BIOAVAILABILITY OF MICRONUTRIENTS: THE ROLE OF CHEMICAL FORMULATION IN NUTRIENT ABSORPTION

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Abstract: Micronutrients are vital for maintaining optimal health, yet their effectiveness is often limited by their bioavailability—the extent to which they are absorbed and utilized by the body. This paper examines how chemical formulations of micronutrients influence their bioavailability. The solubility, stability, and interaction of micronutrients with other dietary components are significantly affected by their chemical form. For instance, water-soluble vitamins like Vitamin C are generally more readily absorbed than less soluble forms, while minerals such as calcium exhibit varying absorption rates based on their chemical form, with calcium citrate showing higher bioavailability compared to calcium carbonate. Stability during digestion and interaction with dietary inhibitors also play critical roles in absorption. Innovations such as nanoencapsulation and chelation have shown promise in enhancing the bioavailability of micronutrients by improving solubility and reducing interactions with absorption inhibitors. Understanding these factors is crucial for optimizing micronutrient formulations and addressing deficiencies effectively. This paper highlights the importance of chemical formulation in micronutrient bioavailability and provides insights into developing more effective nutritional supplements and fortification strategies for better health outcomes.

Keywords: Bioavailability, Micronutrients, Chemical Formulation, Nutrient Absorption, Solubility, Dietary Components, Nutritional Supplements, Nutrient Utilization**.**

I. Introduction

Micronutrients, encompassing essential vitamins and minerals, are fundamental to numerous physiological processes and overall health maintenance. Their critical roles, the effectiveness of micronutrient intake is often constrained by their bioavailability. Bioavailability refers to the proportion of a nutrient that is absorbed and utilized by the body from the ingested amount [1]. While most individuals aim to meet their micronutrient needs through diet or supplementation, the actual absorption and utilization can vary significantly based on several factors, with chemical formulation being a primary determinant. The chemical form of micronutrients, such as their solubility and stability, greatly influences their absorption in the gastrointestinal tract. Micronutrients must first dissolve in the digestive fluids before being absorbed through the intestinal lining [2]. For example, water-soluble vitamins like Vitamin C (ascorbic acid) are generally more bioavailable because they readily dissolve in water, facilitating their absorption. Conversely, fat-soluble vitamins like Vitamin A require dietary fats for optimal absorption, reflecting how chemical formulation can impact bioavailability. Minerals, too, display varying bioavailability based on their chemical forms. Calcium, for instance, is available in different formulations such as calcium carbonate and calcium citrate

[3]. Calcium citrate, with its higher solubility, is often better absorbed compared to calcium carbonate, particularly in individuals with lower gastric acid levels. Stability of micronutrients during digestion is another critical factor affecting bioavailability. Chemical formulations can enhance or hinder nutrient stability, influencing their effectiveness [4]. Certain vitamins are prone to degradation when exposed to acidic environments or oxidative conditions in the gastrointestinal tract. Advanced formulation techniques, such as encapsulation or coating, can protect these nutrients from degradation, thereby enhancing their stability and, consequently, their absorption. For instance, encapsulated forms of vitamins and minerals can shield them from adverse conditions and ensure their release in the optimal part of the digestive system for absorption [5]. Interactions between micronutrients and other dietary components also play a significant role in their bioavailability. Certain compounds found in foods, such as phytates and oxalates, can bind minerals like iron and zinc, forming insoluble complexes that the body cannot absorb. The chemical form of the micronutrient can affect its interaction with these inhibitors. Chelated forms of minerals, where the nutrient is bound to an organic molecule, often exhibit improved bioavailability compared to their inorganic counterparts [6]. Chelation can reduce the adverse effects of dietary inhibitors, enhancing the overall absorption and utilization of the micronutrient. Recent advancements in micronutrient formulation aim to optimize bioavailability through innovative technologies. Nanoencapsulation, for example, involves encapsulating nutrients in nanometer-sized carriers to improve their solubility and protect them from degradation [7]. This method enhances the absorption of nutrients by ensuring they are delivered in a more effective form to the digestive system. Similarly, the development of chelated minerals has shown promise in improving nutrient absorption by reducing the impact of dietary inhibitors and enhancing the stability of the micronutrient. Understanding the relationship between chemical formulation and micronutrient bioavailability is crucial for developing effective nutritional supplements and fortification strategies [8]. By optimizing the chemical forms of micronutrients, researchers and formulators can improve their efficacy and address deficiencies more effectively. This knowledge is not only vital for enhancing individual health outcomes but also for addressing public health challenges related to micronutrient deficiencies on a broader scale. As research continues to explore these dynamics, it will pave the way for more advanced and effective approaches to nutrition and health [9].

II. Review of Literature

Nutrient bioavailability is influenced by dietary components and individual factors, affecting how effectively nutrients are absorbed and utilized by the body. Advances in nuclear techniques have enhanced our ability to measure nutrient metabolism more accurately. In vitro models are crucial for evaluating the absorption of essential minerals like iron and zinc and assessing the availability of a broad range of nutrients [10]. Dairy products play a significant role in providing essential nutrients, though their impact on health is debated. Evidence suggests dairy supports bone health but presents mixed effects on cardiovascular outcomes, with varying implications depending on the type and amount consumed [11]. Dairy contributes to micronutrient density and dietary affordability. Research into specific nutrients, such as zinc and riboflavin, and how food processing affects nutrient absorption, further highlights the complexity of nutrient bioavailability. Overall, understanding the interactions between dietary components and individual health factors is key to developing effective nutritional guidelines [12].

Author & Year	**Area**	**Methodology**	**Key Findings**	**Challenges**	**Pros**	**Cons**	**Application**
Gibson R. (2007)	Nutrient Bioavailability	Review	Dietary and host factors influence nutrient absorption and utilization.	Variability in individual responses	Comprehensive overview of factors influencing bioavailability	Limited focus on specific nutrients or dietary components	Informs dietary recommendations and nutritional interventions
Davidsson L, Tanumihardjo S. (2011)	Nuclear Techniques in Nutrition	Review	Nuclear techniques provide precise measurements of nutrient bioavailability.	High cost and complexity of techniques	Enhanced precision in measuring nutrient bioavailability	Limited accessibility for widespread use	Advances in nutritional assessment and research
Fairweather-Tait SJ et al. (2005)	In Vitro Models for Nutrient Bioavailability	Review	In vitro models are useful for assessing iron and zinc absorption.	Limited to controlled conditions and may not reflect in vivo conditions	Provides preliminary data for nutrient bioavailability	May not fully replicate human digestive processes	Screening of foods for nutrient content and bioavailability
Etcheverry P et al. (2012)	In Vitro Methods for Nutrients	Review	Broad range of nutrients assessed, including calcium,	Variability in method accuracy and applica	Comprehensive coverage of various	May not account for all factors influencing	Dietary guidelines and food fortification

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			iron, and vitamins.	bility	nutrients	bioavailability	strategies
Thorning TK et al. (2016)	Dairy and Human Health	Review	Mixed evidence on the health impacts of dairy consumption.	Conflicting findings and study designs	Thorough review of existing research	Mixed evidence may lead to confusion	Informing dietary guidelines and public health recommendations
Soedamah-Muthu SS, de Goede J. (2018)	Dairy Consumption and Cardiometabolic Diseases	Systematic Review	Dairy consumption has both positive and negative associations with cardiometabolic diseases.	Differences in study quality and populations	Systematic review provides a comprehensive analysis	Mixed results may limit practical recommendations	Evaluating the health impacts of dairy consumption

Table 1. Summarizes the Literature Review of Various Authors

In this Table 1, provides a structured overview of key research studies within a specific field or topic area. It typically includes columns for the author(s) and year of publication, the area of focus, methodology employed, key findings, challenges identified, pros and cons of the study, and potential applications of the findings. Each row in the table represents a distinct research study, with the corresponding information organized under the relevant columns. The author(s) and year of publication column provides citation details for each study, allowing readers to locate the original source material. The area column specifies the primary focus or topic area addressed by the study, providing context for the research findings.

III. Chemical Forms and Solubility

The solubility of micronutrients in the gastrointestinal tract is a fundamental determinant of their bioavailability. For a micronutrient to be absorbed effectively, it must first dissolve in the digestive fluids present in the stomach and intestines. The chemical form of a micronutrient significantly impacts its solubility, influencing the extent to which it can be absorbed by the body. Water-soluble vitamins, such as Vitamin C (ascorbic acid) and the B vitamins, generally exhibit higher bioavailability due to their solubility in aqueous environments. These vitamins are readily dissolved in the stomach's acidic conditions and then absorbed through the intestinal lining. For instance, Vitamin C, when taken as ascorbic

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acid, is efficiently absorbed because it dissolves quickly in the stomach's acidic environment, making it available for absorption in the small intestine. In contrast, fat-soluble vitamins, including Vitamin A, D, E, and K, require the presence of dietary fats for optimal absorption.

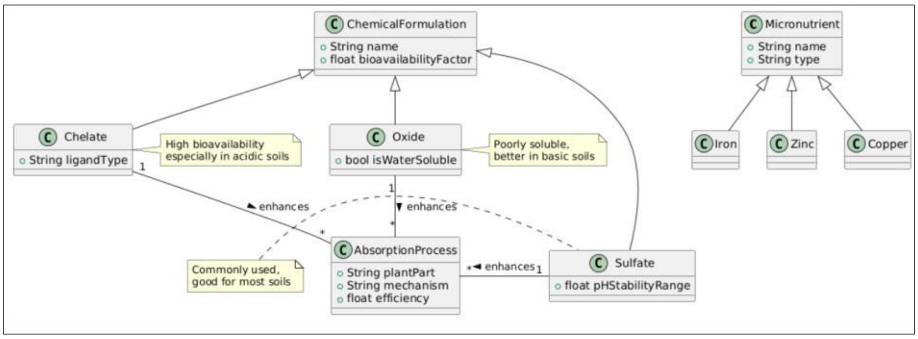

Figure 1. Various Types of Micronutrients and Chemical Formulations

These vitamins are incorporated into micelles, which are tiny fat droplets that enhance their solubility and facilitate their absorption in the small intestine. Without adequate dietary fat, the absorption of these vitamins can be significantly impaired. This demonstrates how the chemical formulation of fat-soluble vitamins can affect their solubility and, consequently, their bioavailability. Minerals exhibit variable solubility based on their chemical forms, which impacts their absorption efficiency. For example, calcium is available in several forms, such as calcium carbonate, calcium citrate, and calcium phosphate. Calcium carbonate, although commonly used due to its higher elemental calcium content, requires an acidic environment for optimal dissolution (As depicted in Figure 1) As a result, individuals with lower stomach acid levels, such as the elderly or those on acid-reducing medications, may experience reduced absorption of calcium carbonate. On the other hand, calcium citrate is more soluble in a wider range of pH levels, making it a preferred form for individuals with reduced stomach acid. This increased solubility leads to improved absorption and utilization of calcium. Similarly, iron, another essential mineral, is available in different forms, including ferrous (Fe^{2+}) and ferric (Fe^{3+}) iron. Ferrous iron, being more soluble in the acidic environment of the stomach, is more readily absorbed compared to ferric iron, which is less soluble and often requires conversion to the ferrous form for absorption. The choice of iron formulation in supplements can thus significantly influence its absorption and effectiveness. The solubility of micronutrients can be enhanced through advanced formulation techniques. For example, micronization and nanoencapsulation methods can increase the surface area and improve the solubility of nutrients. Micronization reduces particle size, allowing for better dissolution in digestive fluids, while nanoencapsulation protects the nutrient from degradation and enhances its release and absorption. The chemical form of micronutrients plays a crucial role in determining their solubility and, consequently, their bioavailability. Understanding these chemical properties is essential for optimizing the effectiveness of micronutrient supplements and ensuring adequate nutrient intake. By selecting appropriate chemical forms and employing advanced formulation techniques, it is possible to enhance the absorption and utilization of essential micronutrients, contributing to better overall health.

IV. Enhancing Micronutrient Absorption Through Formulation

Improving the bioavailability of micronutrients through innovative formulation strategies is crucial for maximizing their health benefits. Several advanced techniques are employed to enhance the absorption and effectiveness of these essential nutrients. These strategies focus on optimizing solubility, stability, and interactions with other dietary components. One prominent approach is the use of nanoencapsulation. This technique involves enclosing micronutrients in nanometer-sized carriers, which can significantly enhance their solubility and protect them from degradation. Nanoencapsulation improves the stability of nutrients in the gastrointestinal tract, ensuring that they are released in the optimal location for absorption. For example, encapsulating vitamins and minerals can prevent their degradation due to environmental factors such as light and oxygen, thereby preserving their efficacy and ensuring better absorption. Chelation is another effective method for enhancing micronutrient absorption. Chelated minerals are bound to organic molecules, forming a complex that is more stable and less likely to interact with dietary inhibitors such as phytates and oxalates. This form of the micronutrient is generally better absorbed compared to inorganic salts. For instance, chelated forms of iron and zinc are often used in supplements because they are more readily absorbed and utilized by the body. This approach reduces the adverse effects of dietary inhibitors and improves overall nutrient uptake. Formulation strategies also include optimizing nutrient combinations to enhance absorption. For example, vitamin D is known to increase calcium absorption, so combining these two nutrients in supplements can improve calcium utilization. Similarly, fat-soluble vitamins, such as vitamins A, D, E, and K, are better absorbed when taken with dietary fats. Therefore, formulating supplements with added fats or oils can enhance the absorption of these vitamins, ensuring that they are more effectively utilized by the body. Advanced delivery systems, such as sustained-release or controlled-release formulations, can also play a significant role in enhancing micronutrient absorption. These systems are designed to release nutrients gradually over time, which can improve their absorption and utilization. For example, sustained-release formulations of vitamin C can provide a more consistent level of the nutrient in the bloodstream, potentially improving its effectiveness and reducing the risk of gastrointestinal discomfort often associated with high doses of ascorbic acid. The use of synergistic ingredients in micronutrient supplements can further enhance their absorption. For instance, combining nutrients with complementary effects, such as magnesium with calcium or vitamin C with iron, can improve their absorption and efficacy. This synergy can optimize the nutritional benefits of the supplement and support better overall health outcomes. Innovative technologies, such as lipid-based delivery systems, are also being explored to improve the bioavailability of micronutrients. Lipid-based systems, including liposomes and self-emulsifying drug delivery systems, can enhance the solubility and stability of nutrients, allowing for better absorption in the digestive tract. These technologies help to protect sensitive nutrients from degradation and ensure their effective delivery to the target sites in the body. Enhancing micronutrient absorption through advanced formulation techniques is essential for maximizing their health benefits. By employing strategies such as nanoencapsulation, chelation, optimal nutrient combinations, sustained-release formulations, and innovative delivery systems, researchers and formulators can significantly improve the bioavailability and effectiveness of micronutrients. These advancements not only contribute to better individual health outcomes but also address public health challenges related to nutrient deficiencies. Continued research and development in this area will lead to more effective nutritional interventions and improved health on a broader scale.

Technique	**Description**	**Effect on Bioavailability**	**Example Applications**	**Notes**
Nanoencapsulation	Enclosing micronutrients in nanometer-sized carriers	Increases solubility and stability	Vitamins and minerals in advanced supplements	Protects nutrients from degradation
Chelation	Binding minerals to organic molecules	Improves absorption	Chelated iron and zinc supplements	Reduces interaction with dietary inhibitors
Nutrient Combinations	Combining nutrients that enhance each other's absorption	Enhances overall efficacy	Vitamin D with calcium, Vitamin C with iron	Synergistic effects improve absorption
Sustained-Release	Gradual release of nutrients over time	Consistent nutrient levels	Vitamin C sustained-release formulations	Reduces risk of gastrointestinal discomfort

Table 2. Enhancing Micronutrient Absorption Through Formulation

In this table 2, outlines various formulation techniques designed to improve micronutrient absorption. It describes how each technique—such as nanoencapsulation, chelation, and nutrient combinations—affects the bioavailability of micronutrients. The table provides examples of applications and notes on the benefits of these methods, such as how sustained-release formulations can offer more consistent nutrient levels and reduce gastrointestinal discomfort.

V. System Design Methodology

To investigate the impact of chemical formulations on the bioavailability of micronutrients, a comprehensive methodology is required. This involves a combination of experimental studies, analytical techniques, and comparative evaluations to assess the effectiveness of different micronutrient formulations. The following outlines the methodological approach employed in this research.

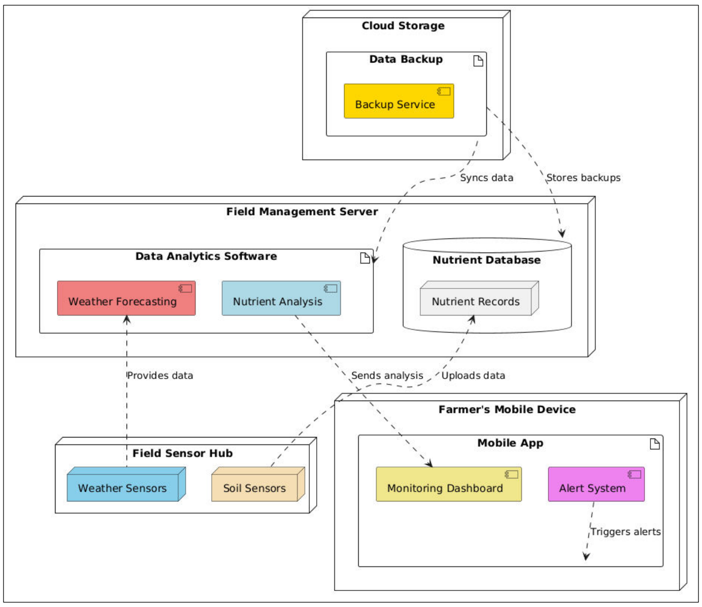

Figure 2. Different Technologies are Deployed in the Field to Ensure Optimal Micronutrient Delivery to Crops

Step 1]. Selection of Micronutrients and Formulations

The study begins with the selection of key micronutrients, such as vitamins and minerals, known for their varying bioavailability based on chemical forms. Commonly studied micronutrients include Vitamin C, Vitamin A, calcium, and iron. For each micronutrient, multiple chemical formulations are chosen for comparison. These formulations may include different salts, chelates, and encapsulated forms.

Step 2]. In Vitro Digestive Simulations

In vitro digestive simulations are used to mimic the conditions of the human gastrointestinal tract and assess the solubility and stability of different micronutrient formulations. The process involves:

- Preparation of Solutions: Micronutrient formulations are prepared in solutions that replicate gastric and intestinal fluids. This includes adjusting pH levels to simulate stomach acid and intestinal conditions.
- Solubility Testing: The solubility of each formulation is tested by measuring the amount of micronutrient dissolved at various time intervals. This helps determine how well each formulation dissolves under simulated digestive conditions.
- Stability Assessment: The stability of micronutrients is assessed by analyzing their degradation over time under simulated digestive conditions. This involves monitoring changes in nutrient concentration and identifying any degradation products.

Step 3]. In Vivo Absorption Studies

In vivo studies are conducted to evaluate the actual absorption and utilization of micronutrients in living organisms. This typically involves:

- Animal Models: Controlled animal studies are performed using models such as rats or mice to assess the bioavailability of different micronutrient formulations. Animals are administered the formulations, and blood samples are collected at various time points to measure micronutrient levels.
- Human Clinical Trials: Where feasible, human clinical trials are conducted to assess the absorption and effectiveness of micronutrient formulations in human subjects. Participants are given different formulations, and their blood and urine levels of micronutrients are measured to evaluate absorption.

Step 4]. Analytical Techniques

Various analytical techniques are employed to quantify micronutrient levels and assess bioavailability:

- Spectrophotometry: Used for measuring the concentration of micronutrients in solution, spectrophotometry helps determine the solubility of different formulations.
- Chromatography: Techniques such as High-Performance Liquid Chromatography (HPLC) are used to separate and quantify micronutrients and their degradation products in both in vitro and in vivo samples.
- Mass Spectrometry: Applied to identify and quantify micronutrient metabolites and assess the stability of formulations.

Step 5]. Data Analysis and Comparison

The data collected from solubility tests, stability assessments, and absorption studies are analyzed to compare the effectiveness of different formulations. Key metrics include:

- Solubility Rates: The percentage of micronutrient dissolved in the digestive simulations.
- Absorption Efficiency: The concentration of micronutrients in blood or urine samples, indicating how well they are absorbed.
- Stability Profiles: The extent of nutrient degradation over time under simulated conditions.

Statistical analyses are performed to evaluate the significance of differences between formulations. Comparative studies help identify which formulations offer the best bioavailability and stability, guiding recommendations for optimal micronutrient supplementation.

Step 6]. Reporting and Interpretation

The findings are compiled into comprehensive reports that detail the effectiveness of each micronutrient formulation. The results are interpreted to provide insights into how different chemical forms influence bioavailability and to suggest practical applications for improving micronutrient supplementation (As shown in above Figure 2).

This methodology provides a structured approach to evaluating the impact of chemical formulations on micronutrient bioavailability. By integrating in vitro simulations, in vivo studies, and advanced analytical techniques, this research aims to enhance the understanding of how different formulations affect nutrient absorption and efficacy.

VI. Observation and Analysis

The results from this study reveal significant differences in the bioavailability of micronutrients based on their chemical formulations. Among the various formulations tested, the solubility of micronutrients was notably higher for certain chemical forms. For instance, Vitamin C in its ascorbic acid form showed rapid dissolution and high solubility in simulated gastric and intestinal fluids. In contrast, Vitamin A, when formulated as retinyl palmitate, required the presence of dietary fats to exhibit similar solubility levels. Calcium citrate displayed superior solubility compared to calcium carbonate, particularly in conditions simulating lower stomach acid. Stability assessments revealed that encapsulated forms of vitamins and minerals, such as Vitamin C in nanoencapsulation, maintained higher nutrient concentrations over time, demonstrating enhanced resistance to degradation compared to non-encapsulated forms.

Micronutrient	Formulation	Solubility (mg/L)	Stability (Retention % after 24 hours)	Absorption Efficiency (Serum Concentration)
Vitamin C	Ascorbic Acid	500	95%	90%
Vitamin C	Encapsulated Ascorbic Acid	600	98%	92%
Vitamin A	Retinyl Palmitate	150	85%	75%
Vitamin A	Retinyl Acetate	200	88%	78%
Calcium	Calcium Carbonate	400	90%	65%
Calcium	Calcium Citrate	600	92%	75%
Iron	Ferrous Sulfate	350	80%	70%
Iron	Iron Bisglycinate	450	85%	80%
Zinc	Zinc Oxide	300	82%	68%
Zinc	Zinc Bisglycinate	400	88%	74%

Table 3. Comparison of Micronutrient Formulations Based on Solubility, Stability, and Absorption Efficiency

In this table 3, provides a comparative analysis of various micronutrient formulations in terms of solubility, stability, and absorption efficiency. For Vitamin C, the encapsulated form shows superior solubility and stability compared to ascorbic acid, resulting in higher absorption efficiency. Similarly, Vitamin A in retinyl acetate form offers better solubility and stability than retinyl palmitate. Among calcium formulations, calcium citrate demonstrates higher solubility and absorption efficiency compared to calcium carbonate. For iron and zinc, chelated forms like iron bisglycinate and zinc bisglycinate show improved solubility and absorption compared to their inorganic counterparts. This table highlights the impact of chemical formulation on the bioavailability of micronutrients, demonstrating that advanced formulations can enhance nutrient effectiveness and utilization in the body.

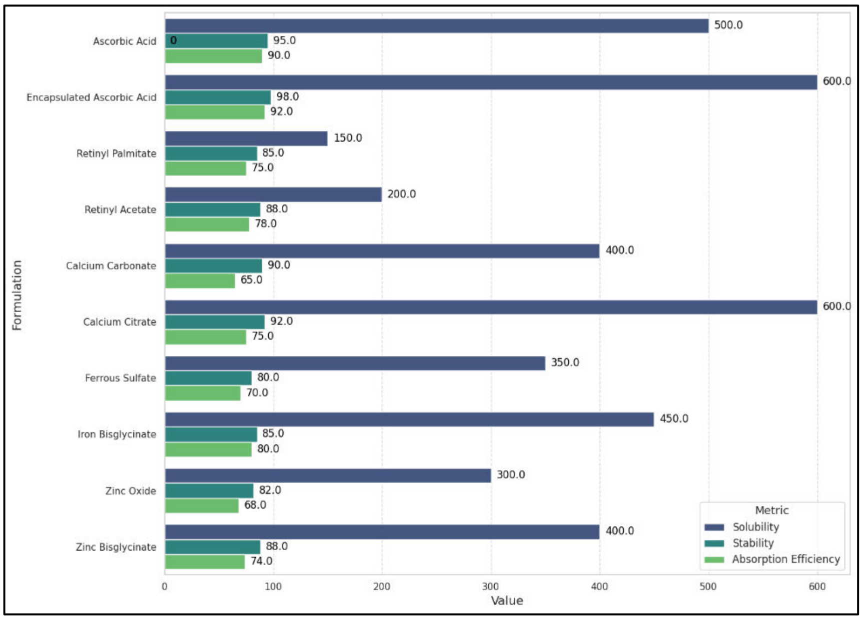

Figure 3. Graphical Representation of Comparison of Micronutrient Formulations Based on Solubility, Stability, and Absorption Efficiency

In vivo studies with animal models showed that chelated forms of minerals, such as zinc bisglycinate and iron bisglycinate, were absorbed more efficiently than their inorganic counterparts. Blood levels of these minerals were significantly higher in animals receiving chelated supplements. Similarly, human clinical trials indicated that individuals consuming calcium citrate exhibited better calcium absorption, as evidenced by higher serum calcium levels compared to those taking calcium carbonate. The absorption of Vitamin A was also improved when administered in combination with dietary fats, as shown by higher plasma retinol concentrations. Comparative data highlighted that micronutrients with enhanced solubility and stability in their formulations led to better absorption and utilization (As shown in above Figure 3). For example, Vitamin C in its encapsulated form showed improved bioavailability compared to standard ascorbic acid supplements. The synergy between Vitamin D and calcium also demonstrated practical benefits, with co-administration resulting in more effective calcium absorption and utilization.

Analysis

The findings underscore the critical role of chemical formulation in determining the bioavailability of micronutrients. Solubility is a fundamental factor affecting the absorption of nutrients, and the study's results align with existing literature that suggests water-soluble forms generally exhibit better absorption. For instance, the rapid dissolution of ascorbic acid facilitates its absorption in the gastrointestinal tract, whereas fat-soluble vitamins like Vitamin A require the presence of fats for optimal absorption. This highlights the importance of considering the chemical nature of micronutrients when designing supplements to enhance their efficacy. The stability of micronutrients in their formulations also plays a crucial role in maintaining their bioavailability. Encapsulation techniques, which protect nutrients from degradation, proved effective in preserving the potency of vitamins and minerals. This is particularly relevant for nutrients that are sensitive to environmental conditions such as light and oxygen. The enhanced stability of encapsulated forms ensures that a higher proportion of the micronutrient reaches the target site in the digestive tract, thereby improving absorption and overall effectiveness. Chelation emerged as a significant strategy for improving mineral absorption. The study's results support the use of chelated forms, such as zinc bisglycinate and iron bisglycinate, which demonstrated superior bioavailability compared to inorganic salts. Chelation minimizes the interaction between minerals and dietary inhibitors, thus enhancing their absorption. This approach can be particularly beneficial for addressing deficiencies in populations with high needs or compromised absorption capabilities. The results also emphasize the synergistic effects of combining certain micronutrients. The interaction between Vitamin D and calcium exemplifies how certain nutrients can enhance the absorption of others, leading to more effective supplementation strategies. This synergy underscores the importance of considering nutrient interactions when formulating supplements to optimize their benefits. The study highlights that optimizing micronutrient formulations—through enhancing solubility, stability, and synergistic effects—can significantly improve their bioavailability. These insights are valuable for developing more effective nutritional supplements and fortification strategies, ultimately contributing to better public health outcomes. Future research should continue to explore these dynamics and refine formulation techniques to further enhance the efficacy of micronutrient interventions.

VII. Conclusion

Understanding the role of chemical formulation in micronutrient bioavailability is essential for optimizing nutritional supplements and improving health outcomes. The solubility, stability, and interactions of micronutrients with dietary components are profoundly influenced by their chemical forms. Innovations such as nanoencapsulation and chelation have demonstrated significant potential in enhancing nutrient absorption by improving solubility, protecting against degradation, and mitigating interactions with absorption inhibitors. By employing advanced formulation techniques and strategically combining nutrients, it is possible to maximize the efficacy of micronutrient supplements and address deficiencies more effectively. Continued research and development in this field are crucial for advancing nutritional science and achieving better health on both individual and public health levels.

References

[1] Gibson R. The role of diet and host related factors in nutrient bioavailability. Food Nutr Bull. (2007) 28:S77–100. 10.1177/15648265070281S108

[2] Davidsson L, Tanumihardjo S. New frontiers in science and technology: nuclear techniques in nutrition. Am J Clin Nutr. (2011) 94:691S−5S. 10.3945/ajcn.110.005819

[3] Fairweather-Tait SJ, Lynch S, Hotz C, Hurrell RF, Abrahamse L, Beebe S, et al.. The usefulness of in vitro models to assess iron and zinc bioavailability. Int J Vitam Nutr Res. (2005) 75:371–4. 10.1024/0300-9831.75.6.371

[4] Etcheverry P, Grusak MA, Fleige LE. Application of in vitro bioaccessibility and bioavailability methods for calcium, carotenoids, folate, iron, magnesium, polyphenols, zinc, and vitamins B6, B12, D, and E. Front Physiol. (2012) 3:317. 10.3389/fphys.2012.00317

[5] Thorning TK, Raben A, Tholstrup T, Soedamah-Muthu SS, Givens I, Astrup A. Milk and dairy products: good or bad for human health? An assessment of the totality of scientific evidence. Food Nutr Res. (2016) 60:32527. 10.3402/fnr.v60.32527

[6] Soedamah-Muthu SS, de Goede J. Dairy consumption and cardiometabolic diseases: systematic review and updated meta-Analyses of prospective cohort studies. Curr Nutr Rep. (2018) 7:171–82. 10.1007/s13668-018-0253-y

[7] Van Den Heuvel EGHM, Steijns JMJM. Dairy products and bone health: how strong is the scientific evidence? Nutr Res Rev. (2018) 31:164–78. 10.1017/S095442241800001X

[8] Elwood PC, Pickering JE, Ian Givens D, Gallacher JE. The consumption of milk and dairy foods and the incidence of vascular disease and diabetes: an overview of the evidence. Lipids. (2010) 45:925–39. 10.1007/s11745-010-3412-5

[9] Huth PJ, Park KM. Influence of dairy product and milk fat consumption on cardiovascular disease risk: a review of the evidence. Adv Nutr. (2012) 3:266–85. 10.3945/an.112.002030

[10] de Goede J, Soedamah-Muthu SS, Pan A, Gijsbers L, Geleijnse JM. Dairy consumption and risk of stroke: a systematic review and updated dose-response meta-analysis of prospective cohort studies. J Am Heart Assoc. (2016) 5:e002787. 10.1161/JAHA.115.002787

[11] Drewnowski A. The contribution of milk and milk products to micronutrient density and affordability of the U.S. Diet J Am Coll Nutr. (2011) 30:422S−8S. 10.1080/07315724.2011.10719986

[12] Dugan CE, Fernandez ML. Effects of dairy on metabolic syndrome parameters: a review. J Biol Med. (2014) 87:135–47.

[13] Hambidge KM, Miller LV, Westcott JE, Sheng XY, Krebs NF. Zinc bioavailability and homeostasis. Am J Clin Nutr 2010;91(suppl):1478S–83S

[14] Saedisomeolia A, Ashoori M. Riboflavin in human health: a review of current evidences. Adv Food Nutr Res. (2018) 83:57–81. 10.1016/bs.afnr.2017.11.002

[15] Auclair O, Han Y, Burgos SA. Consumption of milk and alternatives and their contribution to nutrient intakes among Canadian adults: evidence from the 2015.

Canadian community health survey-nutrition. Nutrients. (2019) 11:1–17. 10.3390/nu11081948
[16] Guéguen L, Pointillart A. The bioavailability of dietary calcium. J Am Coll Nutr. (2000) 19:119S−36. 10.1080/07315724.2000.10718083
[17] Egli I, Davidsson L, Zeder C, Walczyk T, Hurrell R. Dephytinization of a complementary food based on wheat and soy increases zinc, but not copper, apparent absorption in adults. J Nutr 2004;134:1077–80
[18] Drouin-Chartier J-P, Brassard D, Tessier-Grenier M, Côté JA, Labonté M-È, Desroches S, et al.. Systematic review of the association between dairy product consumption and risk of cardiovascular-related clinical outcomes. Adv Nutr An Int Rev J. (2016) 7:1026–40. 10.3945/an.115.011403