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OPTIMISING NUTRIENT BIOAVAILABILITY: DIETARY STRATEGIES

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ABSTRACT:

Bioavailability refers to the proportion of an ingested nutrient that is absorbed from the diet and used for normal body functions (Aggett, 2010). This process includes the absorption, transport, and conversion of nutrients into physiologically active forms, enabling them to support metabolic activities and maintain overall health. Optimising nutrient bioavailability is crucial for ensuring that the body receives adequate nutrition, which is especially important in addressing nutritional deficiencies and promoting health.

Nutrient bioavailability is influenced by several factors, including the food matrix, nutrient interactions, form of the nutrient, digestive health, and the presence of anti-nutritional factors etc. The food matrix affects nutrient release during digestion, while nutrient-nutrient interactions determine how one nutrient can modulate the bioavailability of another, either by enhancing or inhibiting it (Dima *et al.*, 2020). The form in which nutrients are present also affects their absorption and bioavailability in the body. Digestive health plays a pivotal role, as factors like digestive enzymes, pH of the gastrointestinal tract and intestinal integrity directly impact nutrient bioavailability. Furthermore, the presence of anti-nutritional factors can also inhibit nutrient absorption and hinder bioavailability. The role of gut microbes is increasingly recognised in nutrient bioavailability. Gut microbiota can enhance the absorption of nutrients by breaking down food components, producing beneficial metabolites, and modulating the gut environment.

Nutrient bioavailability can be assessed through a variety of methods. Direct approaches include blood testing, urine analysis, and isotope tracing to measure nutrient absorption and utilisation. Indirect methods involve nutrient balance studies and functional tests that evaluate physiological responses to nutrient intake. Additionally, experimental models such as cell cultures, animal studies, and *in vitro* digestion simulations provide valuable insights into nutrient bioavailability. Processing methods can significantly influence nutrient bioavailability, either enhancing or diminishing the absorption and utilisation of nutrients in food. Dietary strategies to optimise nutrient bioavailability include fortification and enrichment of foods, using various cooking techniques, combining specific foods to enhance absorption, and removing anti-nutritional factors.

Emerging technologies are enhancing nutrient bioavailability through nanoencapsulation for targeted nutrient delivery, personalised nutrition based on genetic variants, smart nutrient delivery systems, and gut microbe targeted strategies. Optimising nutrient bioavailability is essential for improving health outcomes and addressing nutritional deficiencies. Further research and the application of innovative strategies will enhance the understanding of nutrient bioavailability and maximize their effectiveness in promoting overall wellbeing.

Keywords:- Bioavailability, absorption, nutrient interactions, anti-nutritional factors, food matrix.

INTRODUCTION:

Nutrient bioavailability plays a pivotal role in determining the extent to which dietary components can be utilized by the body. While the nutritional content of foods is often evaluated based on their composition, it is the bioavailability of these nutrients that ultimately defines their contribution to health. A nutrient's

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journey from ingestion to absorption and utilization is complex, involving multiple physiological processes such as digestion, metabolism, and transportation through various biological barriers. Understanding bioavailability is therefore essential for assessing the real impact of nutrients on human health.

Several factors influence the bioavailability of nutrients, including the physical and chemical properties of the food, the individual's digestive capacity, and interactions between nutrients. The form in which a nutrient exists in food—whether bound, free, or chemically modified—can significantly affect its absorption. Additionally, the food matrix, or the structure and composition of the food, can either enhance or inhibit nutrient release during digestion. These considerations are essential in designing dietary strategies that aim to optimize nutrient intake and improve overall health outcomes.

The study of bioavailability also has broader implications for public health, nutrition policy, and therapeutic interventions. With rising interest in personalized nutrition and functional foods, understanding the variability in nutrient absorption between individuals has gained attention. Genetic, environmental, and lifestyle factors can all affect how efficiently different people absorb and utilize nutrients. As a result, the focus has shifted towards tailoring dietary recommendations to optimize nutrient bioavailability, ensuring that individuals can maximize the health benefits from their diet.

2. Definition of bioavailability

Bioavailability refers to the proportion of an ingested nutrient that is absorbed from the diet and used for normal body functions (Aggett, 2010). It encompasses the processes of digestion, absorption, metabolism, and transport to the target tissues. The bioavailability of nutrients is crucial in determining the efficacy of the diet in meeting physiological needs, and various factors, including nutrient form, food matrix, and individual health, can influence it.

3. Factors influencing bioavailability

Bioavailability is influenced by a variety of factors that determine how efficiently a nutrient is absorbed and utilized by the body. These factors can be broadly categorized into intrinsic and extrinsic components. Intrinsic factors include the nutrient's chemical form and its interactions with other dietary components, while extrinsic factors involve food processing, preparation methods, and overall digestive health. Key determinants of nutrient bioavailability include the food matrix, nutrient interactions, the chemical form of the nutrient, and the individual's digestive health and metabolic status (Schönfeldt *et al.,* 2016). Each of these plays a significant role in modulating how nutrients are absorbed, metabolized, and utilized by the body.

3.1. Food matrix

The food matrix refers to the physical and chemical composition of food, which plays a pivotal role in influencing nutrient bioavailability. Nutrients are embedded within a complex network of macronutrients (proteins, fats, and carbohydrates), micronutrients, and non-nutrient compounds such as fibers, polyphenols, and antinutritional factors (Kamiloglu *et al.,* 2021). The way these components interact can either facilitate or hinder the release and absorption of nutrients during digestion.

The food matrix can act as a barrier or enhancer depending on the nutrient and its surrounding environment. For instance, nutrients such as fat-soluble vitamins (A, D, E, K) are more efficiently absorbed when consumed with a matrix containing fat. This is because dietary fat enhances micelle formation in the intestine, which is necessary for the absorption of these vitamins. Conversely, a fiber-rich food matrix can impede the absorption of minerals like calcium, magnesium, and iron. Fibers such as cellulose, hemicellulose, and pectin bind to these minerals, reducing their bioavailability by limiting their release during digestion or increasing their excretion.

The degree of food processing also greatly influences the food matrix and, subsequently, bioavailability (Shahidi *et al.,* 2022). Cooking, for example, can soften plant cell walls and release nutrients that are otherwise trapped within the matrix. Lycopene, a carotenoid found in tomatoes, has a higher bioavailability when tomatoes are cooked compared to when consumed raw, due to the breakdown of the food matrix. On the other hand, excessive processing, such as refining or ultra-heat treatments, can degrade sensitive nutrients, reducing their bioavailability. For example, vitamin C is prone to degradation during high-heat processing, diminishing its availability in processed fruits and vegetables.

Moreover, the physical structure of the food also influences bioavailability. Whole grains and seeds have intact cell walls that can inhibit nutrient release, requiring more digestive effort to break down and access the nutrients inside. Grinding, chopping, and mashing can disrupt the matrix and increase nutrient release, as seen in the case of mashed potatoes or ground flaxseeds, which improve nutrient accessibility compared to their whole counterparts.

The food matrix is a crucial determinant of how nutrients are processed and absorbed by the body, making it an important factor to consider when assessing dietary strategies to enhance nutrient bioavailability.

3.2. Nutrient Interactions

Nutrient interactions refer to the ways in which different nutrients within a meal influence each other's absorption, metabolism, and bioavailability. These interactions can be synergistic, where the presence of one nutrient enhances the absorption of another, or antagonistic, where one nutrient interferes with or competes for absorption (Parada and Aguilera, 2007). Understanding these interactions is essential for optimizing nutrient bioavailability and overall nutrient utilization in the body.

One well-known example of a positive interaction is the role of vitamin C in enhancing non-heme iron absorption. Non-heme iron, found primarily in plant-based foods, is less readily absorbed compared to heme iron from animal sources. However, when vitamin C (ascorbic acid) is present in the meal, it converts iron from its ferric ($Fe3+$) form to the more absorbable ferrous ($Fe2+$) form, thus significantly improving iron uptake in the intestines. This interaction is particularly important in vegetarian diets where non-heme iron is the predominant source of iron (Nair and Iyengar, 2009).

On the other hand, some interactions inhibit nutrient absorption. For instance, calcium and iron, when consumed together in significant amounts, can interfere with each other's absorption. Calcium competes with iron for absorption sites in the gut, reducing the bioavailability of both minerals when taken simultaneously in large doses. Similarly, zinc and copper share common transport pathways, and excessive intake of zinc can impair copper absorption, leading to deficiencies over time (Wawrzyniak and Suliburska, 2021.).

Phytates, found in whole grains and legumes, are another example of a negative interaction. Phytates bind to minerals like iron, zinc, and magnesium, forming insoluble complexes that the body cannot absorb (Zhang *et al.,* 2022). This reduces the bioavailability of these minerals, particularly in populations that rely heavily on cereal-based diets. However, some food preparation methods, such as soaking, fermenting, and sprouting, can reduce phytate levels and improve mineral absorption.

The type of fat consumed in the diet also affects the bioavailability of fat-soluble vitamins. For example, the absorption of vitamin D is enhanced when consumed with dietary fats, particularly monounsaturated and polyunsaturated fats. In contrast, a low-fat meal may significantly reduce the bioavailability of fat-soluble vitamins, which rely on fats for their intestinal absorption through micelle formation.

Nutrient interactions also occur at the metabolic level, where nutrients influence each other's utilization and storage. For example, vitamin E acts as an antioxidant that protects vitamin A from oxidative damage, thereby preserving its bioavailability. Additionally, protein intake can affect calcium metabolism, with higher protein intake increasing calcium excretion but also enhancing calcium absorption in the intestines through the action of amino acids.

These interactions demonstrate that the bioavailability of nutrients is not solely determined by the amount consumed, but by the complex interplay between different nutrients within the diet. Careful consideration of these interactions is crucial for designing nutrient-rich diets that maximize the absorption and utilization of essential nutrients.

3.3. Form of the Nutrient

The chemical form of a nutrient significantly influences its bioavailability, affecting how efficiently the nutrient is absorbed, transported, and utilized in the body. Nutrients exist in different forms—such as organic, inorganic, or bound to other compounds—and their bioavailability varies depending on their structure and solubility. The physical and chemical form of a nutrient can determine how easily it is absorbed through the intestinal walls and subsequently made available for bodily functions (Gibson *et al.,* 2006).

One of the most well-known examples is iron, which exists in two forms in the diet: heme iron and non-heme iron. Heme iron, found in animal-based foods such as meat and fish, is more bioavailable, with absorption rates ranging from 15% to 35%. Non-heme iron, present in plant-based foods, is much less bioavailable, with absorption rates typically between 2% and 20%, depending on the presence of other dietary factors. This difference in bioavailability is due to the chemical structure of heme iron, which is absorbed intact into the intestinal cells, while non-heme iron is more susceptible to inhibitors like phytates and polyphenols (Dasa and Abera, 2018).

The form of vitamins also affects their bioavailability. For example, vitamin B12 is naturally found bound to proteins in food, and it must be released from these proteins by stomach acid before it can be absorbed in the ileum. In individuals with low stomach acid production (such as the elderly), vitamin B12 may not be efficiently released from the food matrix, leading to reduced bioavailability. Similarly, synthetic forms of vitamins, such as folic acid (the synthetic form of folate), are often more bioavailable than their naturally occurring counterparts, due to their simpler chemical structures that allow for easier absorption. Folic acid is absorbed more efficiently in the intestine compared to naturally occurring folate, which requires further digestion before absorption.

The form of minerals also plays a crucial role in determining bioavailability. For instance, calcium is more bioavailable in the form of calcium citrate than in the form of calcium carbonate, particularly for individuals with low stomach acid. Calcium citrate does not require the presence of stomach acid for absorption, making it more suitable for individuals with reduced gastric acidity. In contrast, calcium carbonate requires acid for absorption and may have lower bioavailability in people with gastrointestinal conditions such as acid reflux or in older adults

(Heaney, 2001.). Similarly, zinc is more bioavailable in its organic forms (e.g., zinc gluconate) than in its inorganic forms (e.g., zinc oxide), with the organic forms being more soluble and therefore more easily absorbed.

The crystalline or bound form of certain nutrients also influences bioavailability. For example, beta-carotene, the plant-based precursor of vitamin A, is more bioavailable when present in an emulsified or micellized form than in a crystalline form. The physical state of beta-carotene, as well as the presence of dietary fat, greatly enhances its absorption by promoting micelle formation, which is necessary for fat-soluble nutrient absorption.

In addition, some nutrients require chemical modification before they become bioavailable. For instance, polyphenols in foods such as tea, fruits, and vegetables exist as glycosides (bound to sugar molecules) and must undergo hydrolysis by intestinal enzymes or gut microbiota to release the bioactive aglycones, which are the forms that the body can absorb and use. This process of converting nutrients to their bioavailable forms is influenced by individual digestive health and microbiota composition.

The bioavailability of a nutrient is, therefore, highly dependent on its chemical form and the conditions required for its absorption and utilization. Understanding the form in which nutrients are present in food or supplements is crucial for determining their potential health benefits and their effective absorption in the body.

3.4. Digestive Health

Digestive health plays a critical role in determining the bioavailability of nutrients, as the entire process of nutrient absorption begins in the gastrointestinal (GI) tract. The efficiency of digestion and absorption depends on several factors, including the integrity of the digestive organs, the presence of digestive enzymes, gut motility, and the balance of gut microbiota (Philipp and Hahn, 2017). Any dysfunction in the digestive system can significantly impair the breakdown of food and, consequently, the bioavailability of essential nutrients.

The digestive process begins in the stomach, where gastric acid and enzymes such as pepsin start breaking down proteins and releasing bound nutrients from the food matrix (Tharifkhan *et al.,* 2021). Adequate stomach acid production is crucial for the proper absorption of several nutrients, including vitamin B12, iron, and calcium. In individuals with hypochlorhydria (low stomach acid) or those who take antacid medications, nutrient absorption can be compromised. For instance, vitamin B12 requires acidic conditions to separate it from food proteins, and reduced stomach acid impairs this process, leading to decreased bioavailability of the vitamin. Similarly, the solubility of minerals like calcium and iron is influenced by stomach acidity, and reduced acid production can lead to poor mineral absorption.

The small intestine is the primary site of nutrient absorption, where digestive enzymes produced by the pancreas and bile acids from the liver facilitate the breakdown and absorption of macronutrients and micronutrients. Any condition that affects pancreatic enzyme secretion, such as chronic pancreatitis or cystic fibrosis, can severely impact the digestion of fats, proteins, and carbohydrates, leading to malabsorption of fat-soluble vitamins (A, D, E, K) and essential fatty acids. The presence of bile is also crucial for the emulsification of fats, enabling the formation of micelles that are necessary for the absorption of fat-soluble nutrients. In cases of bile duct obstruction or liver disease, this process is impaired, reducing the bioavailability of fat-soluble vitamins (Borel, 2003).

The integrity of the intestinal lining is another key factor in nutrient absorption. The small intestine is lined with villi and microvilli, which increase the surface area for absorption. Damage to these structures, as seen in conditions like celiac disease, inflammatory bowel disease (IBD), or severe infections, can reduce the absorptive capacity of the intestine and lead to malabsorption syndromes. In celiac disease, for example, gluten-induced damage to the intestinal villi reduces the absorption of several nutrients, including iron, calcium, folate, and fat-soluble vitamins, leading to deficiencies if left untreated.

Gut motility also affects bioavailability. Rapid transit of food through the GI tract, as seen in conditions like diarrhea or irritable bowel syndrome (IBS), can decrease the time available for nutrient absorption, particularly in the case of water and electrolytes (Jarmakiewicz-Czaja *et al.,* 2020). Conversely, slow gut motility can increase the risk of nutrient degradation by gut bacteria, which can alter the availability of certain nutrients, such as short-chain fatty acids.

The gut microbiota, the diverse community of microorganisms in the intestine, plays a fundamental role in modulating nutrient bioavailability. The microbiota assists in the fermentation of dietary fibers and the synthesis of certain vitamins, such as vitamin K and some B vitamins. In addition, gut bacteria can convert certain dietary compounds into bioactive forms, such as polyphenols and flavonoids, which the human body would otherwise be unable to absorb (Bielik and Kolisek, 2021). Dysbiosis, or an imbalance in gut bacteria, can impair these processes, leading to reduced bioavailability of important nutrients. For example, gut microbial imbalances have been linked to poor absorption of magnesium and reduced production of bioactive short-chain fatty acids from dietary fibers (Weiss and Hennet, 2017).

In summary, digestive health is a crucial determinant of nutrient bioavailability. The integrity of the digestive organs, the efficiency of enzyme production, the presence of healthy gut microbiota, and the motility of the GI tract all contribute to how well nutrients are absorbed and utilized in the body.

3.4.1. The role of gut microbes in bioavailability

Gut microbiota, the diverse community of microorganisms residing in the human gastrointestinal tract, play a significant role in determining the bioavailability of nutrients and bioactive compounds. Bioavailability refers to the extent and rate at which the active ingredient or active moiety is absorbed and becomes available at the site of action. Several mechanisms by which gut microbes influence bioavailability include the following:

1. **Metabolism of nutrients:** Gut microbes possess a wide range of enzymes that can metabolize various dietary components. For example, they can ferment dietary fibers into short-chain fatty acids (SCFAs), which not only serve as an energy source for colon cells but also enhance the absorption of minerals such as calcium and magnesium by modifying gut pH and improving the intestinal environment.
2. **Modification of dietary compounds:** Many nutrients and bioactive compounds are consumed in their conjugated forms, which may have limited bioactivity. Gut microbes can enzymatically modify these compounds, converting them into more bioavailable forms. For example, polyphenols and flavonoids often require microbial action to release their active forms, increasing

their potential health benefits (Bohn, 2014).

3. **Enhancing nutrient absorption:** The presence of a healthy gut microbiome contributes to the integrity of the intestinal barrier, which is crucial for nutrient absorption (Barone *et al.,* 2022). Certain beneficial bacteria help maintain the structural integrity of the intestinal lining, reducing intestinal permeability and promoting efficient nutrient uptake. In contrast, dysbiosis (an imbalance of gut microbiota) can compromise the barrier, leading to impaired nutrient absorption.
4. **Interplay with host metabolism:** Gut microbes can influence host metabolic pathways related to nutrient absorption and utilization. For instance, they produce metabolites that can modulate host signaling pathways, impacting how nutrients are processed and absorbed in the body (De Filippis *et al.,* 2020). This interaction is particularly important for fat-soluble vitamins, which require bile acids for proper absorption—an aspect influenced by gut microbiota.
5. **Influence of dietary patterns:** The composition and diversity of gut microbiota are closely linked to dietary habits. Diets rich in fiber, fruits, vegetables, and fermented foods promote the growth of beneficial bacteria, enhancing their ability to improve nutrient bioavailability. Conversely, a diet high in refined sugars and low in fiber can lead to a less diverse microbiome, negatively affecting the bioavailability of nutrients.
6. **Protection against antinutrients:** Certain dietary components, known as antinutrients (e.g., phytates, oxalates, and tannins), can bind essential minerals and reduce their bioavailability. However, gut microbiota can produce enzymes that degrade these antinutrients, thereby mitigating their negative impact on nutrient absorption.

A study provides compelling evidence that gut microbiota significantly influences the metabolism and bioavailability of curcumin. The depletion of gut microbiota through antibiotic treatment resulted in reduced curcumin metabolization and degradation, highlighting the microbiome's role in enhancing the effectiveness of curcumin. The findings suggest that maintaining a healthy gut microbiota could optimize the therapeutic benefits of curcumin supplementation. Future research may focus on dietary strategies or probiotics that promote gut health to improve curcumin metabolism and maximize its health benefits for individuals (Luo *et al.,* 2024).

3.6. Presence of antinutritional Factors

Antinutritional factors (ANFs) are naturally occurring compounds in various foods that can interfere with nutrient absorption and utilization in the body. While many foods containing ANFs also offer essential nutrients and health benefits, the presence of these compounds can significantly impact the bioavailability of critical vitamins and minerals (Thakur *et al.,* 2019). Understanding the role of antinutritional factors is essential for optimizing dietary intake and ensuring adequate nutrient absorption.

Phytates, commonly found in whole grains, legumes, nuts, and seeds, are among the most studied antinutritional factors. Phytates can bind to essential minerals such as iron, zinc, and calcium, forming insoluble complexes that reduce their bioavailability. This binding occurs primarily in the intestinal lumen, leading to decreased absorption and potential deficiencies, particularly in populations relying heavily on plant-based diets. However, phytates can also exhibit beneficial properties, such as antioxidant activity and potential anticancer effects, highlighting the need for balanced consumption.

Oxalates are another group of antinutritional factors found in foods such as spinach, rhubarb, and certain nuts. They can bind to calcium and form calcium oxalate, which is insoluble and not readily absorbed by the body. This interaction can lead to reduced calcium bioavailability and, in some cases, the formation of kidney stones in susceptible individuals. Cooking methods, such as boiling, can help reduce oxalate content, enhancing the bioavailability of calcium in these foods.

Tannins, present in various fruits, vegetables, teas, and legumes, are polyphenolic compounds that can inhibit the absorption of iron and protein. They can form complexes with dietary proteins and minerals, reducing their bioavailability. While moderate consumption of tannin-containing foods may not pose significant health risks, excessive intake can lead to nutritional deficiencies, particularly in populations with limited dietary diversity.

Lectins are carbohydrate-binding proteins found in many legumes and some grains. While they can offer health benefits, such as antioxidant and anti-inflammatory properties, lectins can also inhibit nutrient absorption by binding to the gut lining and interfering with digestive enzyme function. Soaking, cooking, or fermenting foods can reduce lectin levels and improve nutrient bioavailability, making these foods safer for consumption.

Protease inhibitors are found in various legumes and grains and can hinder protein digestion by inhibiting the action of digestive enzymes like trypsin and chymotrypsin. This inhibition can lead to reduced protein absorption and utilization. However, cooking methods, such as boiling or steaming, can deactivate protease inhibitors, thereby enhancing protein bioavailability.

Saponins, present in legumes and some whole grains, have both beneficial and detrimental effects on nutrient bioavailability. They can reduce cholesterol absorption and possess antimicrobial properties; however, saponins may also impair the absorption of minerals like calcium and iron. The effects of saponins on nutrient bioavailability are complex and may depend on the type and amount of saponin consumed.

Goitrogens are compounds that can interfere with iodine uptake in the thyroid gland, potentially leading to thyroid dysfunction, especially in individuals with iodine deficiency. Foods containing goitrogens include cruciferous vegetables like broccoli, cauliflower, and kale. Cooking methods, such as steaming, can reduce goitrogen content and mitigate their effects on iodine bioavailability.

Glucosinolates are sulfur-containing compounds found in cruciferous vegetables. They can influence the bioavailability of iodine and other nutrients, as their breakdown products can inhibit thyroid function. However, glucosinolates also have potential health benefits, such as anti-cancer properties, and the balance between their beneficial and detrimental effects depends on individual dietary habits and overall nutrient intake.

The presence of these antinutritional factors underscores the importance of food preparation techniques and dietary diversity. Methods such as soaking, sprouting, fermenting, and cooking can significantly reduce the levels of antinutritional factors and improve the bioavailability of nutrients in various foods. While ANFs can pose challenges to nutrient absorption, they can also contribute to health benefits when consumed in appropriate amounts within a balanced diet. A nuanced understanding of these compounds and their interactions with nutrients can aid in formulating dietary strategies that enhance overall nutrient bioavailability and support optimal health.

METHODS :

Methods for Assessing Bioavailability

1. Direct Assessment Methods

a) Blood Tests

Blood tests are among the most common direct methods to evaluate nutrient bioavailability. By measuring the concentration of nutrients, metabolites, or biomarkers in the blood, researchers can assess how effectively a nutrient is absorbed and utilized in the body. Postprandial plasma concentrations of nutrients or their metabolites provide immediate feedback on nutrient uptake. Additionally, serum levels of vitamins and minerals (e.g., vitamin D, calcium) are used to monitor absorption rates, reflecting the efficiency of dietary intake.

b) Urine Tests

Urine tests are another widely used method to assess bioavailability, particularly for water-soluble vitamins and minerals. This method measures the excretion levels of nutrients or their metabolites after consumption. For example, the urinary excretion of vitamin C, B-vitamins, or iodine can be used to gauge how well the body has absorbed and processed these nutrients.

c) Isotope Tracing

Isotope tracing involves using stable or radioactive isotopes to track the absorption, distribution, and metabolism of nutrients within the body. In this method, isotopically labeled nutrients are ingested, and their movement through the body is monitored. Isotope tracing is especially valuable for assessing the bioavailability of minerals like iron, calcium, and zinc, as well as for tracking the metabolism of macronutrients.

at various stages.

2. Indirect Assessment Methods

a) Nutrient Balance Studies

Nutrient balance studies are an indirect method used to estimate bioavailability by comparing nutrient intake with its excretion through urine, feces, and sometimes sweat. The principle behind this approach is that the difference between intake and excretion reflects the amount of the nutrient that is absorbed and utilized by the body.

Method:

Participants are placed on a controlled diet with known amounts of a specific nutrient. Over a set period, their nutrient intake and excretion are carefully monitored and recorded. For example, in a calcium balance study, calcium intake is measured through dietary records, and excretion is tracked via fecal and urinary outputs.

b) Functional Testing

Functional tests assess bioavailability by evaluating the impact of nutrient intake on specific biological functions or clinical outcomes. These tests do not measure the nutrient itself but rather its physiological effects. For instance, the functional bioavailability of vitamin A can be assessed by measuring changes in visual function (such as dark adaptation), while the bioavailability of iron can be indirectly gauged by monitoring changes in hemoglobin levels or anaemia status.

Types of Functional Testing:

1. Biomarker Response: Functional bioavailability can be assessed by tracking biomarkers that respond to the intake of nutrients. For example, changes in serum ferritin levels can indicate the bioavailability of iron.

2. Clinical Outcomes: Testing the bioavailability of nutrients by examining the impact on health outcomes, such as bone density in response to calcium intake or cognitive function as a result of omega-3 fatty acid supplementation.

3. *In vitro* and Experimental Models

In vitro and experimental models are commonly used in the initial stages of bioavailability research to simulate the human digestive process or physiological environment. These methods offer valuable insights while minimizing ethical concerns and resource constraints associated with human trials.

a) Cell Culture Models

Cell culture models involve the use of isolated cells, typically from the human intestinal lining (e.g., Caco-2 cells), to simulate the absorption of nutrients. Caco-2 cells are derived from human colorectal carcinoma cells and differentiate to resemble enterocytes, the cells responsible for nutrient absorption in the small intestine. This model helps assess how nutrients pass through the intestinal barrier and enter circulation. Nutrients or bioactive compounds are introduced into the apical side of the cultured cells, and the basolateral side is monitored for the appearance of these compounds, indicating their transport across the intestinal barrier.

b) Animal Studies

Animal models are extensively used to study nutrient bioavailability, as they allow for the assessment of whole-body absorption, distribution, metabolism, and excretion of nutrients. Commonly used animals in bioavailability research include rats, mice, and pigs, as their digestive systems can model human physiology.

Animals are fed a controlled diet containing the nutrient of interest, and samples are collected from blood, urine, feces, and tissues to assess absorption and metabolism. For example, rodent models are often used in studies of mineral absorption (e.g., calcium, iron), while pigs serve as a model for fat and carbohydrate digestion due to their physiological similarities to humans.

c) Simulated Digestion Models

Simulated digestion models, also known as *in vitro* digestion systems, mimic the human digestive process to estimate nutrient bioavailability. These models replicate the conditions of the mouth, stomach, and intestines using enzymes, acids, and mechanical mixing to simulate food breakdown and nutrient release. One widely used model is the TIM-1 system (TNO Gastro-Intestinal Model), which mimics the physiological conditions of the gastrointestinal tract, including pH, enzyme activity, and peristaltic movements.

***In vitro* Simulation of Gastrointestinal Digestion Models**

In vitro GI digestion models are designed to mimic the human digestive system and its processes, from ingestion to nutrient absorption. These models replicate the biochemical and mechanical conditions found in the different compartments of the digestive tract—mouth, stomach, small intestine, and sometimes large intestine. The TNO Gastro-Intestinal Model (TIM-1), the SHIME model, and other static or dynamic systems are commonly used to estimate the bioavailability of nutrients and the digestion of food matrices. These models are crucial for studying the release of nutrients, their subsequent absorption, and interactions with other dietary components (Hur *et al.,* 2011).

1. Oral Phase (Mouth)

The oral phase simulates the initial breakdown of food as it undergoes mastication (chewing) and mixes with saliva, which contains the enzyme salivary amylase. This enzyme begins the digestion of carbohydrates, breaking down starches into simpler sugars.

Key Components:

- Mechanical Mixing: *In vitro* models incorporate mechanical forces or homogenizers to simulate the action of chewing.
- Saliva Composition: Artificial saliva is prepared with the necessary enzymes (e.g., amylase), ions (chloride, sodium, potassium), and mucins to replicate the environment in the mouth.
- pH Control: The pH is maintained around 6.8–7.2, simulating the slightly alkaline conditions of the mouth.

Processes Simulated:

- Breakdown of carbohydrates by amylase into maltose and dextrins.
- Limited mechanical disintegration of food particles.

2. Gastric Phase (Stomach)

Once food enters the stomach, it is mixed with gastric juices containing pepsin (an enzyme for protein digestion) and hydrochloric acid (HCl). The pH in the stomach is highly acidic (around 1.5–3), which helps denature proteins and activate digestive enzymes. This phase is essential for breaking down proteins into smaller peptides and ensuring the chyme (partially digested food) is liquefied for subsequent absorption in the small intestine.

Key Components:

- Acidic pH: *In vitro* models simulate the acidic environment of the stomach by adding HCl to lower the pH to 1.5–3.0.
- Enzyme Addition: Pepsin is included to break down proteins, and gastric lipase may be used for the digestion of lipids.
- Mechanical Agitation: Models often incorporate stirring or shaking to mimic the mechanical churning of the stomach, helping mix the food with digestive enzymes and acids.

Processes Simulated:

- Denaturation and partial digestion of proteins by pepsin.
- Emulsification of fats in preparation for later digestion.
- Formation of chyme as food is liquefied for passage into the small intestine.

3. Small Intestinal Phase (Duodenum, Jejunum, Ileum)

This phase is the most critical for nutrient absorption. *In vitro* models simulate the action of pancreatic enzymes (lipase, protease, amylase) and bile salts (for fat emulsification). The environment of the small intestine is slightly alkaline (pH 7–8), which is required for optimal enzyme activity. The small intestinal phase is where the majority of nutrient absorption occurs, including the breakdown of fats into fatty acids, proteins into amino acids, and carbohydrates into monosaccharides.

Key Components:

- Pancreatic Enzymes: Pancreatin, a mixture of pancreatic enzymes, is added to break down proteins (proteases), fats (lipase), and carbohydrates (amylase). These enzymes are critical for digesting macronutrients into their absorbable forms.
- Bile Salts: Bile salts (simulated bile) are introduced to emulsify fats, increasing their surface area for enzyme action.
- pH Adjustment: Sodium bicarbonate or other bases are added to neutralize the acidic chyme coming from the stomach and to maintain the pH around 7–8, which is essential for enzyme activity.

Processes Simulated:
- Digestion of proteins into amino acids and small peptides.
- Conversion of fats into fatty acids and monoglycerides.
- Breakdown of carbohydrates into monosaccharides like glucose and fructose.
- Preparation of nutrients for absorption across the intestinal epithelium.

Simulating Absorption in the Small Intestine:
Some advanced models include Caco-2 cell monolayers or other absorptive barriers to simulate the absorption of nutrients across the intestinal lining. This step replicates the passage of digested nutrients from the intestinal lumen into the bloodstream, giving insight into how well a nutrient is absorbed post-digestion.

4. Colonic Phase (Large Intestine)

Although not always included in all *in vitro* models, some advanced systems like the SHIME model incorporate a colonic phase to study the interaction between undigested food components (such as dietary fiber) and gut microbiota. In this phase, microbial fermentation of non-digestible carbohydrates, resistant starch, and fiber occurs, producing short-chain fatty acids (SCFAs) like acetate, propionate, and butyrate, which have beneficial effects on gut health.

Key Components:
- Microbiota Simulation: Some models introduce human gut microbiota into the system to mimic the fermentation process in the colon.
- Anaerobic Conditions: The colonic phase is maintained in anaerobic conditions, as the colon is largely oxygen-free.
- Fermentation Monitoring: The production of SCFAs and gases (such as methane and carbon dioxide) is monitored to assess the extent of fermentation.

Processes Simulated:
- Fermentation of non-digestible carbohydrates by gut bacteria.
- Production of SCFAs, which are absorbed by colonocytes and contribute to overall health.
- Gas production as a byproduct of microbial metabolism.

Types of *In vitro* Digestion Models

1. Static Models: These simulate digestion in separate, isolated phases (oral, gastric, small intestine) with predetermined time points and conditions. Static models are useful for simplicity and ease of execution but lack the dynamic nature of actual digestion. The INFOGEST model is a widely used static model for standardized *in vitro* digestion.

2. Dynamic Models: Dynamic systems like the TIM-1 system or SHIME mimic real-time digestion by continuously adjusting pH, enzyme concentrations, and peristaltic movements throughout the

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simulated digestive process. These models are more sophisticated, providing insights into the dynamic changes in nutrient digestion and absorption.

RESULTS AND DISCUSSION :

7. Impact of processing on nutrient bioavailability

Food processing has a complex impact on nutrient bioavailability, with both beneficial and harmful effects. On the positive side, certain processes like cooking, fermentation, and soaking can enhance nutrient absorption by breaking down antinutritional compounds such as phytates and oxalates, which otherwise inhibit the uptake of minerals like iron and calcium. For instance, cooking increases the bioavailability of lycopene in tomatoes and beta-carotene in carrots. Fermentation improves the digestibility of proteins and enhances the availability of B vitamins, while sprouting can increase the levels of vitamins C and E. Additionally, mechanical processing such as grinding and milling can make nutrients more accessible by breaking down cell walls, making it easier for the body to absorb them.

However, food processing also has several drawbacks when it comes to nutrient bioavailability. High-temperature treatments like frying or excessive boiling can destroy heat-sensitive nutrients, including vitamins C, B-complex vitamins, and certain polyphenols. Refining processes, especially in grains, remove nutrient-dense parts like bran and germ, leading to significant losses in fiber, essential fatty acids, and micronutrients such as magnesium, zinc, and B vitamins. Even processes like pasteurization and canning, while useful for food preservation, can result in the leaching of water-soluble vitamins and minerals into cooking liquids. In addition, the addition of preservatives, excessive salt, and sugar during processing can negatively affect overall nutrient quality and health outcomes. Thus, while some processing techniques can enhance nutrient availability, others may lead to substantial nutrient losses, highlighting the need for balanced and minimally processed diets.

8. Dietary strategies for enhancing nutrient bioavailability

The bioavailability of nutrients refers to the proportion of ingested nutrients that are absorbed and utilized by the body. Food processing techniques, such as fortification, enrichment, and various preparation methods, play a crucial role in influencing nutrient bioavailability. While some processing methods can enhance the accessibility of nutrients by breaking down anti-nutritional factors, others can result in nutrient loss or reduced absorption. By carefully selecting appropriate food processing techniques, we can optimize nutrient retention and absorption, contributing to better health outcomes. This section explores how different processing methods impact the bioavailability of essential nutrients.

a. Fortification and enrichment

Fortification and enrichment are key strategies used in food processing to enhance the nutrient content of foods, which in turn improves nutrient bioavailability.

- **Fortification** refers to the addition of nutrients that are not originally present in the food in significant amounts. This method is commonly used to address nutrient deficiencies in populations. For instance, fortifying salt with iodine helps prevent iodine deficiency disorders. Similarly, cereals fortified with iron, folic acid, and vitamin D have been shown to improve the absorption and utilization of these nutrients by the body.
- **Enrichment**, on the other hand, involves adding back nutrients that are lost

during processing. For example, during the milling of grains, vitamins and minerals in the bran and germ are often removed. By enriching the flour with B-vitamins (such as thiamine, riboflavin, and niacin) and iron, the lost nutrients are restored, making the final product more nutritionally complete.

Both fortification and enrichment significantly enhance the bioavailability of nutrients in processed foods, ensuring better dietary intake of essential vitamins and minerals. However, the effectiveness of these strategies depends on the form of the nutrient added and the processing methods used.

b. Utilizing different food preparation techniques

Various food preparation techniques can significantly influence nutrient bioavailability by altering the structure of food, reducing anti-nutritional factors, and promoting better absorption. These methods range from traditional processes to modern culinary practices, each contributing uniquely to nutrient availability.

- **Soaking and fermentation**: Soaking grains, seeds, and legumes reduces phytates, which inhibit the absorption of minerals like iron and zinc. Fermentation breaks down anti-nutrients further while promoting the growth of beneficial bacteria, which enhances the bioavailability of minerals such as calcium and magnesium, as seen in yogurt or fermented vegetables.
- **Germination**: Sprouting grains and legumes enhances the availability of vitamins (e.g., vitamin C and B-vitamins) and minerals by reducing phytates and tannins. It also boosts nutrient levels, making sprouted foods more bioavailable.
- **Sautéing and blanching**: These quick cooking methods are particularly beneficial for preserving the bioavailability of heat-sensitive vitamins such as vitamin C, while also improving the release of fat-soluble vitamins like beta-carotene. Blanching vegetables in boiling water for a short time, followed by rapid cooling, also helps in retaining nutrients while enhancing texture and color.
- **Boiling**: This method increases the bioavailability of certain nutrients, such as lycopene in tomatoes and beta-carotene in carrots, by softening cell walls and breaking down fibrous material. However, over-boiling can lead to the leaching of water-soluble vitamins, such as B-vitamins and vitamin C, into the cooking water, which is why minimizing cooking time is recommended.
- **Grinding**: By physically breaking down food into smaller particles, grinding improves the bioavailability of nutrients by making them more accessible for digestion. For example, grinding whole grains helps release bound minerals like iron and zinc, while ground flaxseeds have higher omega-3 absorption compared to whole flaxseeds.
- **Pressure cooking**: This method shortens cooking times while retaining most nutrients, especially water-soluble vitamins like folate and vitamin C. Pressure cooking also breaks down tough fibers and reduces anti-nutritional factors such as phytates in grains and legumes, enhancing the bioavailability of minerals like iron and zinc.
- **Marinating**: Marinating foods in acidic mediums (like vinegar or lemon juice)

before cooking can help break down fibers and reduce anti-nutritional factors. For example, marinating meat with an acidic ingredient increases the tenderness and also enhances the absorption of minerals like iron.

By utilizing these diverse food preparation techniques, we can maximize the retention and absorption of nutrients, leading to improved nutrient bioavailability and better health outcomes.

c. Combining foods to enhance absorption

Combining specific foods can significantly improve the bioavailability of essential nutrients by optimizing nutrient synergies. These food pairings help in maximizing the absorption of vitamins, minerals, and other beneficial compounds.

- **Vitamin C and iron**: Non-heme iron, found in plant-based foods such as spinach, legumes, and whole grains, is less readily absorbed by the body. However, consuming these foods with vitamin C-rich items, like citrus fruits, bell peppers, or tomatoes, enhances iron absorption by converting it into its more bioavailable form.
- **Lycopene and fat**: Lycopene, a powerful antioxidant found in tomatoes, is better absorbed when combined with dietary fat. For example, pairing cooked tomatoes with olive oil enhances lycopene's bioavailability, allowing the body to absorb more of this nutrient. This is particularly beneficial for heart health and cancer prevention.
- **Carrot and avocado**: Carrots are rich in beta-carotene, a precursor to vitamin A, but the absorption of this fat-soluble compound is significantly increased when paired with healthy fats. Adding avocado, nuts, or olive oil to carrot-based dishes improves the bioavailability of beta-carotene, promoting better vision and immune function.
- **Curcumin and black pepper**: Curcumin, the active compound in turmeric, has anti-inflammatory and antioxidant properties, but its absorption is limited. Black pepper contains piperine, which enhances curcumin's bioavailability by inhibiting its breakdown in the liver, making the combination of turmeric and black pepper a potent tool in reducing inflammation and oxidative stress.
- **Nuts and chocolate**: Nuts are high in healthy fats, which can aid in the absorption of fat-soluble antioxidants present in dark chocolate. Combining nuts with dark chocolate not only creates a delicious snack but also improves the bioavailability of beneficial compounds like flavonoids, promoting cardiovascular health.
- **Cereals and pulses**: The combination of cereals (like rice or wheat) and pulses (like lentils or beans) creates a complete protein by providing all essential amino acids. This pairing not only enhances the protein quality of the meal but also improves the overall bioavailability of minerals like zinc and iron when consumed together.
- **Eggs and green leafy vegetables (GLV)**: Eggs contain fat, which helps in the absorption of fat-soluble vitamins like vitamin K, found in green leafy vegetables (e.g., spinach, kale). Consuming eggs with these vegetables boosts the bioavailability of vitamins A and K, supporting better eye and bone health.

- **Healthy fats and fat-soluble vitamins**: Fat-soluble vitamins (A, D, E, K) require dietary fats for effective absorption. Consuming sources of these vitamins, such as leafy greens (rich in vitamin K) or carrots (rich in beta-carotene), alongside foods rich in healthy fats, like avocados or olive oil, enhances their bioavailability and overall effectiveness.
- **Calcium and vitamin D**: Calcium absorption is improved when consumed with vitamin D. Dairy products fortified with vitamin D or pairing calcium-rich foods (e.g., spinach, almonds) with vitamin D sources (like salmon or eggs) enhances calcium uptake, which is critical for bone health.

By incorporating these food combinations into daily meals, nutrient absorption is optimized, contributing to better overall health and nutrition outcomes.

d. Reducing anti-nutritional factors

Anti-nutritional factors, such as phytates, tannins, and oxalates, can interfere with the absorption of essential nutrients like iron, calcium, and zinc. However, various food processing techniques can effectively reduce these compounds, improving nutrient bioavailability (Samtiya *et al.,* 2020).

- **Soaking**: Soaking grains, legumes, and seeds in water for several hours before cooking is a simple but effective method to reduce phytates and tannins, both of which inhibit the absorption of minerals like iron and calcium. Soaking softens the food, breaking down the anti-nutritional factors, thus allowing for better mineral uptake.
- **Sprouting**: The process of germination or sprouting activates enzymes in grains, legumes, and seeds that further break down phytates and other anti-nutritional factors. Sprouting also increases the levels of certain vitamins, such as vitamin C and B-vitamins, while improving the bioavailability of minerals like zinc and iron.
- **Fermentation**: Fermentation is highly effective in reducing anti-nutritional factors, as the beneficial bacteria and yeast involved in the process break down phytates, oxalates, and tannins. For example, fermented products like sourdough bread or fermented legumes have improved iron and zinc absorption due to the reduction of these inhibitors. Fermented foods like yogurt and tempeh also have enhanced nutrient bioavailability.
- **Dehulling**: Dehulling, or removing the outer layer of grains and legumes, reduces the content of anti-nutritional factors concentrated in the hull. For example, removing the husk from beans or pulses before cooking decreases the amount of phytates and tannins, improving the availability of proteins and minerals.
- **Boiling**: Boiling is another effective method to reduce anti-nutritional factors such as oxalates and tannins. For instance, boiling spinach helps reduce oxalates, which inhibit calcium absorption. Similarly, boiling beans and legumes can reduce lectins and phytates, making minerals more bioavailable.
- **Malting**: Malting involves soaking grains, allowing them to germinate, and then drying them. This process not only reduces phytates but also increases the activity of enzymes that enhance the bioavailability of minerals like iron and zinc. Malting grains, such as barley or sorghum, leads to higher nutrient

absorption, particularly in products like malted flour or malted beverages.

By utilizing these techniques, the levels of anti-nutritional factors can be significantly lowered, ensuring better absorption of essential nutrients, particularly minerals, and enhancing overall nutrient bioavailability in the diet.

8. Emerging technologies to enhance bioavailability

Advances in food and nutrition science are driving the development of new technologies aimed at improving nutrient bioavailability. These emerging approaches offer innovative solutions for optimizing nutrient absorption, targeting specific dietary needs, and addressing individual variability.

- **Nanoencapsulation**: Nanoencapsulation is a cutting-edge technology that involves packaging nutrients within tiny particles (nanoparticles) to enhance their stability, protection, and delivery in the body. By protecting sensitive nutrients like vitamins, minerals, and antioxidants from degradation during processing, storage, and digestion, nanoencapsulation ensures that more nutrients reach their target sites for absorption (Jafari and McClements, 2017). For example, nanoencapsulated curcumin, which has low bioavailability in its natural form, can significantly increase its absorption and efficacy in reducing inflammation.
- **Personalized nutrition**: Personalized nutrition tailors dietary recommendations based on an individual's genetic makeup, lifestyle, and health status, ensuring that nutrient intake aligns with the body's unique requirements. Advances in nutrigenomics allow for the identification of genetic variants that impact nutrient metabolism, guiding personalized diets that enhance the bioavailability of specific nutrients. For instance, individuals with a variant of the FTO gene linked to obesity may benefit from personalized dietary strategies that optimize fat metabolism and nutrient absorption, promoting better health outcomes.
- **Smart nutrient delivery systems**: Smart nutrient delivery systems are designed to release nutrients in a controlled manner, targeting specific areas of the digestive tract where absorption is most efficient. These systems utilize advanced materials like biopolymer-based carriers that respond to environmental cues (e.g., pH or enzymes) to release nutrients at the optimal time and location. This technology is particularly useful for nutrients that are sensitive to stomach acid or need to be absorbed in the intestines, such as probiotics or omega-3 fatty acids. By improving the timing and precision of nutrient release, smart delivery systems ensure maximum bioavailability.
- **Microbiome-targeted approach**: The gut microbiome plays a crucial role in nutrient absorption, and emerging research focuses on leveraging the microbiome to improve bioavailability (Hadadi *et al.,* 2021). This approach involves tailoring diets or supplements to nourish beneficial gut bacteria that aid in breaking down complex compounds and synthesizing essential nutrients like vitamins and short-chain fatty acids. Probiotic and prebiotic formulations are being developed to promote a healthy gut

environment, enhancing the absorption of nutrients like calcium, magnesium, and certain B-vitamins. Additionally, personalized microbiome-targeted strategies are being explored to address nutrient deficiencies and optimize individual health.

These emerging technologies hold great promise in improving nutrient bioavailability by providing more targeted, efficient, and personalized approaches to nutrition. As these innovations continue to evolve, they will play an increasingly important role in optimizing health and well-being through better nutrient absorption and utilization.

CONCLUSION :

The bioavailability of nutrients is a crucial determinant of how effectively the body can absorb and utilize essential vitamins and minerals from food. Understanding this concept is essential for developing effective dietary strategies that enhance nutrient absorption and overall health. Several factors impact nutrient bioavailability, including food processing techniques, the interactions between different food components, and dietary practices. Key methods, such as fortification and enrichment, play significant roles in improving nutrient levels in food products.

Culinary methods like sautéing, blanching, boiling, grinding, and marinating can significantly alter the nutrient profiles of foods, enhancing or reducing the availability of essential nutrients. Strategic food combinations can further improve the absorption of specific nutrients; for example, pairing foods rich in lycopene with healthy fats enhances lycopene bioavailability, while consuming cereals and pulses together promotes better protein and mineral absorption. Advanced techniques aimed at reducing anti-nutritional factors, including soaking, sprouting, fermentation, dehulling, boiling, and malting, help increase the availability of essential vitamins and minerals, making them more accessible to the body.

Moreover, innovative technologies are being developed to optimize nutrient bioavailability. Nanoencapsulation protects sensitive nutrients during processing and digestion, while personalized nutrition tailors dietary recommendations to individual genetic profiles and health needs. Smart nutrient delivery systems enhance the timing and efficiency of nutrient absorption, and microbiome-targeted approaches focus on improving gut health to facilitate better nutrient utilization. A comprehensive understanding of the factors influencing nutrient bioavailability is vital for designing effective dietary interventions and promoting public health. Ongoing research and technological advancements in this field will contribute to improved nutritional strategies and better health outcomes for individuals.

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