



## Food structure in relation to nutrients for human health

Ogori A.F<sup>1\*</sup>, Jackson V<sup>1</sup>, and Alimi T<sup>2</sup>.

<sup>1</sup>Department of Home Science and Management, Faculty of Agriculture, Federal University Gashua, Gashua, Yobe State, Nigeria; <sup>2</sup>Department of Chemistry, Faculty of Science, Federal University of Education, Kontagora, Niger State, Nigeria

**\*Corresponding author:** Ogori A. F., Department of Home Science and Management, Faculty of Agriculture, Federal University Gashua, Gashua, P.M.B.1005, Gashua, Yobe State, Nigeria

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### ABSTRACT

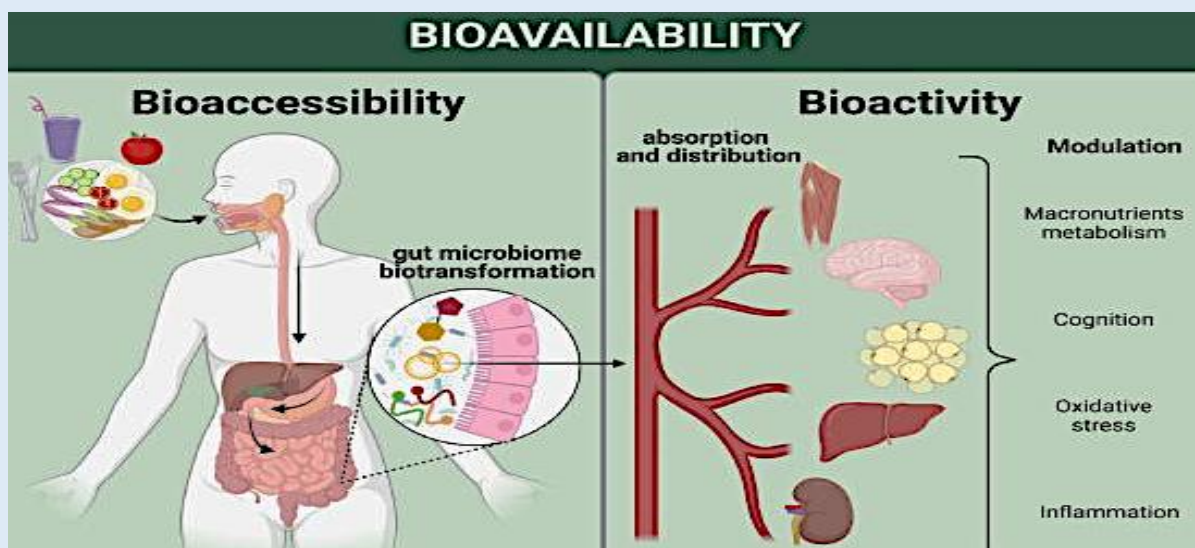
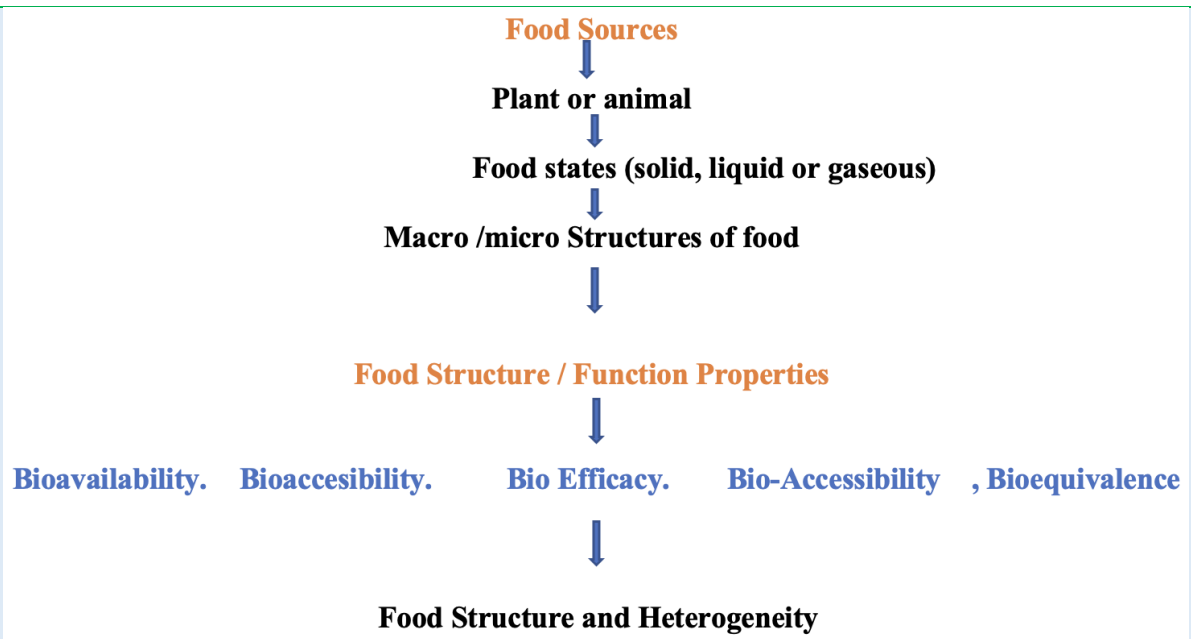
Food structure provides a functional framework for cellular organelles derived from plant or animal sources and plays a major role in the bioavailability, bioaccessibility, bioefficacy, and bioequivalence of functional nutrients and phytochemicals, which significantly influence health and disease outcomes.

Functional foods and biopharmaceuticals are increasingly recognized for their therapeutic potential in preventing and managing chronic diseases such as diabetes, cancer, and hypertension.

Understanding and applying knowledge of food structure in relation to nutrient behavior can help predict the functional bioavailability, bioaccessibility, bioefficacy, and bioequivalence of food components, as well as the effects of food processing and packaging technology. Moreover, this understanding can support the development of novel foods and guide food biochemists and nutritionists in designing optimally structured ingredients designed to enhance mucosal nutrient absorption and improve overall nutrient utilization from the food matrix.

Concepts on food microstructure in relation to food nutrients will assist experts in areas of food processing, storage technology, and the use and application of food ingredients from the farm to the kitchen, helping preserve food nutrients and functionalities. By understanding and manipulating food microstructure, it is possible to optimize nutrient protection, release, and functional delivery in both natural foods and engineered food matrices.

**Keywords:** Bioavailability, Bioaccessibility, Efficacy, Bioequivalence, Food matrix, Nutrient delivery, Bioactive compounds



**Graphical Abstract:** Food structure in relation to nutrients for human health.

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**INTRODUCTION:**

Human health has become a central concern for food scientists and modern food-processing industries. Evidence linking reductions in diseases such as cardiovascular disease (CVD), cancers, and diabetes to dietary patterns continues to grow. These diet-related diseases present challenges but also provide insights into bioaccessibility, bioefficacy, and bioequivalence of

nutrients. Eating habits are directly related to food structure, which, in turn, affects nutrient bioavailability [1-2]. Bioactive compounds (BC) found in functional foods have demonstrated beneficial biological activities, with extra-nutritional benefits arising from antioxidant properties and their preventive abilities. Bioactive compounds, characterized by biomolecules, occur in small amounts in various food sources, and these

biomolecules can potentially reduce the risk or prevent the onset of certain diseases to promote health [28]. They may improve health through physiological mechanisms [3]. Functional foods offer specific, effective, and non-toxic quantities that have been clinically proven and well-documented to offer significant health benefits. These benefits are exhibited through specific biomarkers, promoting optimal health, reducing the risk of chronic and viral diseases, and effectively managing their associated symptoms [3].

Natural substances are often regarded as functional foods due to the presence of bioactive constituents that contribute to their health-promoting properties [4]. These compounds are considered the principal agents underlying the physiological activity of functional food products, such as synbiotics, polyunsaturated and essential fatty acids, various vitamins, dietary minerals, phytochemicals, antioxidants, and phytosterols [5]. With the advances of society, functional foods are becoming recognized for their important role in partially or fully substituting conventional pharmaceutical drugs on shelves against certain diseases [6-7]

Although daily nutrient requirements can be obtained from food composition tables, the actual bioavailability and bioaccessibility of these nutrients within the digestive tract remain uncertain. This uncertainty is often due to the structural matrices of ingested foods [8-9]. Whether nutrients become bioaccessible or remain inaccessible in the gut is important, but the effective availability of nutrients shaped by bioefficacy, bioequivalence, and chemical state is even more critical. Advances in functional food and biopharmaceutical technologies show that nutrient matrix states and structural properties strongly influence biological responses. This review explores the relationship between food structure matrices and how these factors determine the functional bioavailability, bioaccessibility, convertibility, and stability of food ingredients within the human gastrointestinal tract prior to and during nutrient absorption.

**Structure of food:** Foods, whether natural or processed, are composed of organized structures at cellular, subcellular, and molecular levels. These structures are assembled into functional units. Natural food structures fall into categories such as fibrous forms (e.g., muscle cells), encapsulated tissues, and complex liquid matrices such as milk. These classifications depend on cellular specificity and give each food unique functional characteristics [10-11]. Most plant- and animal-derived foods are consumed with their native macro- and microstructures intact, although processing may modify these structures. Processing, whether chemical, thermal, or mechanical, alters bioactive components and reorients nutrient matrices. Such structural reorientation can shift the quantum and tempo of food microstructures, resulting in functional changes even at the molecular [12-13] and nanoscale [14] levels. Typical structural components include fructose, glucose, peptide isolates, and nutrient concentrates. According to [13], nutrients function as small structural elements crucial to biological activities, such as cellular metabolism. This supports the argument that functional food structures may relate to principles of uncertainty over time, similar to Heisenberg's concept [15-16]. The pseudoplastic flow behavior of food materials within the gut varies with physiological conditions determined both *in vivo* and *in vitro*—this variability forms the basis of the quantum and tempo theory [12-13,17]. Food matrices can be understood as small, organized nutrient units within a continuum derived from microcellular origins. Nutrients are therefore structured in a way that allows interaction with each other or their surrounding medium across scales and over time. For example, Carotenoids in carrots exist within macromolecular pockets of starch granules and bound proteins. Isoflavones can be embedded in baked food matrices. So-propyl compounds occur in onion layers. Sulfhydryl matrices are present in raw and fried egg structures. Similarly, the functional potential of *M. oleifera* extends far beyond its nutritional profile to

antioxidant and hypertensive therapeutic properties, including anti-inflammatory, antimicrobial, and anti-diabetic effects [18-19].

**Food Structure and Function Property:** Nutrients in natural foods are held within cellular compartments or assembled linkages that must be disrupted during digestion or processing for functional nutrient release. [10] The study of fat availability in almond seeds through fecal analysis observed intact cell walls in samples from subjects fed almond-rich diets. This suggested that unbroken cellular structures prevented the release of intracellular lipids into the bloodstream. Complete breakdown of cellular matrices during digestion is not guaranteed, but nutrient absorption depends on interactions with other food components and the presence of certain structural and available features. For example, fiber-rich food structures can reduce provitamin A absorption, whereas ferulic acid absorption is enhanced in the presence of bran fibers [20-21]. Food structure also influences acid–base balance,

micronutrient availability (e.g., vitamins and proteins), and overall nutrient accessibility in the gut. The physical state of food—solid, liquid, or gaseous—affects how nutrients become available, accessible, and functionally effective during digestion.

#### Bioavailability of Food Nutrients in Relation to Food Structure:

Nutrient bioavailability refers to the proportion of an ingested nutrient that is released from food, absorbed, and made available for use in normal physiological processes or for storage. The Food and Agriculture Organization defines nutrient bioavailability as the rate and extent to which an active nutrient, structural component, or therapeutic moiety present in food or drugs becomes available and elicits a functional effect. However, the concept of food bioavailability has evolved, partly due to its association with terms such as efficiency and structure [22]. Food bioavailability can be measured *in vivo*, but it is influenced by various factors, including the nutrient's structure and molecular size.



**Figure 1.** Process of food bioavailability in the gut.

**Bioaccessibility of nutrients in relation to the food matrix:** Bioaccessibility refers to the fraction of a nutrient that is released from the food matrix during digestion and becomes available for absorption in the gastrointestinal tract. Reference [23] defined bioaccessibility as the portion of a nutrient that is accessible for uptake in the gut. Not all digested nutrients are absorbed; therefore, bioaccessibility can be influenced by the structural properties of the food matrix, such as its shape and size.

These structural characteristics affect nutrient activity in relation to their physical form and can influence both enzymatic and chemical processes involved in digestion [24].

**Nutrient Bio Efficacy of food nutrients:** Nutrient bioefficacy refers to the fraction of an ingested nutrient that produces a measurable physiological or health-related effect. It describes how effectively a nutrient that has been digested exerts a functional impact on health or

contributes to maintaining the body's normal state. Bioefficacy is influenced by the structural properties of the food matrix, because the rate of nutrient absorption—often determined by molecular size, structural form, and nutrient functionality—affects how efficiently a nutrient is utilized. The potential for synergistic effects between Moringa extracts and other functional food ingredients, such as milk extracts, presents opportunities for enhanced product efficacy. Combination with other hepatoprotective compounds, such as turmeric extract, has provided additive benefits for liver health support [25-26, 27]. Similarly, combining Moringa leaf extract with probiotics could create functional foods that support both liver health and digestive wellness [25, 28]. The antioxidant properties of Moringa leaf extract make it an excellent partner for omega-3 fatty acids, helping to prevent oxidative stress with complementary health benefits [29-30]. This combination approach aligns with current functional food trends toward multi-benefit products that address multiple aspects of health and wellness due to the bioefficacy of Moringa extract [31-32].

**Bio-Accessibility of food nutrients:** Bioaccessibility, which is the ability of a nutrient released during digestion to reach its target cells in a timely and functional state, can be limited by properties such as membrane permeability, transient transport mechanisms, and cellular or tissue-level barriers. The efficiency of bioactive nutrients may be hindered by these limitations; however, such inefficiencies can be improved when the structural properties of the food matrix are properly modified or reoriented during processing and digestion, as observed with flavonoid and phenolic compounds identified in *Moringa oleifera* extracts, which demonstrate excellent stability, making them suitable for incorporation into acidic beverages and fermented products [33-34].

**Bioequivalence of food nutrients:** Bioequivalence is a situation in which two or more functional nutrients, food

ingredients, or formulations do not differ significantly in the rate or extent to which their active components become available at the site of physiological need or activity. Bioequivalence is determined when nutrients show similar absorption profiles under comparable molar doses and physiological conditions.

**Determination of nutrient bioavailability and bioaccessibility:** Bioavailability and bioaccessibility can be assessed using *in vivo*, *ex vivo*, and *in vitro* methods.

*In vivo* studies provide direct evidence of nutrient absorption and physiological response, typically measured after consumption of purified nutrients or equivalent dietary doses [35]. *Ex vivo* approaches involve examining nutrient interactions or uptake using isolated tissues, fluids, or organs. *In vitro* models simulate digestion and absorption processes without the need for human or animal subjects. This approach does not require ethical approval and is widely used to study gastrointestinal release, digestibility, and nutrient interactions [36].

**Bioavailability of nutrients from plant foods:** Plant-based foods contain numerous bioactive compounds, and their bioavailability is significantly influenced by food microstructure. Processing techniques such as grinding, fermentation, and ohmic heating can enhance bioavailability by disrupting cell walls, releasing nutrient complexes, and modifying molecular structures. Storage and processing may further influence these structural changes.

**Carotenoids:** Dietary carotenoids are associated with reduced risk of various cancers and chronic diseases. Their release from plant cell walls occurs primarily when the food matrix is disrupted during preparation—processing, cooking, or mastication—rather than during digestion alone.[37] reported that pectin-like fibers and crystalline carotenoid structures in carrot chromoplasts

contribute to incomplete carotenoid release.  $\beta$ -carotene bioavailability can be improved through cooking, pureeing, or enzymatic treatment. Release and absorption dynamics in the digesta have been described by [38-39].

**Lycopene:** The red carotenoid in tomatoes exhibits increased bioavailability and bioaccessibility after thermal processing. Heating weakens plant cell structures and enhances the conversion of naturally occurring trans-isomers to the more bioavailable cis-isomers. This transformation contributes to the higher lycopene concentrations typically found in tomato paste compared to fresh tomatoes.

**Xanthophylls:** Xanthophylls are oxygenated carotenoids responsible for the yellow pigmentation of plant leaves. In mammals, some xanthophylls accumulate in the eye, where they support vision and protect against oxidative stress. Their bioavailability is strongly influenced by lipid presence, molecular structure, and nutrient interactions [38].

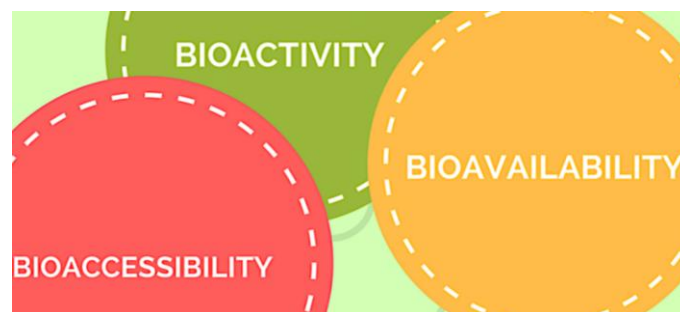
**Folates / Folic Acid:** Folate (B-vitamin) is essential for cell growth, reproduction, and tissue maintenance. Folate deficiency is associated with cancers of the digestive system, esophagus, pancreas, and with neurological disorders, including depression [40]. Naturally occurring folates are often bound to macromolecules; their structural entrapment can limit absorption unless the matrix is disrupted. However, excessive disruption can also degrade folates, reducing

functionality. Food structure, therefore, influences folate release and absorption efficiency.

**Polyphenols:** Polyphenols—including flavonoids, isoflavones, and anthocyanins—are secondary plant metabolites with highly variable bioavailability [41]. Their functional outcomes depend on molecular size, structural complexity, binding properties, and transport pathways.

Approximate functional bioavailability ranges include: Sugars: ~0.05%; Anthocyanins (berries, red wine): 1–5%; Flavones: 9.9–29.8%; and Isoflavones: 50–79.5% [42]. Polyphenols are sensitive to high gut pH, and their absorption depends heavily on cell wall structure, glycoside location, and binding within the plant matrix [42]. Transformations during digestion are often observed [3]. Pancreatic digestion has been shown to significantly enhance the bioavailability of phenolics from grapes and nuts, whereas gastric or salivary digestion alone does not.

**Food Structure and Heterogeneity:** The absorption of many functional nutrients depends on food structure and fat content [14,]. For example, the bioavailability and bioaccessibility of heterocyclic aromatic amines from meat vary with cooking doneness [14-15]. Food heterogeneity—differences in nutrient concentration, binding angle, particle size, or matrix density—can significantly influence nutrient bioavailability by affecting how nutrients are released and transported across cellular interfaces.



**Figure 2.** Subsets of food bioactivity

## CONCLUSION

Food matrices or structures play a central role in nutrient bioavailability, bioaccessibility, and bioefficacy. Food macromolecules or microstructures protect nutrients from degradation; they may also impede release and absorption. Processing, such as thermal, mastication, fermentation, and enzymatic digestion, can assist nutrient liberation, yet not all bioactive components are fully released. This review will assist in unveiling the food macro- or microstructure in relation to food nutrients and further assist experts in various processes and storage applications of food from the farm to the kitchen, helping maintain food nutrient functions. Understanding and manipulating the macro- or microstructure of food can help optimize nutrient protection, release, and delivery in both natural and engineered foods.

**Conflict of interest:** The authors declare that they have no conflict of interest.

**Credit authorship contribution statement:** Ogori Akama F: Writing – original draft, Formal analysis, Conceptualization. Jackson Vala; Supervision, Conceptualization. Ogori Akama F: Writing – review & editing, Software. Alimi T: Writing – review & editing, Analysis, Conceptualization.

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**Data availability:** Data will be made available on request.

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