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Food matrix impact on macronutrients nutritional properties

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A B S T R A C T

The food industry is aware of the consumer's desire to purchase delicious, convenient and nutritious foods. Rapid development of functional foods has induced the food industry to evaluate and revise the composition of their processed foods as well as their processing conditions and methods to improve nutritional and health effects. The addition of new bioactive compounds to a food requires that the bioactive agent is in the active form by the time it reaches the gastrointestinal tract, where it is assimilated. However, the question is whether or not the processes and the composition of traditional foods are carefully balanced to ensure the optimal nutritional properties. This paper aims to review the concepts and facts that are the basis of the new area of research regarding the role of food structure on the nutritional properties of conventional and functional foods. Several original approaches have emerged, bringing together scientists from fields such as food science, nutrition and physiology, which bring enlightening new perspectives to the development of delicious and nutritional foods.

1. Introduction

Food is a worldwide concern. While some parts of the world experience food shortages, chronic metabolic diseases have emerged from food overconsumption in other parts of the world. Both situations can result in shorter life expectancy and represent a major global health problem. Health care costs are rising due in part to several obesity-related chronic diseases such as type 2 diabetes, high blood pressure and cardiovascular diseases. More than ever, it is essential that all the knowledge on food conception, formulation and processing is wisely exploited to develop foods that will provide a healthy lifestyle. This is favorable to the fast development of functional foods and has brought the food industry to evaluate and revise the composition of their processed foods as well as their processing conditions and methods to improve nutritional and health effects and to address the functional food market. The improvement of food product has been done through several ways, such as by incorporating bioactive components in standard foods, by reformulating standard food composition to withdraw some less nutritive or even deleterious compounds (e.g., industrial trans fatty acids, salt, fast sugar, etc.), by addition of bioactive nutrients or by developing new foods with healthier constituents. The need to develop nutritious foods and functional foods has brought the entire industry to reconsider every aspect of their food processing to evaluate the health benefits of food.

The addition of new bioactive compounds to a food requires that the bioactive agent is in an active form by the time it reaches the gastrointestinal tract where is could be assimilated. The food to which the bioactive compound is added can be selected to be a good vector. However, for traditional foods, are the current processes used and the composition of the food carefully balanced to ensure optimal nutritional properties? This is usually evaluated by nutritionists based on individual nutrient content; however, the potential effect of the food matrix on the nutritional properties is seldom considered. This paper aims to review the concepts and facts which are the basis of the new area of research considering the role of food structure on the nutritional properties of conventional and functional foods. Several original approaches have emerged, bringing together scientists from fields such as food science, nutrition and physiology, which should permit the enlightenment of new perspectives in developing "delicious" and nutritional foods.

2. Nutritional properties of food

The nutritional evaluation of food has been, and is still, largely based on the respective quantities of each nutritive constituent such as protein, lipids, carbohydrates, vitamins and minerals. As more knowledge is gained on human needs and the health properties of various nutrients, this information is transferred to the consumer through nutritional labeling, presenting the actual contribution of each food portion on the daily recommended consumption of nutrients. With the introduction of functional foods, some bioactive compounds are added to common foods that

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are not a usual source of these compounds. For example, some plant phytochemicals and marine lipids can be added to dairy products. In doing so, food scientists have performed amazing feats to develop new ways to incorporate, stabilize and deliver these diverse bioactive molecules (water or lipid soluble substances, suspensions, colloidal particles, etc.). However, to obtain the real benefit of these compounds, they should be bioaccessible and bioavailable. Bioaccessibility refers to the release of the nutritive compound from its food matrix (or a tablet, capsule, etc. for a nutraceutical ingredient or a drug) into the digestive juices of the gastrointestinal tract (Versantvoort, Oomen, Van de Kamp, Rompelberg, & Sips, 2005). Once this compound has been released, the proportion that is adsorbed and actually reaches the systemic circulation represents its bioavailability. Some components will pass through the digestive tract without being digested and adsorbed, and these are evacuated.

2.1. Elements of food digestion

Ingested foods are subjected to a series of mechanical, enzymatic and biochemical transformations during their passage through the human alimentary tract from the mouth to the evacuation of the residual unutilized portion from the anus. Table 1 shows a summary of these digestive steps and presents the different mechanical, enzymatic and dilution processes undergone by food during the digestion process.

Kong and Singh (2008) presented the digestion of solid foods in 2 steps: the disintegration of food into small fragments and their dissolution so they can dissolve into the gastric juices. Briefly, mouth processing aims to mechanically breakdown foods into smaller sizes, depending on the texture of the food consumed (Jalabert-Malbos, Mishellany-Dutour, Woda, & Peyron, 2007). Saliva and amylase contribute by lubricating the bolus and reducing the viscosity of starchy foods. In the stomach, the food is mixed with the gastric secretions, and the food particles are crushed as a result of the muscular contractions. The acidic conditions contribute to food solubilization. The stomach content, known as chyme, is released in the intestine by the pylorus when the particle sizes are less than 1–2 mm (Thomas, 2006). Intestinal pH conditions change drastically to basic values, and a complex cocktail of enzymes work to free nutrients into their basic units (amino acids, free fatty acids, monosaccharides, etc.) for their absorption through the intestinal epithelia. The undigested components continue to the gut section, in which the microflora can complete their breakdown by fermentation, and solutes are adsorbed (Klein, Cohn, & Alpers, 2006). Readers are referred to (Kong & Singh, 2008; Lentle & Janssen, 2008) for more details on food digestion (rheological modifications and decomposition due to mechanical and enzymatic digestive processing).

2.2. Bioaccessibility and bioavailability of macronutrients

The digestion of major macronutrients, such as carbohydrates, proteins and lipids, are reviewed with a focus on how their rate of digestion could be influenced by processing and food matrix organization. The related physiological effects of the differences in digestion kinetics are presented. Minor nutrients can also be affected but are not discussed in this review.

2.2.1. Carbohydrates

Carbohydrate components of food vary in their identity. Monosaccharides (glucose, galactose, fructose, etc.) are the building blocks of more complex structures such as disaccharides (sucrose), oligosaccharides (inulin, maltodextrin) and polysaccharides (amylose and amylopectin of starch, pectin, cellulose, etc.). Each carbohydrate has its own gastrointestinal fate in terms of the rate of breakdown and absorption, which is influenced by processing and food matrix organization (Englyst & Englyst, 2005). Several papers have reviewed carbohydrate metabolism (Englyst & Englyst, 2005; Grabitske & Slavin, 2008). Simple carbohydrates or easily digested polysaccharides, such as starch, are readily bioavailable shortly after their consumption, while other carbohydrates, such as fiber, are more resistant to digestion. Free glucose and glucose from hydrolyzed starch can be absorbed from the upper intestine and become measurable in the blood serum rapidly after their consumption.

Table 1
Brief summary of the digesting steps.

Digestive step	Mechanical action	Enzymatic/biochemical conditions	Macronutrients
Mouth and oesophagus	Mechanical breakage	Near neutral pH	
		Amylase	Starch digestion
		Mucin	Lipid emulsification and flocculation
Stomach	The distal stomach (antrum) mixes and sieves and pumps the chyme to the intestinal compartment	pH 1–3; ionic strength 100 mM	Solubilization of macronutrients
		Pepsin	Protein hydrolysis
		Lipase	Lipid hydrolysis
		Residence time depends on food viscosity, size of particles (<3 mm)	
Small intestine	Peristaltic move	Basic pH	
		Pancreatic secretion:	Peptide and amino acid release
		- Trypsin	
		- Chymotrypsin	
		- Carboxypeptidase	
		- Aminopeptidase	
		- Elastase	
		- Collagenase	
		Bile acids	
		Lipase	Fatty acids
		Amylase	
		Glucosidase	Monosaccharides
Gut	Longitudinal contractions. Rate of flow of digesta varies from 0.73 to 2.35 mL/min	Microflora fermentation	Liquid absorption

Klein et al., 2006; Kong & Singh, 2008; Lentle & Janssen, 2008.

The kinetics of glucose appearance in the blood after food consumption has been evaluated using the glycemic index concept introduced by Jenkins in 1981 (Jenkins et al., 1981). Food can be classified in relation to a food reference, usually glucose or white bread. The glycemic index is measured from the ingestion of 50 g of available carbohydrate (Wolever & Jenkins, 2001) relative to the reference given in the same proportion. A food resulting in a rapid and high glucose concentration in blood (glycemia) has a high glycemic index value. The rate of digestion and absorption of carbohydrates have attracted a lot of interest because fast and elevated glycemic responses can have many benefits for sports nutrition; however, carbohydrates are also related to a range of metabolic risk factors (Jenkins et al., 2002; Opperman, Venter, Oosthuizen, Thompson, & Vorster, 2004; Wolever & Jenkins, 2001). Therefore, the slow release carbohydrates are associated with many health benefits (Jenkins et al., 2002).

Several factors, such as enzyme inhibition, fiber content, and food matrix composition, can influence carbohydrate availability through different mechanisms. Several mechanisms depend on hindering or retarding starch hydrolysis. Glucose is only partially released from starch, if at all, and does not contribute to glycemia. Phenolic compounds found in some medicinal plants, such as salacinol and kotalanol, can inhibit α-amylases and α-glucosidases (Kim, Kwon, & Son, 2000; McCue, Kwon, & Shetty, 2005; Williams, Choe, Baumgartner, Noss, & Mustad, 2006), hindering starch hydrolysis. Food processing, heat, mechanical or pressure treatments as well as food composition can affect starch enzymatic sensitivity. The crystallinity as well as size of starch granules vary depending upon the botanical origin or processing (gelatinization and retrogradation) and affect its bioaccessibility. Similarly, a dense food matrix organization has been shown to delay the enzymatic degradation of starch, as observed for pasta. The presence of other food components can also affect the absorption of glucose at the intestinal wall. Foods that are rich in soluble fiber and have high fat content create a more viscous chyme and have been associated with longer gastric emptying. This also contributes to the prolonged absorption of glucose.

The fiber effect on glycemia depends on specific characteristics such as the solubility and structure of the food. The concept of fiber has been introduced to represent the part of a plant that is resistant to upper-intestinal human enzymes (Asp, 1995). In Canada, food fiber is defined as "the endogenous components of plant material in the diet which are resistant to digestion by enzymes produced by humans. They are predominantly non-starch polysaccharides and lignin and may include, in addition, associated substances" (Canadian Food Inspection Agency, 2010). For ESFA, dietary fiber is "defined as non-digestible carbohydrates plus lignin."

Fiber can be divided into soluble and insoluble fiber, with each being related to different physiological effects. As mentioned, soluble fiber has been shown to delay the appearance of glucose in the blood. The exact mechanism is still debated, but several possible hypotheses have been suggested, such as an increased viscosity slowing enzyme efficacy and/or delaying gastric emptying (Holt, Carter, Heading, Prescott, & Tothill, 1979; Jenkins et al., 1978) and/or delaying glucose transport to the absorption site (Makelainen et al., 2007; Ou, Kwok, Li, & Fu, 2001; Panahi, Ezatagha, Temelli, Vasanthan, & Vuksan, 2007). The mechanism is still controversial; however, authors agree on the effect of viscosity. Wood, Beer, and Butler (2000) found a correlation between the peak blood glucose rise and the molecular weight and concentration (log–log relationship) of a liquid beverage. This effect was later confirmed in solid food (oat bran muffins) (Tosh, Brummer, Wolever, & Wood, 2008). A procedure allowing the determination of the quantity and viscosity of soluble β-glucan under digestive conditions was used. Subsequent experiments showed how different processing steps could affect the solubility of β-glucan and its physiological effect. Freeze-drying cycles lowered the solubility and affected the effectiveness in lowering the postprandial blood glucose response. Enzymatic hydrolysis reduced the molecular weight of β-glucan as well as its effect on glycemia. The same effect was previously reported for hydrolyzed guar gum (Jenkins et al., 1978). Recently, addition of β-glucan in fruit-based beverages showed that some oxidative reactions can depolymerize the polysaccharide (Kivela, Gates, & Sontag-Strohm, 2009; Paquet, Turgeon, & Lemieux, 2010). A minimal viscosity seems to be required to obtain the targeted health effects. Viscosity is a prerequisite for activity; however, the intrinsic characteristics of the fiber are also important because not every viscous polysaccharide has an impact on glycemia. Interestingly, recent results showed that possible synergistic effects that occur between polysaccharides can foster the viscosity of β-glucan and its blood glucose-lowering effects in fruit-based beverages (Paquin, 2007).

Soluble fiber also has cholesterol-lowering properties that are recognized in several countries for health claims (Finland, Sweden, Netherlands and USA) (Lehtinen et al., 2009; Tiwari & Cummins, 2009). A recent paper (Gunness & Gidley, 2010) reviews the various hypotheses for these cholesterol-lowering properties, and three potential physicochemical mechanisms are proposed. One of these mechanisms is related to the reduced glycemic response associated with a lower insulin stimulation of hepatic cholesterol synthesis. Viscous soluble fiber can prevent some of bile salt reabsorption from the small intestines, and finally, fermentation of soluble fibers by gut microflora can produce short chain fatty acids with an inhibiting effect on cholesterol metabolism (Gunness & Gidley, 2010). As previously studied with blood glucose, the impact of the food matrix on the capacity of β-glucan in lowering serum cholesterol was studied in extruded breakfast cereal. The molecular weight of β-glucan was altered using various temperatures and pressures during cereal extrusion (Wolever et al., 2010). The authors proposed a correlation between lower cholesterol levels and glycemia (Regand, Tosh, Wolever, & Wood, 2009) with the molecular weights and concentrations (MW $\times$ C) of the products of β-glucan. The β-glucan value used represents the amount that is solubilized by an *in vitro* digestion step.

Undigested soluble and insoluble fibers in the small intestine can reach the gut and potentially be fermented by the microflora, producing various potentially bioactive metabolites. Unfermented or partially fermented fiber, such as insoluble wheat bran, absorb water and contribute to fecal bulk (Cummings, Edmond, & Magee, 2004). This helps reduce the entire gastrointestinal transit time (Skibniewska, Zakrzewski, Siemianowska, Polak-Juszczak, & Aljewicz, 2010).

Whole grains were fractionated to produce refined fractions, such as white flour, allowing improvement of dough functionality. However, nutritional properties were altered because it is now recognized that diets high in dietary fiber and whole grains are associated with a reduced risk of chronic diseases (Poutanen, Lyly, Juvonen, & Karhunen, 2010) and a lower body mass index (Harland & Garton, 2008). Currently, whole grains are reintroduced in various dough formulations, and fiber is added to several other product types.

The beneficial health-related properties of fiber is a very practical example of the role of the food matrix in the digestion process and the resulting influence on the kinetics of glucose and cholesterol metabolism, as reviewed here. However, the same effects can be expected for other nutrients. The content of polysaccharides and fiber can also modulate the kinetics of protein digestion. Polysaccharides have been shown to decrease proteolysis (Peyron, Mouecoucou, Fremont, Sanchez, & Gontard, 2006). Their action can be the result of increasing viscosity, interfering with enzymatic action or forming electrostatic interactions between polysaccharides, proteins and peptides, limiting access to the cleavage site for the enzyme.

2.2.2. Proteins

The major source of food proteins are found in milk, meats (including fish and poultry), eggs, cereals, legumes and oilseeds (Damodaran, 2008). These proteins are either consumed alone or used as food ingredients in other food products. The complexity of food proteins resides in their composition of amino acids that contain several functional groups, such as sulfhydryl and carboxyl groups that affect their structure. Several forces are involved in the stability of protein structure. Steric strain, hydrogen and disulphide bonds, van der Waals electrostatic and hydrophobic interactions all contribute to protein folding and stability (Damodaran, 2008). Throughout those interactions, proteins are able to interact with other molecules, such as polysaccharides, in the food system or with a receptor to activate biological function. Further details on protein chemistry are available elsewhere (Damodaran, 2008). As stated earlier, proteins are digested in the gastrointestinal tract. Proteins are first hydrolyzed by pepsin in the stomach and then by duodenal enzymes including trypsin, chymotrypsin, elastase and carboxypeptidase to liberate small peptides and free amino acids into the gut for their local or postabsorptive action.

2.2.2.1. Physiological function of dietary proteins, peptides and amino acids. Dietary proteins, peptides and amino acids have a wide array of physiological functions such as protein synthesis, gastrointestinal functions and the regulation of metabolism and food intake (Anderson & Aziz, 2006; Luhovyy, Akhavan, & Anderson, 2007). Their main functions are summarized in Table 2. These functions are affected by the quantity and the quality of ingested proteins (amino acid composition) as well as their digestibility (Dangin et al., 2001).

Protein synthesis is probably the major utilization of amino acids in the body. Protein consumption influences the balance between muscle protein synthesis and muscle protein breakdown (Phillips, Tang, & Moore, 2009). In the fasted state, protein breakdown is increased; however, after normal feeding, dietary protein intake increases muscle protein synthesis. Young and elderly persons have different needs for dietary proteins because the protein synthesis in bones and muscle are different for these two groups. In elderly people, protein synthesis decreases with an overall muscle mass decline, which leads to a reduction in the overall condition (increasing bone fracture risk) (De Souza Genaro & Martini, 2010; Phillips et al., 2009). Thus, several strategies were developed to stimulate protein synthesis in elderly persons; however, increasing protein consumption over 2 g/kg/d showed an increase in the risk of kidney malfunction (Walrand et al., 2008). The consumption of protein hydrolysates was shown to increase the availability of plasma amino acids and increase the synthetic response of postprandial muscle proteins compared with the intact protein in young (Calbet & Holst, 2004) and in elderly persons (Koopman et al., 2009). This shows that the kinetics of the liberation and absorption of amino acids are the main factors influencing their bioactivity.

The regulation of metabolism and food intake after protein digestion seems to be influenced by the amount and the sources of consumed proteins. High-protein foods have been shown to cause higher sensory-specific satiety and decrease of the feeling of hunger than similar low-protein foods (Vandewater & Vickers, 1996). Several mechanisms have been proposed to explain the satiety-maintaining effect of proteins (reviewed in Veldhorst et al., 2008; Westerterp-Plantenga, Nieuwenhuizen, Tome, Soenen, & Westerterp, 2009): increases in the concentrations of hormones involved in satiety signals, increases in energy expenditure, variations in amino acid concentrations, and increases in the process of gluconeogenesis. Different protein sources seem to exert various specific effects on satiety (Uhe, Collier, & Odea, 1992), energy intake

Table 2
Examples of physiological functions of dietary proteins, peptides and amino acids.

Functions	Dietary protein, peptides and amino acids	Actions	References
Protein synthesis	Arginine, leucine and other branched amino acids (Ile and Val), hydrolyzed casein, soy	Enhance protein synthesis	Bos et al., 2003; Calbet & Holst, 2004; Kimball & Jefferson, 2001; Koopman et al., 2009; van de Poll, Luiking, Dejong, & Soeters, 2005; Zhang et al., 2007
Gastrointestinal function	Beta-casomorphin peptides	Modulating its permeability and motility	Brinson et al., 1990; Zaloga & Siddiqui, 2004
	Bovine serum albumin and β-lactoglobulin	Ileum contraction	Nagpal et al., 2011
Gastric emptying and secretion	Micellar casein	Slow gastric emptying	Mahe et al., 1991, 1996
Enzyme activity	Tryptophan, tyrosine, histidine	Precursor of serotonin, dopamine and histamine respectively	Wurtman et al., 2003
Gut hormones release	Milk, soy, gluten, whey, casein, beta-casomorphin peptides	Modulate one or many of the listed above hormones: CCK, GIP, GLP-1, peptide YY (PYY), ghrelin	Bowen, Noakes, & Clifton, 2006; Hall et al., 2003; Morley et al., 1983; Pusztai et al., 2008; Tome et al., 2009
Insulin secretion and glucose metabolism	Dietary proteins and branch chain amino acid	Increase insulin and decrease glycemia	Luhovyy et al., 2007; Nilsson, Holst, & Bjorck, 2007; Zhang et al., 2007
Food intake	Casein	Block peripheral opioid and cholecystokinin-A receptor	Luhovyy et al., 2007
	Leucine	Reduce food intake through mTOR activation	Cota et al., 2006
Blood pressure	Fish, egg, wheat, bovine serum albumin, whey, α-lactalbumin, β-lactoglobulin, whey derived peptides (α -and β-lactorphin)	Angiotensin I-converting enzyme (ACE) inhibitors	Erdmann, Cheung, & Schroder, 2008; Luhovyy et al., 2007; Miguel, Gómez-Ruiz, Recio, & Aleixandre, 2010
Energy balance	High-protein consumption, whey and α-lactalbumin	Increase energy expenditure and thermogenesis	Hursel, van der Zee, & Westerterp-Plantenga, 2010; Tremblay, Lavigne, Jacques, & Marette, 2007

(Borzoei, Neovius, Barkeling, Teixeira-Pinto, & Rossner, 2006), and energy expenditure. However, Lang et al. (1998, 1999) found no difference in satiety and energy intake (24 h) between egg albumen, casein, gelatin, soy and bean protein or wheat gluten. In the latter study (1999), differences in post-meal levels of glucose and insulin were observed, which were suggested to be dependent on the differences in stomach emptying rates caused by the different proteins.

Gastrointestinal function is also modified after the ingestion of dietary proteins. For example, β-casomorphin peptides (Tyr-Pro-Phe-Pro-Gly-Pro-Ile) have been shown to stimulate gut function by modulation of its permeability and motility and increase gut hormone secretion after binding to gut luminal receptors (Brinson, Pitts, & Benoit, 1990; Morley et al., 1983; Zaloga & Siddiqui, 2004).

Others have demonstrated that once ingested, dietary proteins activate the release of peptides from enteroendocrine cells in the intestine (Cummings & Overduin, 2007). These messengers diffuse through interstitial fluids to activate nearby nerve fibers and/or enter the bloodstream to function as hormones (Cummings & Overduin, 2007). The main peptides classified by their major sites of excretion are the ghrelin, obestatin, and gastric leptin of the stomach; cholecystokinin (CCK) and glucose-dependent insulinotropic polypeptides (GIP) of the upper-intestinal region; glucagon-like peptide-1 (GLP-1), oxyntomodulin, and pancreatic polypeptide–tyrosine–tyrosine (PYY) of the lower-intestinal region; and insulin, amylin, and pancreatic polypeptide (PP) in the pancreas (Cummings & Overduin, 2007). These hormones regulate processes such as food intake and glucose metabolism (Tome, Schwarz, Darcel, & Fromentin, 2009).

Hall, Millward, Long, and Morgan (2003) compared the effect of milk casein and whey on blood amino acid profiles, secretion of gut hormones, and appetite and observed that whey caused a higher secretion of CCK, GLP-1 and GIP and had a higher satiating effect than casein. After whey ingestion, the blood concentration of branched amino acids leucine and valine was significantly higher than that after the ingestion of casein. The different satiating effects of different types of protein may depend on differences in their digestion and absorption. After ingestion of whey protein, the plasma appearance of dietary amino acids is fast, high and transient (Boirie, Dangin, Gachon, Vasson, & Maubois, 1997), while for casein, it is slower, lower and more prolonged. This fact has been explained by a slow gastric emptying of caseins because they form a viscous coagulate due to the acidic pH in the stomach. Accordingly, a fast protein, such as whey, would be more satiating than a slow protein, such as casein.

The effect of gastric emptying has been controversial in many studies for casein and whey protein. In one particular study, the casein form is not specified; however, a difference in gastric emptying between casein and whey was observed (Hall et al., 2003). From studies using milk (Mahe, Messing, Thuillier, & Tome, 1991) or phospho-caseinate (micellar casein) (Mahe et al., 1996), a difference in the speed of gastric emptying was observed between casein and whey. However, those who used sodium or calcium caseinate were not able to see a difference in the gastric emptying between the two proteins (Calbet & Holst, 2004; Lang et al., 1998, 1999). Sodium and calcium caseinate are not in their native micellar forms and can no longer form clots in the stomach. This modifies the speed of gastric emptying and enzyme susceptibilities. For example, β-lactoglobulin is resistant to pepsin hydrolysis. Its passage through the stomach is fast, and hydrolysis begins in the upper part of the intestine. However, micellar caseins coagulate in the stomach because of the acidic pH, and pepsin can hydrolyze these proteins before their arrival into the intestine. Following this behavior, some authors have introduced the concept of slow and fast proteins. Micellar caseins are considered slow proteins, while whey and soy are considered fast proteins (Boirie, 2004; Bos et al., 2003). Plasma amino acids appear sooner in fast proteins than slow proteins mainly due to different digestion kinetics.

Mellinkoff (Mellinkoff, Frankland, Boyle, & Greipel, 1956) suggested in 1956 that an elevated concentration of plasma amino acids serves as a satiety signal for the food-intake regulating mechanism. Administration of leucine directly to the brain or an increase in dietary leucine not only reduces food intake (Zhang et al., 2007), but also protein synthesis (Kimball & Jefferson, 2001). Dietary proteins and amino acids induce the release of the anorexigenic gut hormones CCK, GLP-1, and PYY (Tome et al., 2009). Furthermore, some specific amino acids have been suggested to act as precursors of hormones, such as tryptophan for serotonin (Wurtman et al., 2003), tyrosine for dopamine and histidine for histamine. The transport of these amino acids to the brain may depend also on the presence of other large neutral amino acids (valine, leucine, isoleucine, tyrosine and phenylalanine) because they utilize the same transporters. α-lactalbumin, a milk protein found in soluble whey proteins, is very effective in appetite suppression and contains high levels of tryptophan associated with an elevated Trp-large neutral amino acid ratio (Beulens, Bindels, de Graaf, Alles, & Wouters-Wesseling, 2004). However, plasma tryptophan concentrations were not correlated to hunger; the addition of tryptophan to a non-satiating protein that is low in tryptophan did not contribute to the increased satiety effect (Nieuwenhuizen et al., 2009). The exact mechanism of action of each amino acid is complex and needs further research.

Here, we give examples of how single proteins affect important physiological functions after their digestion. Food structure and composition can have an impact on the kinetics of protein hydrolysis and subsequently on amino acid absorption. A concept similar to the glycemic index can be used to characterize the kinetics of amino acid appearance, which is similar to the glucose release from food after consumption. Similarly, one could consider the factors that have an effect on glucose release from food, such as the viscosity of food and fiber content, could also influence protein digestion and amino acid and peptide release in plasma.

2.2.3. Lipids

The lipids consumed by humans contain mostly triglycerides (97%), and the remainder consists of phospholipids, cholesterol and other minor lipid compounds such as fat-soluble vitamins and carotenoids. The triglycerides are found in foods emulsions (milk, cream, and other emulsified formulated food), liquids (vegetable or fish oil) and solid forms (butter, palm oil, etc.). After consumption, lipid components will be transformed through their passage through the digestive tract to allow their absorption. A brief description of lipid digestion and absorption is given here, and readers are referred to recent review papers for more details (Armand, 2008; Bowen, Noakes, & Clifton, 2008; Lairon, 2009; van Aken, 2010). Lipases are water-soluble and consequently, their efficacy in hydrolyzing lipids is based on their adsorption at the interface of the emulsified lipid. Lipid emulsification begins in the stomach and continues in the intestinal tract (with peristaltic movements). Then, the hydrolysis of triglycerides into free fatty acids and monoglycerides begins in the stomach. Approximately 10–30% of triacylglycerols are hydrolyzed (Fave, Coste, & Armand, 2004), and lipid hydrolysis is mainly realized in the small intestine through the synergistic actions of pancreatic lipase and bile (Fave et al., 2004). Free fatty acids can then be absorbed by intestinal cells mostly in the duodenum and jejunum (Lairon, 2009). Depending on the fatty acid chain length, short and medium chain lengths form complexes with albumin and are secreted into portal blood circulation, while longer chain fatty acids are transported as chylomicrons (Lairon, 2009). Following food consumption, circulating triacylglycerols (TAG) show a marked increase, called postprandial lipemia, within one hour and subsequently can remain elevated for several hours (Lairon, 2009; Lopez-Miranda, Williams, & Lairon, 2007). The postprandial lipemia varies depending on several factors, such as the amount and nature of dietary triglycerides and the presence of other nutrients. As mentioned before, oat bran can change cholesterol availability, decreasing the occurrence of chylomicron postprandially. Changes in diet, such as the adoption of the Mediterranean-type diet, can also modify the postprandial response (Lairon, 2008). Several formulated foods contain a high proportion of lipids incorporated within the food structure, such as stabilized emulsions (salad dressing, gravies, soups and cream desserts). Little information is available about the intragastric behavior of these formulated lipid emulsions and how they can affect the mechanisms of digestion (Marciani et al., 2009).

Some information has been obtained using model systems. The behavior of an acid-stable emulsion and an acid-unstable emulsion during gastric digestion were studied in humans. The acid-stable emulsion delays gastric emptying and stimulates the release of CCK, which is believed to maximize satiety signaling to reduce food intake (Marciani et al., 2007). In a latter study, the same emulsions were used to determine their influence on plasma fatty acids and satiety (Marciani et al., 2009). Again, the acid-stable emulsion decreases hunger and appetite while increasing fullness and the concentration of palmitic acid in the chylomicron lipid fraction. Thus, emulsion interfacial composition is an important factor to consider when designing novel foods.

The physicochemical properties and structure of emulsions to control lipid bioavailability has been studied by McClements et al., and readers are referred to recent review papers for more details (McClements & Decker, 2009; McClements, Decker, & Park, 2009).

3. Industrial food processing

Food structure affects the rate and extent of digestion and the rate of absorption of nutrients. Independent of the form of food, the rate of stomach emptying and satiety have been correlated (Bergmann et al., 1992). Glycemic index has also been controlled by food, which can alter stomach emptying. Usually, solid foods with strong tissue structure, such as fresh whole fruits and vegetables, breads containing whole grains, and whole meat products, are digested more slowly and are more satiating than foods that have soft, overripe or a highly processed structure (Porrini, Crovetti, Riso, Santangelo, & Testolin, 1995). Thus, processing is an important factor because it influences the food matrix structure. For example, the impact of freezing, defrosting and toasting on the glycemic response of white bread was studied (Burton & Lightowler, 2008). Breads that were frozen and defrosted, fresh and toasted, and toasted after freezing and defrosting showed a lower incremental area under the glucose response curve compared with fresh white bread. This could be explained by the increased resistant starch content after the cooling and freezing steps, limiting its enzyme susceptibility.

This section reviews the effect of some important food processing methods on food nutritional properties and their possible effects on the kinetics of digestion and absorption. Three examples of important processes affecting macronutrients' bioaccessibility and bioavailability will be presented.

3.1. Homogenization

The goal of homogenization is the disruption of fat globules into smaller ones. For milk, it also alters the interface composition throughout the absorption of casein and whey protein at the surface of the milk fat globule membrane (MFGM) (Michalski, 2007). This process is believed to modify milk health properties. Following homogenization, rennetting, souring or heating at high temperatures, processing will cause casein micelles to aggregate and thus, change the network structure. The effect of homogenization on dairy products was extensively reviewed by Michalski et al. (Michalski, 2007, 2009; Michalski & Januel, 2006), and only certain highlights will be presented in this section.

Milk homogenization is usually followed by pasteurization or ultra-high-temperature (UHT) treatment (described in Section 3.2). Subsequently, whey protein is denatured, and the extent of denaturation is proportional to the temperature used (neglectable for pasteurization, ~60% for UHT) (Michalski & Januel, 2006). Thus, micellar fragments and semi-intact casein micelles cover the fat droplet interface, and the denatured whey protein can interact through disulphide bonds with MFGM proteins and micellar caseins absorbed at the interface (Michalski, 2009).

After milk homogenization, coagulation of caseins and lipids droplets occurs simultaneously during gastric digestion, and they were found to be much finer and more digestible. Gastric emptying is delayed with smaller fat droplets; however, larger lipolysis is found due to a larger interface area. Michalski (2009) hypothesized that homogenization reduces the size of fat droplets and favors fat lipolysis. However, lipase activity is important because according to the MFGM composition, TAG will be more or less accessible by lipase. It seems that fat droplets covered by protein (whey and/or casein) have higher lipase activity *in vitro* (Armand, 2008). Lipase's access to TAG is affected by the native structure of milk fat globules and the physicochemical changes induced by homogenization processes (Michalski, 2009). Also, TAG appearance in the plasma of animals was higher for an unemulsified fat milk preparation compared to homogenized and unhomogenized cream (Michalski et al., 2006). The authors suggest that gastric emptying and lipase activities are most likely factors influencing the results. However, the consumption of butter, milk or mozzarella cheese in type 2 diabetic patients did not affect plasma TAG concentration and gastric emptying. However, the TAG peak was delayed for butter and cheese compared with milk (Clemente et al., 2003).

3.2. Heat treatments

Food products are cooked, fried, or heated in ways that ensure food safety. Adverse effects, such as nutrient destruction, are observed after heat treatment. Others, such as the Maillard reaction and lipid oxidation, are promoted after heat treatment, which leads to negative appearance and taste. The heating process also influences protein structure by causing protein denaturation. When heated above the critical temperature, protein hydrogen bonding and electrostatic interactions are destabilized, while hydrophobic interactions are stabilized (Damodaran, 2008); the latter being mostly responsible for the protein unfolded state. Each protein has a different optimal stability temperature, which is influenced by the amino acid content. For example, Val, Ile, Leu and Phe are hydrophobic amino acids and have shown to be more stable than hydrophilic amino acids.

Extrusion cooking is a high-temperature, short-time process of intense mechanical shear, which is utilized for ready-to-eat cereals, salty and sweet snacks, and croutons for soups and salads (Singh, Gamlath, & Wakeling, 2007). This process is also used for weaning foods, dietetic foods, and meat replacers, in which the nutritional quality is important. The review from Singh et al. (2007) conclude that mild extrusion conditions (high moisture content, low residence time, and low temperature) can improve the nutritional quality of food. A better retention of amino acids and vitamins as well as a higher protein and starch digestibility was observed. Moreover, there is an increase in the soluble dietary fiber content, a decrease in lipid oxidation and a better absorption of minerals (Singh et al., 2007).

Wheat proteins found in pasta and bread are most often cooked or baked. Heat treatment has been shown to also influence the digestibility of wheat proteins. Bread crumbs and crust are considered to have different heat treatment intensities of <100 and >180 °C, respectively (Pasini, Simonato, Giannattasio, Peruffo, & Curioni, 2001). After pepsin digestion, the digestibility of bread crumbs and crust is reduced compared to the unheated dough. However, the digestibility of bread crumbs and dough were similar at the end of the pancreatic digestion, while the digestibility remained much lower for the bread crust (Pasini et al., 2001). Others studied the effect of different drying temperatures (20–180 °C) on wheat digestibility (De Zorzi, Curioni, Simonato, Giannattasio, & Pasini, 2007). After *in vitro* digestion with pepsin and pancreatin, wheat pasta dried at 180 °C had a lower digestibility compared to the other drying temperatures. This might be caused by the formation of disulfide bond and protein aggregates at high temperature. Both studies conclude that high heat treatment increases wheat protein aggregation and denaturation.

Protein conformation, and consequently their enzymatic susceptibility, is modified after heat treatment. *In vitro* studies conducted by Mullally, Mehra, and FitzGerald (1998) showed that thermally induced protein unfolding resulted in increased susceptibility of β-lactoglobulin to pepsin and trypsin proteolysis. Furthermore, molecular interactions (protein–protein, protein–polysaccharide or protein–lipid) can modify the protein's enzymatic susceptibility and behavior in the acidic pH of the stomach. Recently, Lacroix et al. (2008) presented a difference in plasmatic amino acid appearance between UHT milk and pasteurized milk. The kinetics of dietary nitrogen transfer to serum amino acids, proteins, and urea was significantly higher in UHT than in the pasteurized milk. The higher anabolic use of dietary nitrogen in plasma proteins after UHT ingestion strongly suggests that these differences are due to modifications to digestive kinetics and the further metabolism of dietary proteins subsequent to this particular treatment of milk. Thus, the kinetics of protein digestion and the release of amino acids may vary between foods that look similar.

3.3. Coagulation, thickening and gelling

Several product processes and formulations will influence the product viscosity and consistency. Traditional sauce formulation uses starch gelatinization to increase viscosity. Similarly, some thickening agents, such as polysaccharides, can increase viscosity and form a gel, depending on the conditions. Some commonly eaten foods, such as fermented dairy products and cheese, are in a semi-solid or solid state due to enzymatic, microbial and processing steps (draining, cooking, pressing, etc.).

Increasing viscosity has an impact on the digestive process. Both gastric emptying and intestinal transit are affected by the liquid to solid ratio in the chyme (Low, 1990). Several nutrients, such as fibers, proteins, and interacting nutrients, can impact chyme viscosity (e.g., gelling protein–polysaccharide, etc. (Turgeon & Laneuville, 2009; Turgeon, Schmitt, & Sanchez, 2007)) and trigger the digestion process. Three examples are given from different food products. Some authors (Gaudichon et al., 1995) compared the kinetics of nitrogen absorption of ^{15}N-labeled milk and yogurt in miniature pigs and showed a modulating effect of gastric emptying due to the higher viscosity of yogurt.

Polysaccharides used in similar concentrations as found in fiber-rich food can also have a marked effect on the viscosity and stomach emptying. Using magnetic resonance imaging techniques, Marciani et al. (2000, 2001) showed that viscous fluid meal was slowly diluted by gastric acid and emptied at a slower rate, which will affect the rate of nutrient release and digestive processes (Burton-Freeman, 2000). *In vitro* studies also highlight the effect of viscosity on enzymatic activity. The understanding of the changes in ingredients and food rheological properties in the stomach has inspired the design of gels with physical properties that can change with various conditions in the gastrointestinal tract (Lentle & Janssen, 2010). Alginate gels that form in acidic conditions have been proposed to increase viscosity in the stomach (Norton, Frith, & Ablett, 2006). Similarly, some ingredients could be protected to be non-viscous in the food but released in the stomach to create viscosity. This could limit the effect of the gelling agent on the sensory properties of the enriched food, while allowing the thickening into the stomach.

The addition of a thickening agent and fat content in a custard formulation can modify its *in vitro* fat bioaccessibility. Bioaccessibility was higher for starch-based custards than cellulose-based custards due to starch degradation by amylase. Fat addition also modified the bioaccessibility of lipophilic active compounds (Sanz, Handschin, Nuessli, & Conde-Petit, 2007; Sanz & Luyten, 2006). There is little information on gelled products, and more research is necessary on this type of products to better understand the digestive fate of their nutrients. An example of the effect of lipid digestion in a cheese matrix is given in Section 3.1. Lopez et al. highlighted in a recent review that cheese consumption has not been correlated to the risk of cardiovascular diseases, and suggests that it could be due to a possible cheese matrix effect. A comprehensive approach considering cheese composition and processes used to obtain it in human intervention studies is needed.

4. Case study of the nutritional properties of a conventional food: dairy products and satiety

There has been a long tradition of milk and dairy products in human nutrition (Haug, Hostmark, & Harstad, 2007). The presence of numerous essential nutriments contributes to their exceptional nutritional value, and the term 'nutrient density' has been recently introduced to describe it (Drewnowski, 2005). Continuous research on the health aspects of dairy products and their components result in the possibility to consider these traditional dairy foods as potential health foods that could contribute to the prevention of disease (Playne, Bennett, & Smithers, 2003). Bovine milk contains approximately 32 g protein/L. Milk protein is a good source of essential amino acids and contains an array of proteins with biological activities (antimicrobial, facilitating absorption of nutrients, growth factors, enzymes, etc.) (Severin & Xia, 2005). The casein content represents 80% of milk proteins, and the remaining 20% is composed of various soluble proteins, of which β-lactoglobulin is the major component. During digestion, caseins and whey are not digested at the same rate, suggesting a natural time-dependent process that distributes amino acids and peptides. Furthermore, proteolysis of milk proteins can produce a wide variety of peptides with different bioactivities (antithrombotic, anticholesterolemic, opioid, immunomodulatory, antimicrobial, etc.) (Korhonen, 2009).

There is some evidence that milk products could be beneficial for weight management (Van Loan, 2009). Dairy products have been linked to weight management, and calcium and dairy food intake can influence many components of energy and fat balance, indicating that inadequate calcium/dairy intake may increase the risk of positive energy balance and other health problems (Major et al., 2008). Zemel, Thompson, Milstead, Morris, and Campbell (2004) have shown that increasing the amount of dietary calcium significantly augments weight and fat loss, and calcium given from a dairy source was substantially more efficient than calcium supplements. Furthermore, some dairy protein sources contain specific peptides or proteins that may elicit direct effects on satiety. In addition to the satiating effect of whey and casein (Dunshea, Ostrowska, Ferrari, & Gill, 2007), a specific peptide produced during cheese making, the glycomacropeptide, has been shown to stimulate the pancreatic and gastrointestinal secretion of hormones involved in satiety to a greater extent than whey alone (Dunshea et al., 2007).

Another contribution of dairy products for weight management can be through an effect on satiety. Although studies investigating the effect of liquids supplemented with whey or casein (both dairy proteins) generally report an appetite-suppressing effect (Anderson, Tecimer, Shah, & Zafar, 2004; Bertenshaw, Lluch, & Yeomans, 2008; Bowen, Noakes, & Clifton, 2006; Bowen, Noakes, Trenerry, & Clifton, 2006), several studies using milk have failed to show a reduction in energy intake. Recently, Dove et al. (2009) reported a significant reduction of energy intake at lunch (8.5%) when skim milk was consumed at breakfast instead of a fruit drink. This could be related to the kinetics of protein digestion. The main difference between the studies was the time to assess *ad libitum* food intake.

Yogurt and cheese, as viscous and solid foods, should induce increased satiety as compared with liquid milk (Leidy, Apolzan, Mattes, & Campbell, 2010). The effect of the modification of yogurt composition on satiety has been studied. Addition of fiber (inulin) promoted the satiety of a low-energy density yogurt to the level of a high-energy density yogurt (Perrigue, Monsivais, & Drewnowski, 2009). Moreover, two recent nutritional studies have experimented with yogurt enriched in two ingredients recognized for their effect on satiety: protein and fiber (Lluch et al., 2010). A serving of a low-fat dairy product enriched with milk protein and guar gum significantly reduced appetite over 2 h following its consumption compared with non-enriched control products. A second trial associated these changes in appetite with a reduction of food intake at a subsequent meal. Little have been reported on the potential satiating effect of cheese and how it varies depending on composition.

These examples show the possible unresolved link between food microstructure and nutritional properties. Dairy products have been considered for their potential as a matrix to deliver bioactive components. However, do we already know the impact of processing and formulation steps to improve/control their nutritional properties? Consumers traditionally look for delicious and convenient foods and are more and more concerned about the nutritional value of food. The food industry has developed skills to control processes to optimize sensory properties, and this knowledge now needs to be extended to the nutritional properties (Fig. 1). This approach rests on studies integrating food science, nutrition and physiology. The basics of the understanding of digestion mechanisms of major nutrients gained from the studies that use individual ingredients will be useful in reaching another level of complexity—the microstructural organization of a real food matrix.

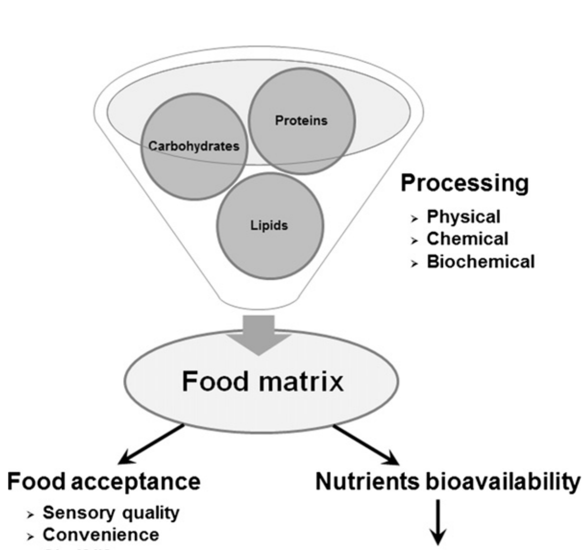

Fig. 1. Impact of processing and formulation steps to improve/control macronutrients nutritional properties.

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