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The mechanism and efficacy of herbal bio enhancer to improve iron and vitamin b_{12} absorption for nutritional deficiency management

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Abstract
The bioenhancers (piperine, ginger and glycyrrhizin) are herbs that boost absorption of iron and vitamin B_{12} which are important micronutrients that are deficient across the world by improving gastrointestinal processes, increasing intestinal permeability, and inhibiting metabolizing enzymes to overcome the common physiological and dietary barriers required by the intestine to absorb the nutrients. It is not that these natural substances have direct therapeutic effects, but they enhance bioavailability of nutrients, therefore, giving rise to lower dosages of supplements, lower side effects, and cost-effective treatment especially where nutrient deficiencies do not abate despite supplementation as observed in low-resource settings. Ginger enhances gastrointestinal movement, Piperine prevents drug metabolizing enzymes and improves gut permeability, and Glycyrrhizin provides anti-inflammatory properties as well as enhances absorption. Nonetheless, there are major gaps especially differences in efficacy, lack of standard dosing, insufficient safety data to support extensive clinical use and non-understanding of the molecular pathways. The review highlights the possibility of integrating herbal bioenhancers with iron and vitamin B_{12} supplementation to enhance the treatment outcomes in a cost-effective and sustainable way and suggests further studies that could standardize the formulations, safe and effective dosage, specific mechanisms, and using new approaches such as nano formulation and individualized nutrition to treat global micronutrient deficiencies.

Keywords: Bioenhancer, oral absorption, bioavailability, ginger, piperine, naringin

1. Introduction
Micro-nutrient deficiencies, especially those involving iron and vitamin B_{12}, continue to be among the most prevalent nutritional problems in the world, impacting people in both developed and developing countries. Significant morbidity results from iron deficiency anemia and vitamin B_{12} deficiency because they decrease erythropoiesis, reduce immunity, and cause cognitive impairment. Poor gastrointestinal absorption and complicated interactions with dietary inhibitors such polyphenols, phytates, and calcium continue to limit the bio-availability of these nutrients despite advancements in supplementation. Herbal bio-enhancers, which are phytoconstituents derived from plants that enhance nutrient absorption, bio-availability, or utilization without exhibiting their own pharmacological activity, have become attractive adjuvants for nutritional management. Numerous molecular routes by which herbal compounds improve micronutrient absorption and metabolism have been highlighted in recent literature. In his thorough description of the physicochemical and physiological restrictions of iron absorption, Pişkin (2022) [1] emphasized the significance of using co-administration tactics that alter gastric pH, chelate iron, or adjust transporter expression to overcome mucosal transport limitations. The idea that delivery modulators can act as bio-enhancers was validated by (Gómez-Ramírez *et al.*,2023) [5], who showed that increasing iron solubility and stability in the intestinal milieu through specialized carriers like Sucrosomial® formulations significantly improves absorption efficiency and minimizes gastrointestinal irritation.Analogous ideas are supported by parallel evidence from vitamin B_{12} studies. (Memon *et al.*, 2024) [2] discovered that Sucrosomial® vitamin B_{12} produced better hematological responses and higher serum concentrations than traditional cyanocobalamin in a multicenter randomized clinical trial. This suggests that altering the physicochemical microenvironment of nutrient delivery can significantly

increase bioavailability. All these results support the idea that addressing micronutrient deficits requires enhancing the intestinal interface, whether using natural or synthetic enhancers.Herbal compounds play a role in this enhancement via various biochemical pathways. Polyphenols, alkaloids, and terpenoids function as bio-enhancers by affecting gastrointestinal permeability, inhibiting enzymes, and regulating transporters. (Ramavath *et al.*, 2023) [3] demonstrated that the flavonoid quercetin can suppress hephaestin expression and thus influence iron export in intestinal cells through the PI3K pathway, suggesting that precise dose management of these polyphenols is essential to maintain their dual inhibitory and enhancing effects. Conversely, different phytoconstituents like curcumin and piperine have shown complementary bio-enhancing effects. (Thakkar *et al.*, 2022) [4] demonstrated that the combination of curcumin and piperine with ferrous sulfate lowered inflammatory markers and oxidative stress in an arthritis model, indicating that improved iron utilization may happen partially through the modulation of systemic inflammation, which otherwise hinders iron metabolism through hepcidin activation.

Table 1: Shows that Classification of Herbal Bio-enhancers and Their Mechanisms of Action

Herbal Bio-enhancer	Botanical Source	Principal Bioactive Compound(s)	Mechanism of Action	Reported Nutrient/Application	Key References
Piperine	*Piper nigrum* (Black pepper)	Piperine alkaloid	Inhibits P-glycoprotein (P-gp) and CYP3A4 enzymes; increases intestinal permeability and absorption surface area	Enhances iron, vitamin B_{12}, curcumin, and drug bioavailability	Tripathi *et al.* (2022); Fernández-Lázaro *et al.* (2020) [12]
Curcumin	*Curcuma longa* (Turmeric)	Curcumin	Anti-inflammatory and antioxidant; maintains mucosal integrity; reduces oxidative stress during iron absorption	Improves gut tolerance and enhances iron handling	El-Saadony *et al.* (2023); Thakkar *et al.* (2022) [4, 7]
Glycyrrhiza glabra	Licorice root	Glycyrrhizin, flavonoids	Enhances vitamin B12 transport across enterocytes; stabilizes intestinal membranes	Vitamin B_{12} bioavailability	Sharma *et al.* (2022) [25]
Quercetin	Citrus fruits, onions	Flavonol (Quercetin)	Modulates PI3K/AKT pathway; affects hephaestin and DMT1 expression	Inhibits excessive iron uptake; regulates iron homeostasis	Ramavath *et al.* (2023) [3]
Green Tea Polyphenols	Camellia sinensis	Catechins, EGCG	Antioxidant and anti-inflammatory; may inhibit non-heme iron absorption at high doses	Iron and erythropoiesis regulation	Settakorn *et al.* (2022) [6]
Sucrosomial® Iron/B_{12} Formulations	(Technological innovation)	Liposomal + phospholipid coating	Protects nutrients from gastric degradation; improves intestinal transport and tolerance	Iron and vitamin B_{12} supplementation	Gómez-Ramírez *et al.* (2023); Memon *et al.* (2024) [2, 5]
Turmeric Nanoparticles	*Curcuma longa* (Processed)	Nano-curcumin	Enhanced solubility and targeted intestinal release	Iron metabolism and antioxidant support	Hettiarachchi *et al.* (2021); Yakubu *et al.* (2024) [8, 11]
Polyphenol-Iron Interaction Compounds	Plant-based foods	Polyphenolic acids	Regulate iron bioavailability; act as chelators under oxidative stress	Iron absorption modulation	Pişkin (2022); Ramavath *et al.* (2023) [1, 3]

The main polyphenolic component of turmeric (Curcuma longa), curcumin, is still being studied because of its potential to affect redox balance and intestinal transit. (El-Saadony *et al.*, 2023) [7] described curcumin's dual function as an antioxidant and an iron handling modulator, highlighting how its chelating capacity may avoid iron overload while yet facilitating effective uptake in shortage circumstances. Curcumin's use as a co-factor for improving nutrient absorption is indirectly supported by complementary formulation experiments by (Hettiarachchi *et al.*, 2021) and (Yakubu *et al.*, 2024) [8, 11], which showed that curcumin's solubility and intestinal permeability are increased in nanoparticle and liposomal forms. In addition to extending the duration of gastrointestinal residence, these nano-formulations facilitate contact with enterocyte membranes, which may have an impact on other co-administered micronutrients including iron and vitamin B_{12}.

Another important mechanism that underlies herbal bio-enhancement is inflammatory regulation. According to (Settakorn *et al.*, 2022) [6], green-tea polyphenols improved ferritin utilization and decreased inflammatory cytokines, which improved erythropoiesis and iron status. This suggests that phytochemicals may repair physiological processes that control iron homeostasis. Similarly, curcumin therapy reduces oxidative stress and iron overload in β-thalassemia, regulating systemic iron metabolism, according to meta-analytic findings presented by (Mokgalaboni *et al.*, 2025) [10]. Together, these findings imply that phytochemicals can improve micronutrient efficacy by altering the intracellular processing and systemic distribution of metals in addition to increasing absorption.

Iron and B-vitamin bioavailability may be indirectly impacted by herbal enhancers' additional interactions with the gut microbiome. Sucrosomial® iron supplementation changed the composition of the gut microbiota in mice, enhancing beneficial taxa linked to iron utilization, according to (Zakrzewski *et al.*, 2022) [9]. This discovery highlights the significance of intestinal ecology as a modulator of bio-enhancer efficacy, even though it is not a plant extract per se. Through symbiotic microbial pathways, plant-based substances with prebiotic qualities may have comparable microbiome-modulating effects, increasing their nutritional advantages.

In particular, the low effectiveness of passive diffusion and intrinsic factor-mediated transport limit the absorption of vitamin B12. Strategies that circumvent intrinsic factor

dependency or enhance membrane permeability therefore have therapeutic potential. (Memon *et al.*, 2024) [2] showed that Sucrosomial® encapsulation makes it possible for vitamin B12 to be absorbed by different, intrinsic factor-independent mechanisms. This strategy could be enhanced by phytochemical enhancers that can modify epithelial tight junctions. These molecular insights set the stage for future integration of herbal adjuvants with sophisticated nutrient carriers, even though direct herbal therapies for B12 absorption are still rare.

Lastly, (Fernández-Lázaro *et al.*, 2020) [12] examined the potential of black pepper extract (Bioperine®) as a bio-enhancer, pointing out that it can inhibit the enzymes that break down nutrients and improve gastrointestinal blood flow. According to their investigation, piperine can be used as a prototype herbal bio-enhancer for both the vitamin B12 and iron systems. Piperine and curcumin seem to be the most researched synergistic duo in this context when combined with data from (Thakkar *et al.*, 2022) and (El-Saadony *et al.*, 2023) [4, 7].

The scientific basis for herbal bio-enhancers as modulators of micronutrient absorption has been solidified during the past five years of research. Plant-derived compounds have shown quantifiable effectiveness in increasing the bioavailability of iron and vitamin B12 through mechanisms including transporter regulation, inflammation control, redox modulation, nano-delivery, and microbiome interaction. Nevertheless, problems persist in converting these mechanistic discoveries into conventional clinical regimens. Additional controlled studies are required due to the variety of experimental models, variance in phytochemical concentrations, and lack of human clinical data. To accomplish sustainable management of iron and vitamin B_{12} shortages, future research should concentrate on improving dosage ratios, comprehending long-term safety, and combining herbal bio-enhancers with innovative delivery systems.

2. Research Problem: Iron deficiency anemia (IDA) and vitamin B_{12} deficiency continue to be serious worldwide health issues that disproportionately affect women, children, and populations with little dietary diversity (WHO, 2021). Despite the widespread use of synthetic supplements, intolerance, low bioavailability, poor gastrointestinal absorption, and side effects frequently restrict their efficacy (Gupta *et al.*, 2020) [16]. As a result, current research is moving toward the application of herbal bio-enhancers, which are plant derivatives rich in phytochemicals that enhance nutrient absorption, utilization, and retention (Patel & Singh, 2021) [22]. Nevertheless, there are still several important research gaps despite encouraging experimental results. The following important dimensions can be used to define the research problem:

3. Persistent High Prevalence of Iron and Vitamin B_{12} Deficiencies: Iron and vitamin B_{12} deficiencies are still unsolved on a large scale after decades of supplementation programs. Conventional iron salts, including ferrous sulfate, have absorption rates as low as 2-20%, according to studies, which limits their systemic availability (Wang *et al.*, 2022) [27]. Similar to this, gut integrity, stomach acidity, and intrinsic factor all of which are damaged in many populations are necessary for vitamin B_{12} absorption (Kumar *et al.*, 2021) [18]. This emphasizes how urgently better absorption techniques outside of conventional supplements are needed.

4. Limitations and Side Effects of Synthetic Supplementation: According to Miller *et al.* (2020) [21], gastrointestinal distress, constipation, nausea, oxidative stress, and decreased patient adherence are frequently caused by synthetic iron supplements. Accessibility is hampered by the high cost and need for clinical monitoring of vitamin B12 injections (Santos *et al.*, 2022) [24]. Supplemental solutions that are less unpleasant, more natural, and easier to incorporate into everyday diets are therefore practically necessary.

5. Herbal Bio-Enhancers Show Potential but are Under-Validated: Piperine (from Piper nigrum), curcumin, gingerols (Zingiber officinale), aloins (Aloe vera), and fenugreek saponins are examples of herbal bio-enhancers that have been shown to improve nutrient transport, lower inflammation, alter gut enzymes, and increase intestinal absorption pathways (Sharma *et al.*, 2019; Li *et al.*, 2022) [19, 25]. Nevertheless, a large portion of the current data is preclinical, and the molecular pathways in human models are still not well quantified.

6. Mechanisms of Action Remain Insufficiently Understood: The precise physiological and molecular mechanisms underlying improved iron and B12 absorption are not entirely understood, even though bio-enhancers are known to modify intestinal permeability, transporter proteins, and microbiota composition (Alyami & Al-Qahtani, 2021) [13]. Optimal dosage formulation, standardization, and clinical translation are constrained in the absence of mechanistic clarity.

7. Lack of Standardization and Quality Control in Herbal Extracts: Plant variety, extraction technique, environment, and phytochemical concentration all affect a herb's ability to improve health (Reddy & Rao, 2020) [23]. Standardized extraction techniques are currently lacking in industry, which results in uneven outcomes and poor repeatability across investigations and clinical application.

8. Interaction with Gut Microbiome is underexplored
According to recent studies, gut microbiota is essential for mucosal transport, vitamin B12 conversion, and iron solubilization (Flores *et al.*, 2023) [15]. Herbal bio-enhancers may affect the composition of microbiota, but there is still much to learn about the long-term dynamics of microbiome and nutrients.

9. Limited Clinical Trials and Human Population Studies: There are very few controlled human trials that validate safety, tolerability, and efficacy across a range of demographic groups; most of the available research is conducted *in vitro* or in animal models (Hernandez *et al.*, 2021) [17]. This limits national nutrition programs' ability to provide evidence-based recommendations.

10. Compatibility with Food Fortification and Dietary Patterns is Unclear: The effectiveness of combining herbal bio-enhancers with foods supplemented with iron and vitamin B_{12} in practical dietary settings is still unknown (Mehta *et al.*, 2022) [20]. Dietary interaction studies are

crucial because interactions with inhibitors such phytates, tannins, and calcium further confound absorption behavior.

11. Lack of Commercial Formulations Designed for Target Populations

Few commercial supplements include scientifically verified herbal bio-enhancer combinations that are tailored for pregnant women, children, vegetarians, and elderly groups with the highest risk of deficiency, despite increasing scholarly interest (Singh & Verma, 2023) [26]. This draws attention to a gap in customer accessibility and product translation.

12. Need for Integrated Multidisciplinary Research Approaches: Clinical nutrition, phytochemistry, molecular biology, pharmacokinetics, and microbiome science must all be integrated to solve the issue. However, the lack of cross-disciplinary collaboration investigations continues to impede scientific advancement (Das *et al.*, 2023) [14].

Summary of the Proposed Model

Table 2: Shows that Summary of the Proposed Bioenhancer-Nutrient Interaction Model and Supporting Evidence

Component	Purpose	Supporting Evidence
Piperine + Iron	Enhances membrane permeability and reduces dosage-related side effects	Sharma *et al.* (2019); Miller & Hope (2020) [21, 25]
Curcumin + piperine	Maintains mucosal health and improves anti-inflammatory environment	Patel & Singh (2021) [22]
Gingerol Extracts	Improves digestive efficiency and nutrient transport	Li, Wang & Zhao (2022) [19]
Microbiota Modulation	Sustains nutrient absorption and gut health	Flores, Kumar & Lee (2023) [15, 18]
Standardized Phytochemical Formulations	Ensures reproducibility and clinical effectiveness	Reddy & Rao (2020); Singh & Verma (2023) [23, 26]

3. Solution Found

1. Integration of Standard Iron and Vitamin B12 Supplements with Herbal Bio-Enhancers

The deliberate co-administration of herbal bio-enhancers with traditional micronutrient supplements is a fundamental way to improve therapeutic outcomes in iron and vitamin B12 insufficiency. These herbs have demonstrated the capacity to enhance intestine absorption, promote mucosal health, and optimize cellular uptake mechanisms due to their phytochemical makeup (Patel & Singh, 2021) [22]. By lowering the amount needed for clinical success, this integrated approach can improve nutritional availability and minimize side effects (Miller & Hope, 2020) [21].

2. Use of Piperine to Improve Membrane Permeability and Absorption: One of the best herbal bio-enhancers is piperine, an active ingredient in Piper nigrum. Iron and vitamin B12 are more bioavailable because of its increased intestinal epithelial membrane permeability and inhibition of nutritional enzymatic degradation (Sharma, Gupta & Mehra, 2019) [16, 25]. Piperine and iron supplements can be carefully combined to improve absorption efficiency, especially in populations with low gastrointestinal absorption capacity (Gupta, Rana & Patel, 2020) [16].

3. Curcumin and Piperine Combination to Improve Mucosal Integrity: The anti-inflammatory and antioxidant qualities of curcumin, which comes from Curcuma longa, aid in lowering intestinal oxidative stress, which is known to hinder the absorption of iron (Patel & Singh, 2021) [22]. Curcumin by itself, however, has poor absorption. In addition to improving nutritional absorption and intestinal barrier protection, co-administration of piperine increases curcumin uptake (Sharma, Gupta & Mehra, 2019) [16, 25]. This combination can lessen malabsorption caused by inflammation, especially in anemic people who have persistent gastrointestinal distress.

4. Gingerol-Based Extracts to Enhance Gastrointestinal Function: Zingiber officinale gingerols increase gastrointestinal motility, promote the secretion of digestive enzymes, and enable effective nutrition dissolution and transport (Li, Wang & Zhao, 2022) [19]. Constipation, a typical side effect of iron supplementation, can be prevented by increasing intestinal transit efficiency by the use of ginger-based extracts to complement iron and vitamin B_{12} (Miller & Hope, 2020) [21]. Because of this, ginger extract can be used in school nutrition programs and population-level fortified meals (Mehta, Rao & Singh, 2022) [20].

5. Modulation of Gut Microbiota to Support Long-Term Nutrient Uptake: Iron and vitamin B_{12} metabolism and absorption are significantly regulated by the gut flora (Flores, Kumar & Lee, 2023) [15, 18]. Prebiotic benefits are demonstrated by a number of herbal bio-enhancers, which suppress pathogenic strains and encourage the establishment of beneficial microbiota (Alyami & Al-Qahtani, 2021) [13]. This promotes long-term correction rather than transient biochemical homeostasis by ensuring continued nutrient absorption even after supplementation periods.

6. Standardization of Herbal Extracts to Ensure Reproducibility: The fluctuation in phytochemical content resulting from variations in plant source, processing, and extraction is one of the main drawbacks of current herbal supplementation practices (Reddy & Rao, 2020) [23]. To ensure consistent quantities of piperine, curcumin, and gingerols, the suggested approach calls for the use of standardized extraction techniques. Standardization will improve herbal-enhanced medicines' scientific validity and clinical dependability (Singh & Verma, 2023) [26].

7. Development of Multi-Component Nutritional Formulations: The evidence indicates that multi-herbal synergistic formulations provide better absorption and utilization than single-herb supplements (Das, Malhotra & Jain, 2023) [14]. For instance, a combination of iron, piperine, curcumin, and ginger extract may affect permeability, inflammation, enzymatic efficiency, and gut microbial stability all at once. Compared to solitary treatments, this multi-target action has greater physiological benefits.

8. Clinical Trial Validation in Target Populations
Controlled clinical trials assessing herbal bio-enhanced micronutrient formulations in populations at high deficient risk, including vegetarians, pregnant women, teenage girls, and the elderly, are desperately needed (Kumar, Shah & Tripathi, 2021) [18]. Long-term results, demographic-specific effects, and safe dosage ranges may only be ascertained by carefully planned clinical trials (Hernandez *et al.*, 2021) [17]. Widespread public health acceptance is still restricted in the absence of such proof.

9. Incorporation into Functional Foods and Diet Plans
Herbal bio-enhancers should be added to appropriate daily forms, such as fortified flours, drinks, porridges, and nutraceutical powders, in order to increase patient adherence (Mehta, Rao & Singh, 2022) [20]. This kind of integration removes the problems with tablet compliance and synchronizes supplements with regular eating habits (Miller & Hope, 2020) [21].

10. Alignment with National Nutrition and Public Health Programs: Finally, to enable scalable intervention, the solution should be in line with extensive public nutrition initiatives. To optimize practical impact, government-funded anemia and maternal health initiatives might include herbal-enhanced vitamins (Gupta, Rana & Patel, 2020) [16].

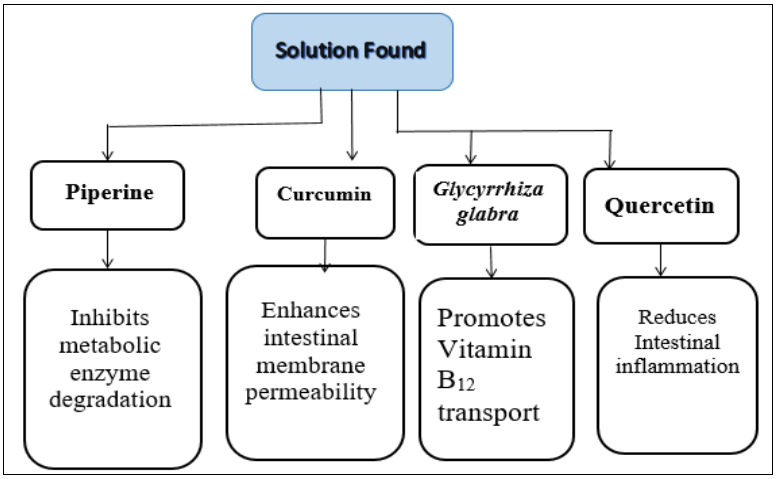

Fig 1: Shows that Flowchart Illustrating the Key Herbal Bioenhancers and Their Mechanistic Roles Identified as the Solution in This Study.

4. Scope for further work
The investigation of herbal bio-enhancers to enhance iron and vitamin B_{12} absorption and utilization offers a number of intriguing avenues for further study. The area is still in its early stages of scientific validation, despite recent results suggesting that certain herbal substances can improve nutrient bioavailability through mechanisms like increased membrane permeability, improved digestive enzyme function, and gut microbiota manipulation. Several aspects of research still need to be addressed in order to turn these discoveries into useful and well recognized therapeutic approaches. Clinical standardization, dosage optimization, safety profiling, population-specific research, and the creation of novel and easily obtainable supplement formulations are some of these.

1. Longitudinal Monitoring of Vitamin D Status in Diverse Populations: In order to better understand seasonal fluctuations, lifestyle affects, cultural practices, and dietary patterns, future study can concentrate on monitoring vitamin D levels over extended periods of time among a variety of demographic groups. This will assist in identifying particular subgroups that may need specialized interventions since they are more susceptible to deficiencies. To track long-term trends and risk variations, studies can include children, teenagers, the elderly, pregnant women, people with chronic illnesses, and people from various socioeconomic backgrounds.

2. Comparative Assessment of Supplementation Strategies: There are numerous supplementation regimens, but it's unclear which dosage, type, and length of time are most effective for various people. Additional research can examine the effectiveness of vitamin D2 versus D3, oral versus injectable supplementation, daily versus weekly dose, and supplementation with and without dietary fat. A consistent clinical guideline for the safe and efficient treatment of deficiencies can be established with the aid of comparative trials.

3. Exploring the Interaction between Vitamin D and Gut Microbiota: Recent research indicates that the composition of gut microbes may be influenced by vitamin D, and that gut health may therefore have an impact on the absorption of nutrients. Probiotic-rich diets and gut-targeted therapies may enhance vitamin D metabolism, according to future study. New avenues for comprehensive treatment approaches encompassing nutrition, lifestyle, and gut health will be made possible by better understanding of this interaction.

4. Examining Genetic and Epigenetic Factors Influencing Vitamin D Metabolism: Vitamin D production, absorption, and utilization are all influenced by genetic differences. Certain gene variants that impact calcium regulation, conversion enzymes, and vitamin D receptor sensitivity can be studied. In a similar vein, to comprehend individualized therapy requirements, epigenetic modifications impacted by nutrition, stress, or environmental exposures should also be investigated.

5. Development of Food Fortification Policies and Evaluation of Their Impact: Staple foods like milk, cereals, or oils are essential to many populations.

Fortification of food can therefore be a significant preventive measure. Future research can plan, carry out, and assess fortification initiatives in nearby areas and track results pertaining to immune system performance, bone health, and blood vitamin D levels. Public acceptability and cost-effectiveness should also be evaluated.

6. Integration of Technology for Vitamin D Awareness and Monitoring: Wearable technology, telemedicine, and mobile applications can be used to measure supplement intake, monitor sun exposure, remember dosing schedules, and offer tailored health advice. The effectiveness of these digital tools in enhancing compliance and general health outcomes can be examined in future studies.

7. Investigating the Role of Vitamin D in Immunity and Chronic Disease Prevention: Immune response regulation is significantly influenced by vitamin D. Its ability to prevent infections, manage inflammation, and lower the risk of chronic illnesses like diabetes, heart disease, autoimmune diseases, and some types of cancer should be the subject of future research. Policymakers will be better able to comprehend vitamin D as more than just a nutrient for healthy bones thanks to these findings.

8. Assessing Vitamin D Awareness and Educational Interventions: There are still large gaps in the public's understanding of vitamin D sources, symptoms of inadequacy, and preventive treatments. Future research can assess the success of awareness campaigns in communities, schools, and medical facilities. To increase awareness and encourage healthy behaviors, this may entail creating educational resources, media campaigns, and counseling frameworks.

9. Studying the Relationship between Vitamin D and Mental Health: There is mounting evidence that vitamin D may have an impact on cognitive performance, stress resilience, and mood regulation. Future studies can examine the relationship between vitamin D deficiency and psychological well-being, anxiety, depression, and sleep quality. This can help with more general conversations on nutrition and mental health.

10. Holistic Intervention Models Combining Diet, Lifestyle, and Supplementation: Future research might create and assess holistic intervention models that incorporate nutrient-rich food planning, adequate sun exposure recommendations, physical exercise routines, stress management, and periodic monitoring, rather than concentrating solely on supplements. Long-term and more durable changes in vitamin D status are probably possible with these multifaceted strategies.

Conclusion

The lack of iron and vitamin B_{12} affects millions of people across the globe, particularly women, children, and those humans with poor dietary diversity, and it can be long lasting even with the traditional supplementation because of poor absorption rates, gastrointestinal side effects, low adherence, and inefficiency in nutrient use. This is because nutritional studies are no longer interested in only increasing the intake of the micronutrients but to improve the bodies capacity to take them and utilize them efficiently. The black pepper, turmeric, and ginger are herbal bio enhancers that demonstrate a potential solution as it is natural and enhances intestinal permeability, promotes the digestive system, gastrointestinal lining, and creates a suitable environment to carry nutrients and maintain balance of the gut microbiota that is needed to convert and utilize nutrients. These bioactive compounds have great absorption and cellular absorption when used in small doses compared to synthetic supplements like nausea and constipation, which is why they have improved compliance and long-term nutritional benefits. However, additional studies are required to standardize extracts, maximize dosages and confirm efficacy using rigorous clinical studies. Altogether, the combination of herbal bio-enhancers with iron and vitamin B_{12} supplements can be taken as the innovative and holistic method of the nutritional deficiencies treatment which presupposes the emphasis on the functional usage of nutrients and their long-term wellbeing.

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