick et al. 2016). Recent evidence indicates that the dairy matrix may induce attenuated negative nutritional effects than previously thought for dairy products (e.g., high contribution of cholesterol and saturated fat to the diet, higher risk of hypertension, etc.). Physical characteristics of the matrix (e.g., compactness, hardness and elasticity, size of fat globules) as well as chemical parameters such as the protein/lipid ratio, P/Ca ratio, appear to have a positive influence on the bioavailability of amino acids, fatty acids and calcium (Fardet et al. 2018). Long chain saturated fatty acids may be precipitated as Ca soaps or form crystals at body temperature during digestion, thus increasing fecal excretion of saturated fats and reducing their absorption (Gallier and Singh 2012). Some recent studies have shown a significant reduction in the risk of stroke and type 2 diabetes by consuming milk, cheese and yoghurt (Givens 2017). This topic has recently been addressed in Thorning et al. (2017) who concluded that "evidence to date indicates that the dairy matrix has specific beneficial effects on health, e.g., in bodyweight, cardio-metabolic disease risk, and bone health". Research underway will shed light on the potential beneficial effects of the matrix of dairy products on health.

Almonds

In spite of their high-caloric density, nut consumption may reduce the risk of coronary heart disease and favor a lower incidence of obesity and weight gain (Sabaté and Ang 2009). The effect of the cellular matrix on the digestibility of hard nuts has been given a strong attention. Intact cell walls in almonds are a physical barrier that encapsulate lipids (and other nutrients) during digestion, thus, reducing their bioaccessibility and increasing their discharge in the feces. Fatty acids released after 60 min of *in vitro* simulated duodenal digestion were more than double for finely ground almonds than for natural almonds cut as 2 mm cubes (Mandalari et al. 2008). Grundy, Lapsley, and Ellis (2016) have recently reviewed the subject, emphasizing the large variability in the amount of lipid released from the almond tissue matrix and the fatty acids produced from lipolysis depending on type of product structure, degree of processing and particle size. Thus, energy values of whole almonds (and several other foods whose matrix is only partly obliterated during digestion) calculated using composition data and Atwater factors may overestimate the energy derived from their consumption (Capuano et al. 2018). Studies on bioaccessibility of polyphenols and minerals in nuts are also underway (Kafaoglu et al. 2016; Rocchetti et al. 2018). Unveiling the effects of the food matrix on the actual energy contribution and nutrient content of nuts and other commercial foods are quite important to guide consumers' choices toward healthier food items (Capuano et al. 2018).

Pasta products

Cooked pasta products exhibit a low glycemic index (GI) compared to other wheat products containing the same proportion of starch. For example, white bread and wheat flakes (a breakfast cereal) have GI's of 75 and 69 (glucose =100), compared to a GI of 49 for cooked spaghetti (Atkinson, Foster-Powell, and Brand-Miller 2008). Dry pasta has a compact structure in which starch granules (around 70% of the total weight) are trapped as filler particles in a continuous gluten matrix (Schiedt et al. 2013). During cooking of pasta, water and heat are transferred to the interior of the product, gelatinizing starch and coagulating the protein into a firm matrix. The presence of the protein network surrounding starch granules limits their water uptake and the complete gelatinization of starch in the interior of the piece, reducing the overall *in vitro* starch digestibility (Fardet et al. 2018; Kim et al. 2008; Petitot, Abecassis, and Micard 2009). The unswollen state of starch granules in the central region of cooked spaghetti was elegantly demonstrated by microscopy techniques (Heneen and Brismar 2003). Size reduction of cooked spaghetti to a porridge condition (close to what may occur during extensive mastication) increased significantly the digestibility of starch from a GI = 61 (intact spaghetti) to a GI = 73, meaning that mechanical obliteration of the protein matrix as well as a smaller particle size exposes more starch to the action of amylases (Petitot, Abecassis, and Micard 2009). The encapsulating effect of starch in a dense protein matrix deserves further study as a mean of lowering the GI of protein/starch foods.

An estimated 422 million adults were living with diabetes in 2014 and the disease caused 1.5 million deaths in 2012 (WHO 2016). Digestion of starch and the rate of release of glucose in the small intestine are important factors in the control of diabetes type 2. The effect of starch digestion is usually expressed as the glycemic index (GI), or the postprandial response of sugar in the blood after ingesting the equivalent to 50 g of starch in comparison to a similar amount of glucose (control). It has been recognized for a long time that the GI of different staple foods vary widely in diabetic subjects (Bornet et al. 1987). The GI of starchy foods depend on many factors such as the source of starch and size of the granule, ratio of amylose to amylopectin, interactions with other components in the meal (fiber and fat), breakdown of food during mastication, and the state of the starch matrix (e.g., gelatinized, dextrinized and/or retrograded) (Singh, Dartois, and Kaur 2010; Parada and Aguilera 2011). Intensive heating and mechanical shearing have a major effect in the digestibility of starchy foods, with extrusion-cooking providing the highest increase in starch digestibility, cooked legumes the lowest and cooked pasta products an intermediate rise (Singh, Dartois, and Kaur 2010). Enzyme-resistant starch passes directly to the large intestine where it performs as a probiotic and delivers only 30% of the energy of the starch digested in the small intestine. This kind of densely packed starch matrix with reduced enzymatic digestibility may be induced by partial gelatinization, re-crystallization (retrogradation), complexing of amylose with lipids, and annealing and extrusion of high-amylose starch (Zhang, Dhital, and Gidley 2015). Figure 3 illustrates some of the mechanisms related to the food matrix that influence the bioaccessibility and bioavailability of nutrients and bioactives.

Impact of the food matrix on nutrition

During the past century, nutritionists contributed quite successfully to the alleviation of several nutrient deficiencies by recommending the consumption of the needed quantity of nutrients through foods or supplements. Some representative examples are scurvy and ascorbic acid, pellagra and niacin, beriberi and thiamin, rickets and vitamin D, and neural tube defects and folic acid (Jacobs and Tapsell 2013).

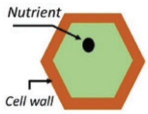
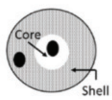
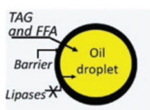
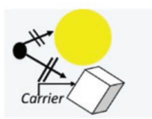
Scheme	Mechanism	Examples	Selected references
	Entrapment inside a natural food matrix e.g., within plant cell walls or organelles	Lipids in almond cells	Grundy, Lapsley, and Ellis 2016
		Lycopene in chromoplasts	Schweiggert et al. 2012
	Immobilization inside a man-made gel or solid matrix. Basis of encapsulation and entrapment	Encapsulated nutrients and bioactives	Pegg and Shahidi 2007; Lakkis 2016.
		Probiotic bacteria entrapped in gels	Sheu and Marshall 1993; Champagne and Fustier, 2007.
	Complex formation with the food matrix, some of its components, or poorly bioavailable as released	Some carotenoids membrane-bound in chloroplasts	Honest, Zhang, and Zhang 2011; Raikos 2017
		Most polyphenols (conjugates with proteins)	Rein et al. 2012
		Lycopene *all-trans* isomers	Honest, Zhang, and Zhang 2011
	Presence of physical barriers and/or steric impediments to the action of digestive enzymes	Lipids digested in oil droplets with protective interfaces	Wilde and Shou 2011; Gallier and Singh 2012
		Lipophilic bioactive components in excipient emulsions	McClements and Li 2010; Zou et al. 2015
		Starch occluded in protein matrices	Singh, Dartois, and Kaur 2010
	Absence of the lipid phase to dissolve or the adequate carrier for transport to absorption site	Fat-soluble vitamins (A, D, E and K)	Rein et al. 2013
		Carotenoids release and absorption	Carbonell-Capella et al. 2014
		Lipophilic carotenoids incorporated in mixed micelles	Raikos 2017
	Interactions with other components (e.g., fiber, phytate, proteins) once released from the matrix.	Binding of antioxidants to indigestible polysaccharides (fiber)	Palafox-Carlos, Ayala-Zavala, González-Aguilar 2011
		Minerals bound to phytate from plant sources	Parada and Aguilera 2007
		Binding of casein and whey proteins to polyphenols	Gallo et al. 2013

Figure 3. Common food matrix effects relevant to the digestion/absorption of nutrients and bioactives.

The recent emphasis on the nutritional content of foods (nutritionism) has been confronted with the fact that several nutrients do not behave equally when studied isolated than in whole foods. Foods with matching chemical composition exhibit major differences in nutrient delivery and biological function, integrity of the gut microbiota, and in their health outcomes. These discrepancies arise from the multiplicity of interactions, positive (even synergistic) and negative, that take place between nutrients, the food matrix, and other food components present in a meal, not to mention the host-related effects (Lecerf and Legrand 2015; Wahlqvist 2016; Peters 2017). Moreover, high doses of single nutrients (e.g., vitamins and antioxidants) exert no beneficial health effects and may even be deleterious in some groups of the population (Holst and Williamson 2008). However, the "single or isolated nutrient approach" is still applied to the study of health effects with questionable and even conflicting results which are difficult to interpret (Jacobs and Tapsell 2013).

To complement the already mentioned examples of FM-effects and interactions of nutrients in foods, a few more cases are presented. The bioaccessibility and bioavailability of carotenoids is not proportional to their relative abundance in the original food matrix. The structural integrity of the plant material in which they are embedded and their chemical interactions with other food components seem to be critical factors for their release and their subsequent uptake by cells at the intestinal epithelium (Palafox-Carlos, Ayala-Zavala, and González-Aguilar 2011; Raikos 2017). In whole apples a synergistic relationship has been found between the fiber and flavonoids, which may be mediated by the gut microbiota, while clear apple juice (devoid of the cellular matrix) may induce adverse nutritional effects due to its high fructose and low fiber content (Bondonno et al., 2017). When enteral formulas containing Fe, Zn and Ca were mixed into food preparations having different composition and type of "matrices" (rice pudding, chocolate and tea), the amount recovered during simulated gastrointestinal digestion and dialysis diminished due to interactions with promoters (vitamin C) and inhibitors (phytic acid, tannins and polyphenols) of mineral absorption (Galán and Drago 2014). Phytosterols/phytostanols (PSs) have been added to several commercial foods (margarine, mayonnaise, yogurt, milk, cheese, meat and juices, among others) to lower the plasma concentration of LDL cholesterol. Those foods which had matrices that contained poly- and monounsaturated fatty acids (that lower LDL) and allowed a high solubility of PSs, had the most pronounced LDL lowering effects (Cusack, Fernandez, and Volek 2013). New strategies and testing procedures should be implement to change the paradigm of nutrient-centered research to one whose focus is the food or even whole meals, and accounts for possible interactions and synergisms.

Allergies, intolerances and the food matrix

Food allergies are immune responses (mediated and non-mediated by IgE antibodies) while food intolerances are adverse reactions of our body to a chemical compound. Food allergens are small proteins whose molecular weight varies from 15 kDa to 40 kDa, and also glycoproteins. Some 3 to 8% of the population are allergic to some type of food, with cow's milk, egg, peanut, tree nuts, soy, shellfish and finned fish being the most common carriers of food allergens (Turnbull, Adams and Gorard 2015). Interestingly, while genetics and heritability have a strong influence in allergies, environmental factors explain why only 68% of identical twins share the allergy to peanuts (Hong, Tsai, and Wang 2009). Some molecules in foods causing sensitive reactions are lactose (in milk), sulfur dioxide (in wines) and biogenic amines (in some fermented products).

Molecules released from food matrices during digestion may cause allergies or elicit adverse reactions in our body (Vissers, Wichers, and Savelkoul 2012). Verhoeckx et al. (2015) have reviewed the effect of food processing (mainly heating) on allergies caused by most of the common food allergens mentioned before. These authors concluded that although heating does induce changes in individual proteins, they may result in a higher (e.g., from products of the Maillard reaction) or lower (e.g., as in extensively heated egg white) allergic sensitivity. However, the effect of processing on the susceptibility to digestion of the food matrix and the release and absorption of allergens has not been given enough consideration. Conventional food processing seems not to reduce significantly the allergenicity of proteins, as opposed to microbial fermentation and enzymatic or acid hydrolysis that in some cases may lead to a diminution of the effects but not to completely abolish the allergenic potential of proteins (Verhoeckx et al. 2015). Allergens in liquid matrices (e.g., caseins and whey proteins in milk) and precursors of intolerance (lactose in milk) are easy to hydrolyze by processing into inactive forms and used safely in products (e.g., infant formulas and delactosed milk). Interactions of allergens with other proteins, fat and carbohydrates present in the food matrix may result in an attenuation of the severity of allergic reactions (Nowak-Wegrzyna and Fiocch 2009). However, in simulated digestion studies similar food matrices rich in proteins and carbohydrates have originated secondary food allergens with sensitizing capacity (Schulten et al. 2011). In summary, the whole subject of FM-effect of food processing on allergenicity is still poorly understood and further studies are required using specific food matrices and improved assay procedures.

FM-effect on analytical methods

The extent to which individual food components of interest are attached or interact with the food matrix also affects the quality and relevance of results of analytical techniques. Four decades ago, Yasumoto et al. (1977) recognized that although laboratory assays for vitamin B6 in rice bran were well established, their results did not represent the amount available in the organism. Analytical procedures were able to release the vitamin bound *in situ* to other constituents of the food matrix, something that did not happened during digestion. Later, Ekanayake and Nelson (1986) proposed an *in vitro* method using pancreatin digestion to simulate the release of the biologically available vitamin B6 from the food matrix. Hanson, Frankos and Thompson (1989) reported that the low bioavailability of oxalate could be attributable to the complex matrix of beet fiber and its high ratio of minerals (Ca and Mg) to oxalate. De Pee and West (1996)[TQ2] cautioned about relating the total amount of carotenoids in fruits and vegetables and their role in overcoming vitamin A deficiency since the bioavailability of dietary carotenoids and their conversion to retinol were influenced by the species of carotene, their molecular linkage and the matrix in which they were incorporated. In the case of allergens, Verhoeckx et al. (2015) questioned whether the current analytical protocols could solubilize aggregated proteins, hence, the meaning of results obtained for allergens from blood sera. Burrows (2016) had also reported on difficulties in the recovery of allergens in milk and peanuts when introduced in different food matrices and analyzed by ELISA. The use of biosensors has been proposed to directly measure the bioactivity of phytochemicals in complex food matrices, and circumvent problems associated with classical analytical techniques (Lavecchia et al. 2011).

Determining actual concentrations of chemical compounds in foods extends also to toxic substances and pollutants in foods. Assessing pollutant concentrations in milk can be hampered by its complex matrix (Heaven et al. 2014). The issue of matrix effect and interactions with metabolites has been extended to blood, a commonly used source for biomarkers in nutritional studies. Prabu and Suriyaprakash (2012) discussed the difficulties in analyzing blood samples (in their case, for drugs) due to the complexity of the blood matrix and the possibility of analytes binding to components in blood plasma, specifically, to proteins. Yu et al. (2011) found that a series of metabolites from the same original blood sample were higher in serum than in plasma, attributing this difference to a "volume displacement" effect. Glucose, an important metabolite of food digestion, was 5% lower in plasma than in serum. Given the importance of blood analysis to assess the concentration of nutrients and bioactives, further studies should be accomplished to resolve the analytical problems in different food matrices.

It is often neglected that *in vitro* analytical procedures to assess the bioaccessibility and bioavailability of nutrients call for a size reduction step to facilitate extraction, mixing with solvents and/or enzymatic action. In foods with a cellular structure (e.g., fruits, vegetables, grains, etc.) fine grinding means destroying the cell walls of the matrix, thus, exposing the internal contents. In the case of complex matrices (e.g., pasta products) extensive size reduction eliminates the encapsulating effect of the protein matrix on starch granules. Thus, analytical results involving fine grinding do not preserve the FM-effects provided by intact cells or complex matrices which may be relevant in bioaccessibility and bioavailability studies. Taking into account that plant cells have sizes in the order of 100 μm, assays performed on samples ground to an average particle size below 0.2 mm (200 μm) may not fully account for the entrapment of compounds within the cell walls. Villanueva-Carvajal et al. (2013) showed that the antioxidant activity of the calix of Roselle determined by various methods (TPC, FRAP, and DMPD) varied significantly if samples analyzed by *in vitro* digestion were ground to mean particle sizes of 2.00 mm or 0.21 mm. Furthermore, the stability of antioxidants in foods, thus their abundance, changes during storage, processing and digestion, and so does their bioaccessibility from the food matrix (Holst and Williamson 2008; Podsędek et al. 2014). Similar artifacts occur in the determination of the reactions orders and kinetic parameters of vitamin losses on homogenates of vegetable tissues where the matrix effect is absent but interactions of vitamins with matrix debris and released compounds may still occur (Giannakourou and Taoukis 2003). Particle size is also relevant in the determination of starch digestibility *in vitro*, as demonstrated by Ranawana et al. (2010) in the case of cooked rice. These authors found that glucose released in masticated samples was six times higher for particle sizes $<500\,\mu$m than for sizes >2 mm. So, preservation of the food matrix in analytical samples is essential to determine FM-effects.

Evaluating the availability of nutrients using humans is not only subject to individual variability but also time consuming, expensive, and restricted by ethical considerations. Alternatively, artificial digestion systems have been proposed to study food digestion that simulate the biochemical, mechanical and flux conditions in parts of the GIT (e.g., the stomach) or in the whole tract. One of the most successful artificial GIT systems is the TIM-1 system, a multi-compartmental, computer-controlled model that simulates the upper human gastro-intestinal tract, allowing the determination of the bioaccessibility of nutrients (Minekus 2015). Incorporating advances by biologists in artificial organs and tissues to these digestion systems are likely to approach real conditions and improve the predictability of results.

Matrices for healthy foods

Some targets for "healthy" foods include the reduction in salt, sugar and fat and a decrease in calorie density of existing products, as well as the development of gluten-free and high-fiber foods (Poutanen, Sozer, and Della Valle 2014). To date, commercial products which attempt to comply to a significant extent with these goals do not compare well in taste and texture with their original counterparts, so they are unattractive for the majority of consumers. Low sodium chloride in wheat doughs delays hydration and unfolding of gluten proteins impeding their alignment into a fibrous network with a high strength, elasticity and extensibility that can hold the expanding gases and water vapor in the oven (McCann and Day 2013). NaCl also moderates the activity of yeast and gas production in the dough, and improves the flavor and volume of bread. In comminuted meat products, salt solubilizes and extracts the myofibrillar proteins which later will form stable gel matrices that immobilize fat droplets. Salt interacts by ionic bonding with lean meat, thus, reducing salt in the formulation leaves less available free salt for saltiness perception (Kuo and Lee 2014). Moreover, salt reduction results in a lower water holding capacity leading to loss of juices and a poor texture of meat products (Ruusunen and Puolanne 2005).

In the case of cakes and biscuits, sugar is the major ingredient by weight after flour. Thus, sugar is not easily substituted by potent sweeteners because it provides bulk, competes for water with gluten proteins and delays the gelatinization of starch, permitting that gases are held within the dough matrix and expand in the oven (Clemens et al. 2016).

Fat has the highest caloric density among major nutrients, so there has been a considerable interest in the creation of reduced-fat products. Lipids play multiple roles in food matrices contributing to structure, a tender texture and lubricity, and by acting as a moisture barrier and as a lipophilic carrier for fat-soluble vitamins and flavors. Fat replacers (analogs, substitutes, etc.) may mimic some of these properties but not all. However, the successful development of functionality of these ingredients remains a challenge given the high quantities of fat used in dressings, baked products and fried foods (Wu, Degner, and McClements 2013). Margarines and fat spreads can be formulated to contain high levels of PUFAs as well as a lower caloric density, and yet keep a desirable consistency and spreadability due to a three dimensional matrix formed by a fat crystal network that occludes water droplets and air bubbles (Juriaanse and Heertje 1988). Palzer (2009) suggested that some fat-containing foods may be redesigned into versions with a lower volumetric caloric density by adding more air (as small bubbles) and "structuring" an abundant aqueous phase in the product matrix with added hydrocolloids. Guo et al. (2017) proposed that fat and oil digestion could be modulated by the structure and rheology of the food matrix surrounding dispersed oil droplets and the structure of the interfacial layer.

In general, gluten-free (GF) pasta and GF baked products are less desirable in terms of appearance, taste, aroma and texture when compared to their all-wheat counterparts (Gao et al. 2018). In most cases the structure of GF foods is provided by wheat flour substitutes (e.g., flours from rice, maize, chickpeas, etc.) and additional ingredients such as starches, proteins, hydrocolloids and fiber. A high-fiber diet may reduce the risk of several diseases (e.g., hypertension, stroke and heart disease), so its consumption has been promoted through high-fiber foods and fiber-enriched or fiber-added products. The characteristics of commercial fiber ingredients vary considerably depending on their origin, microstructure and physicochemical properties, i.e., particle size, porosity, hydration capacity, solubility, etc. (Guillon and Champ 2000). In the particular case of GF pasta, the absence of gluten debilitates the matrix network making the cooked products less firm and stickier (Gao et al. 2018). The presence of fiber in pasta disrupts the starch–protein matrix of the dough and competes with starch for water, impacting the firmness, stickiness, cooking loss and sensory attributes of the product (Rakhesh, Fellows, and Sissons 2015). Even small additions of particles of insoluble fiber to baked foods weaken the food matrix causing moderate to large reductions in appearance, flavor and overall acceptability (Grigor et al. 2016). In the case of extruded starchy products, fiber particles rupture the cell walls of gas bubbles in the extrudate, producing a noticeable decrease in the expansion ratio and an increase in product density and hardness (Robin, Schuchmann, and Palzer 2012; Korkerd et al. 2016). From a nutritional viewpoint, fiber matrices entrap phenolic compounds during digestion in the upper intestine, and restrict the hydrolysis of some antioxidants bound to polysaccharides in the chyme (Palafox-Carlos, Ayala-Zavala, and González-Aguilar 2011).

The positive effects of probiotics and gut microbiota on health have been extensively documented in the past decades. Probiotic bacteria can be produced by fermentation in the food or added as encapsulated probiotic microorganisms. Recent reviews have attempted to cover the effect of food matrices on probiotics (as enounced in their titles), but they actually analyze the viability of bacteria in specific food products rather than the interaction of beneficial microorganisms with their immediate surrounding medium in the food (Shori 2016; Flach et al. 2017). Flach et al. (2017) have reviewed the effect of different "matrices" (in fact, commercial foods) on the viability of probiotic strains and health effects, including fermented dairy products, ice-cream, fruit and vegetable juices, oats and cereals. The authors have correctly concluded that trials should move from evaluating a single "matrix" with a different probiotic content, to a more fundamental study of the effect of the matrix itself on the viability and activity of different probiotics. Common matrix materials used to encapsulate probiotic bacteria include alginate and other seaweed hydrocolloids, chitosan, whey proteins, skim milk powder and starch (Rokka and Rantamäki 2010; Corona-Hernandez et al. 2013; Martín et al. 2015). Although in the aforementioned works the influence of processing and encapsulating technologies was amply discussed, little attention was paid to the effect of matrix materials and the microstructure of matrices on the viability and activity of encapsulated bacteria in the gut.

The development of healthy and tasty foods for the elderly has received a dedicated attention since this group is the fastest growing population segment in the world (Aguilera and Park 2016). Those seniors having mastication and swallowing difficulties (e.g., dysphagia) need soft but cohesive food matrices that convey easily digestible and absorbable proteins, fiber, and micronutrients (e.g., Ca for women), as well as phytochemicals, particularly polyphenols which are deemed essential to achieve the genetic lifespan potential (Holst and Williamson 2008; Raats, de Groot, and van Asselt 2016). Two approaches have been taken to supply soft foods for the elderly: texture modification of real foods (by enzymatic treatments, freeze-thaw cycling, and high-pressure processing, among others), and the fabrication of soft microgel matrices used as carriers of nutrients and bioactive compounds (Aguilera and Park 2016).

Conclusions

The concept of food matrix is extensively used by food and nutrition scientists to try to explain why a component or nutrient behaves differently in a food than in isolated form (e.g., in a solution). However, the term food matrix, conveniently used to mean that "some part" of a food interacts (physically or chemically) with a constituent, is seldom described in detail. In fact, the food matrix may be viewed as a part of the microstructure of foods, usually corresponding to a spatial physical domain that contains, interacts or gives particular functionalities to a specific constituent of the food (e.g., a nutrient, aroma molecules, beneficial bacteria, etc.). Associations between individual nutrients and chronic diseases have been difficult to assess given their complex interactions with the food matrix and other constituents of foods. Several types of matrices can be recognized in foods which are also referred to in other disciplines: liquids, emulsions, cellular tissues, polymer networks, etc. It follows from this viewpoint that the food matrix is component-specific and scale-sensitive. In nutrition, the food matrix is related to bioaccessibility (release of nutrients from the matrix) and bioavailability (absorption of nutrients in the GIT), as well as the maintenance of a healthy microbiota. In food technology, the food matrix influences structure and consequently, the appearance, texture, breakdown in the mouth and flavor release. The extensions of the food matrix to health, as reviewed in the text, include satiation and satiety that control calorie intake, action of metabolites absorbed in the GIT by our body, as well as its effects on food allergies and intolerances. Analytical procedures assessing the bioaccessibility of nutrients should preserve the matrix effects otherwise the results will represent the total amount present in a sample. The engineering of food matrices that contain, protect and control de release of nutrients is the basis for a rational design of "healthy" foods. A more rigorous approach to the characterization of food matrices and their interactions with food components will improve our understanding of their specific roles in product functionality, nutrient bioaccessibility during digestion, and the development of improved *in vitro* models and *in vivo* methods for nutritional assessment. Nutrition research should embrace new strategies and testing procedures that replace the single-nutrient approach and focus more strongly on actual foods and on dietary patterns.

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