Indian Journal of Experimental Biology
Vol. 62, July 2024, pp. 475-483
DOI: 10.56042/ijeb.v62i07.12071

Navigating the frontiers of mineral absorption in the human body: Exploring the impact of probiotic innovations

Keshab Chandra Mondal[1]*, Sudipta Samanta[1], Subhadeep Mondal[2], Saswati Parua Mondal[3], Krishnendu Mondal[1] & Suman Kumar Halder[1,4]

[1]Department of Microbiology; [2]Center for Life Sciences, Vidyasagar University, Midnapore-721 102, West Bengal, India
[3] Department of Physiology, Bajkul Milani Mahavidyalaya, Purba Medinipur-721 626, West Bengal, India
[4]Department of Microbiology, Vivekananda Mahavidyalaya, Burdwan-713 103, West Bengal, India

Received 31 January 2024; *revised: 30 March 2024*

Essential minerals play a crucial role in diverse physiological processes, and their deficiencies can give rise to significant health challenges. Probiotics, residing as beneficial microorganisms in the gut, have recently garnered attention for their potential in modulating mineral absorption and alleviating deficiencies. However, the difficulties arise from the variability of probiotic strains, varying dosages, and the distinct composition of individuals' gut microbiota, rendering it challenging to establish universal guidelines. A more nuanced understanding of these mechanisms holds the key to developing targeted probiotic interventions, ultimately optimizing mineral absorption and fostering human health. This review explores the complex relationship between probiotics and the assimilation of essential minerals such as iron, calcium, selenium, zinc, magnesium, and potassium, decoding how probiotics influence the absorption of these minerals. Further research on the role of probiotics in mineral absorption is necessary for optimizing nutrient uptake and informing personalized interventions to support overall health.

Keywords: Essential minerals, Gut microbiota

Introduction

Probiotics, as outlined by the Food and Agriculture Organization (FAO), are living microorganisms that naturally flourish in the gut, providing health advantages when appropriately ingested. Employing diverse mechanisms, they inhabit the gastrointestinal tract and maintain bacterial equilibrium in the gut. Beyond this, probiotics play a crucial role in the gut-brain axis, contributing to mental well-being and fortifying immune function[1]. Prominent for their probiotic attributes, microorganisms like the *Lactobacillus* family (*lactis*, *acidophilus*, *brevis*, etc.), *Bifidobacterium* (*bifidum*, *infantis*, *breve*, etc.), *Streptococcus* group (*thermophilus* and *alivarius*), and yeast such as *Saccharomyces boulardii* have garnered recognition[2]. These beneficial microbes are commonly present in certain foods and dietary supplements. Recently, probiotics have gained significant attention for their role in modulating nutrient absorption and creating a barrier against pathogenic bacteria in the intestinal mucosa, thus influencing the gut-brain axis[3]. Probiotics play a role in mineral metabolism, including calcium (Ca), iron (Fe), magnesium (Mg), selenium (Se), potassium (K), copper (Cu), and zinc (Zn), enhancing their absorption[4]. Mineral levels in the body, crucial for its functioning, are linked not only to intake but also to proportional absorption. Research indicates that probiotics can influence mineral absorption, with certain strains enhancing or inhibiting absorption. However, the precise mechanisms vary among probiotic strains and mineral types, remaining incompletely understood[5].

Importance of minerals within the human body

Numerous researchers emphasize the vital importance of minerals such as calcium (Ca), selenium (Se), zinc (Zn), magnesium (Mg) and potassium (K) in the human body[6-9]. These essential minerals play a structural role in the body and are indispensable for various metabolic functions[10]. Minerals, acting as structural components for bones, regulate hydration and impact muscle and nerve function[5]. They are crucial for the catalytic action of hormones, enzymes, and other bioactive components.

*Correspondence:
E-Mail: mondalkc@gmail.com.

Additionally, minerals are linked to the proper functioning of the immune system, influencing susceptibility to infections and the development of chronic diseases, including neurodegenerative diseases, osteoporosis, and diabetes[11]. While a balanced diet typically provides sufficient minerals, certain circumstances, such as chronic diseases, pregnancy, aging, or specific lifestyles, may increase the risk of mineral deficiencies. Approximately, 50% of the global population faces micronutrient malnutrition[12], with 2 billion people estimated to have micronutrient deficiencies, according to the World Health Organization (WHO)[13]. The localization of mineral absorption in the intestine is visually depicted in Fig. 1, highlighting each section's role. The mechanism of mineral absorption in the intestine, involves paracellular and/or transcellular pathways. Specific transporters and pumps, such as TRPV6 for calcium, facilitate mineral uptake. Exchange with other ions during absorption, as seen in zinc absorption influenced by transporters like ZIP4, is also noted. Enterocytes synthesize proteins like calbindin D and claudin to aid in mineral absorption. Absorbed minerals are then transported across the basolateral membrane into the bloodstream for systemic distribution via various mechanisms, including ATPase pumps and binding to carrier proteins like transferrin[4]. A summary of various minerals, their role, rate of absorption in the human body, dietary sources, and recommended doses are given in Table 1.

Interaction between gut microbiota and mineral absorption

The gut microbiota (GM), residing in the gastrointestinal tract, interacts with minerals through diverse mechanisms. Microorganisms in the GM can either enhance or inhibit mineral absorption in the digestive tract, involving complex interactions between microorganisms, minerals, and host cells[23].

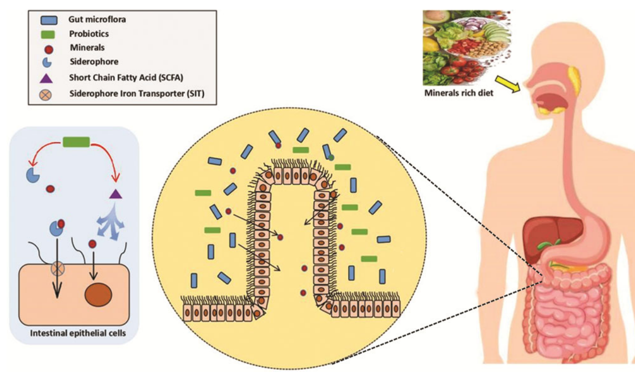

Fig. 1 — Schematic diagram of mineral absorption with the help of gut microbiota

Table 1 — Role of minerals in human health, their absorption rate, daily requirement and dietary sources

Mineral	Role in human health	Absorption rate in human body	Dietary sources	Daily requirement
Calcium[10,11,14]	It plays vital role in vascular contraction, vasodilation, muscle functions, nerve transmission, intracellular signaling, and hormonal secretion	25-60%	Dairy products like milk, yogurt, curd.	200 mg for infants 260-1300 mg for children 1000-1300 mg for adults
Selenium[15,16]	It has important role in reproduction, thyroid hormone metabolism, DNA synthesis, and protection from oxidative damage and infection	40-50%	Breads, cereals, poultry, red meat, and eggs	15 mcg for infants 20-55 mcg for children 55-70 mcg for adults
Zinc[17,18]	It involves in growth of cells, building proteins, healing damaged tissue, and supporting a healthy immune system	16-50%	Seafood, nuts whole grains, breakfast cereals, and dairy products.	2 mg for infants 3-11 mg for children 11-13 mg for adults
Magnesium[19]	It helps to maintain normal nerve and muscle function, supports a healthy immune system, keeps the heartbeat steady, and helps bones remain strong. It also helps adjust blood glucose levels	30-40%	Green leafy vegetables, such as spinach, legumes, nuts, seeds, and whole grains	30 mg for infants 75-400 mg for children 410-420 mg for adults
Potassium[20]	It plays important role in maintaining normal levels of fluid inside our cells	90%	Dried fruit, lentils, spinach, sweet potatoes, and orange juice	400 mg for infants 860-2500 mg for children 2500-3400 mg for adults
Iron[21,22]	It primarily involved in the transfer of oxygen from the lungs to tissues	2-20%	Red meat, fish and poultry, and is easily absorbed by your body. Non-heme iron is found in eggs and plant-based foods such as beans, lentils, nuts and seeds	0.27 mg for infants 7-15 mg for children 8-27 for adults

One mechanism involves the production of enzymes, such as phytases, by gut bacteria, breaking down complex minerals like phytic acid found in plant-based foods. This enzymatic action releases minerals like Ca, Mg, Fe, and Zn for absorption in the small intestine, with notable phytase producers being *Bacillus subtilis*, *Bacillus coagulans*, and various *Lactobacillus* strains[24]. Additionally, the GM can influence mineral absorption by modulating the gut environment through the production of short-chain fatty acids (SCFAs) from dietary fiber metabolism (Fig. 1). SCFAs enhance mineral solubility, impacting absorption and overall nutrient status. Furthermore, the GM can affect gene expression in host cells, influencing the absorption of minerals like iron (Fe)[25]. These intricate interactions underscore the vital role of the gut microbiota in shaping nutrient status and overall health. Recent studies on the role of various probiotics in mineral absorption have been summarized in Table 2.

Synergistic relationship between probiotics and mineral absorption

Effectiveness of probiotics in enhancing calcium absorption

Evidence suggests a robust link between a healthy gut microbiota (GM) and enhanced calcium (Ca^{2+}) absorption, potentially mediated by the modulation of serotonin production in the gut. Serotonin, a neurotransmitter, is implicated in bone metabolism and may serve as a nexus between the microbiota and bone health. Probiotics have been shown to positively impact bone health by influencing osteoblast bone formation and osteoclast bone resorption in various studies[35]. One plausible mechanism for heightened Ca^{2+} absorption involves probiotics increasing the bioavailability of Ca^{2+} in the intestine. Notably, certain *Lactobacillus* strains demonstrated improved total Ca^{2+} transport, influencing both transcellular and paracellular pathways. Probiotic supplementation, such as *L. rhamnosus* in broilers and a symbiotic blend in pediatric individuals, showcased improved Ca balance and serum Ca levels. Additionally, enriched yoghurt with *L. plantarum* in postmenopausal women significantly increased bone mineral density after six months[36]. Another potential mechanism involves the production of metabolites from probiotic fermentation, such as short-chain fatty acids (SCFAs). SCFAs have anti-inflammatory properties, influencing Ca-absorption by increasing cecal villi surface area and enhancing Ca-binding protein expression. They also regulate pH, improving Ca solubility and delivery to cells through the paracellular pathway, ultimately impacting bone density[37]. Experimental models further support the regulatory role of SCFAs in osteoclast metabolism and bone mass[38]. These findings underscore the potential of probiotic supplementation as an advantageous strategy for improving bone health and optimizing Ca absorption mechanisms, offering viable alternatives to traditional Ca and vitamin D therapies.

Probiotics pave the way for improved selenium absorption, offering a more effective route

The gut microbiota (GM) plays a pivotal role in shaping selenium (Se) status and selenoprotein (SeP) expression in mice, demonstrating its ability to sequester Se and limit host accessibility when Se levels are constrained[39]. Enriching the *Lactobacillus plantarum* strain with Se and Zn resulted in elevated blood Se levels and heightened antioxidant activity[40]. In rat studies, Se-enriched strains of Enterococcus faecium and Streptococcus thermophilus exhibited substantial potential to enhance Se absorption mechanisms, with SeCys prevailing in the liver and kidneys[41]. Administering Se-*B. longum* to rats demonstrated increased Se absorption and distribution into the pancreas compared to Na_2SeO_3 formulation, suggesting its potential for biotransforming inorganic Se into bioactive SePs and amino acids. While

Table 2 — Impact of probiotics in mineral absorption

Probiotic	Mineral	Type of the study	Outcome of the study
*La*Preschool going child*ctobacillus salivarius* (UCC 118) and *Bifidobacterium infantis* (UCC 35624)[26]	Calcium	*In vivo* Caco-2 cells	Calcium transport is significantly increased.
Lactobacillus and *Bifidobacterium*[27]	Calcium	*In vivo* Rat	Increase bone mineral density.
L. paracasei and *L. plantarum*[28]	Calcium	*In vivo* Mice	Trabecular number was increased .
L .plantarum[29]	Iron	*In vivo* Rat	Iron absorption increases 50 percent.
L. acidophilus[30]	Iron	*In vivo* Children	Increase MCHC concentration.
L .planterum[31]	Zinc	*In vivo* Chicken	Zn status significantly increased.
L. rhamnosus[32]	Magnesium	*In vivo* Rat model	Improved Mg absorption.
B. bifidum[33]	Magnesium	*In vivo* Rat model	Increased bio-availability of Mg
B. amyloloquefacicus[34]	Potassium	*In vivo* Pigs model	Positive impacts on Na+/K+-ATPase enzyme activity,that ultimately help in K balance.

Na_2SeO_3 showed a rapid reach of maximum absorbable concentration, organic Se formulations (selenized yeast and Se-*B. longum*) displayed more efficient absorption, accumulating and retaining Se in the blood for a longer duration. Co-administration of probiotics (*Lactobacillus acidophilus*, *Bifidobacterium bifidum*, and *Bifidobacterium longum*) with Se enhanced Se absorption in plasma for Alzheimer's patients, improving cognitive function[42]. Se-enriched probiotics, when incorporated into foods, not only facilitate digestion, absorption, and immunity but also serve as a rich organic Se source, meeting both nutritional and healthcare needs. Currently prevalent in the livestock industry, Se-enriched microorganisms aim to enhance meat product quality and offer organic Se conducive to human intestinal absorption[43].

Probiotics enhance zinc absorption, empowering the fortification with zinc

Recent research indicates that specific probiotics may enhance zinc (Zn) absorption through diverse mechanisms[44]. Some studies propose that Zn absorption from the diet can be heightened by the expression of specific proteins involved in Zn transport across the intestinal wall. Additionally, other studies suggest that Zn absorption may be mediated by the production of short-chain fatty acids (SCFAs), which lower the gut's pH, enhance Zn solubility, and absorption. Notably, investigations into Zn-enriched probiotics have shown promising outcomes. For instance, research on *Lactobacillus plantarum* enriched with Zn demonstrated increased blood Zn levels and enhanced antioxidant activity. Other strains like, *L. fermentum* were found to biotransform inorganic Zn into its organic form, facilitating absorption in Wistar rats. These findings highlight the potential of Zn-enriched probiotics as functional foods, offering a promising strategy to address Zn deficiency and related health issues[45]. In a study conducted by Cai et al., zinc and selenium were given to rotavirus enteritis child patients along with *Bifidobacterium* triple variable capsule probiotics for three days[46]. Probiotic along with zinc and selenium, successfully treated the condition and restored the level of cardiac enzymes.

Probiotics are emerging as facilitators for achieving optimal magnesium absorption

The intricate relationship between magnesium (Mg) and probiotics is an area that warrants further exploration, with existing studies offering insights into potential mechanisms. Notably, the *L. rhamnosus* strain HN001 demonstrated an improvement in calcium (Ca) and Mg absorption in rats, enhancing bone density after 12 weeks of daily intake[47]. Probable action mechanisms include the production of short-chain fatty acids (SCFAs), which lower intestinal pH and increase mineral solubility. SCFAs may also stimulate enterocyte proliferation, expanding the absorption area in the rat's large intestine and facilitating Ca and Mg absorption[48]. Additionally, probiotics might enhance Mg absorption by improving intestinal motility, increasing the time Mg is in contact with the gut lining for efficient absorption. Probiotics could also contribute to reducing gut inflammation, enhancing overall intestinal health, and improving nutrient absorption. The transcellular and paracellular pathways involved in Mg absorption are potential targets for probiotic influence, with studies suggesting that probiotics may enhance the expression and activity of transport proteins involved in Mg absorption and regulate the tightness of tight junctions[49]. While specific strains like *L. acidophilus* and *B. bifidum* have shown promise in improving Mg absorption, individual differences in gut microbiota composition and overall gut health may influence outcomes. The synergistic effect of probiotics and Mg in addressing conditions like SSRI-resistant depression emphasizes the potential therapeutic role of probiotics in enhancing Mg absorption and promoting overall well-being[50]. Moreover, the administration of functional foods containing prebiotics, probiotics, or symbiotics has demonstrated positive impacts on Mg status in bone composition and bone mineral density. However, it's crucial to consider factors such as dosage and duration of probiotic supplementation, as excessive or deficient Mg intake may lead to disruptions in the gut microbiota and subsequent health issues[51]. Future research is needed to unravel the complexities of the probiotic-Mg interaction, specifying optimal strains, doses, and duration for therapeutic efficacy.

Enhanced potassium absorption facilitated by probiotics

Probiotics may play a role in potassium (K) absorption through diverse mechanisms, potentially influencing gut microbiota composition and improving gut health. One such mechanism involves the regulation of tight junctions between gut epithelial cells, facilitating the paracellular transport of K ions[52]. Studies exploring the relationship between probiotics and K absorption reveal varying outcomes. For example, in lambs supplemented with *Bacillus subtilis*, the serum K concentration increased, correlating with improved growth performance. However, a double-blind study in chronic kidney disease patients with probiotic intervention showed minimal impact on K absorption. Other experiments with probiotic strains, such as *Lactobacillus casei Shirota* and *Bacillus amyloliquefaciens*, demonstrated enhanced serum K levels, possibly attributed to microbiota modulation and improved enzyme activity facilitating K absorption[51,52]. While probiotics, like *Lactobacillus rhamnosus*, showed increased K concentrations in certain dairy products, further research is essential to comprehend the precise mechanisms and validate the results for human applications. Despite promising evidence, optimizing probiotic use for K absorption requires more extensive investigation, considering individual gut microbiota differences and overall gut health[53].

Role of probiotics in Iron absorption

Iron is an essential micronutrient for humans. Its amount totally depends on heme and non-heme iron in the diet, physiological needs, and bioavailability. Several reports suggested that probiotics enhance iron absorption in humans by lowering the pH, activating phytates. This organic acid can chelate iron, and which can increase iron absorption. Recent research suggested that probiotics produce siderophore which help in iron chelation and increase iron availability (Fig. 1). Siderophore is a low molecular weight compound with a high affinity for ferric iron. Structurally, they are a varied group of compounds and mainly secrete three types of siderophores carboxylate, catecholate, and hydroxamate, named according to their functional groups[54]. Siderophore bacteria transported iron with the help of the TonB-ExbB-ExbD protein complex[55] and the ATP-binding cassette (ABC)transporter[56]. The most investigated probiotic microorganisms are *Lactobacillus*, *Bifidobacterium*, *Enterococcus*, and *S. boulardii* yeasts. An experimental study was conducted on the effect of multistrain probiotic supplementation on Fe metabolism in rats[57]. This study shows that multi-strain probiotic feeds rats have increased hemoglobin, serum iron concentration and related parameters that are also significantly higher than the control ones. Table 3 provides details on studies conducted on different probiotics and minerals, including dosage information.

Factors influencing probiotic effects on mineral absorption

Probiotic strain specificity in facilitating different mineral absorption

Various probiotic strains interact with minerals in distinct ways, resulting in different impacts on mineral absorption. Certain probiotic strains might produce specific enzymes that improve the absorption of particular minerals, whereas others may not[64]. For instance, phytase, produced by certain lactic acid bacteria strains increases bioavailability of minerals including Ca, Mg, Zn by breaking down phytic acids. Phytic acid, found in grains and seeds can bind to these minerals and make them less available for absorption[65]. Moreover, it was found that certain probiotic strains exhibit distinct interactions with particular minerals. For example, siderophoric probiotic strains like *L. plantarum*, *L. herbarum* positively influence Fe absorption, while Se absorption can be enhanced by *S. thermophilus*, *E. faecium*, *B. longum*. In addition, different probiotic strains can establish unique gut environments by modulating gut pH, producing metabolites, and competing with other microbes, which will impact mineral absorption. Therefore, it is important to select the right probiotic strain to maximize mineral absorption[63,66].

Table 3 — Dose and duration of co-supplementation of probiotics and minerals

Mineral	Probiotic	Dose and Duration	Study type
Calcium[58]	*Lactobacillus reuteri* DSM 17934 *Lactobacillus casei* CRL 431	Calcium 440 mg/day Probiotics 5×10^{8} CFU/day. 6 months	*In vivo* (Children)
Selenium[59]	*Enterococcus faecium* CCDM 922A *Streptococcus thermophilus* CCDM 144	Selenium 0.183-0.445 mg/kg Probiotics 10^{9}CFU/g. 58 days	*In vivo* (Rats)
Zinc[60]	*Bifidobacterium* sp. *Lactobacillus*, *Saccharomyces*, *Streptococcus* and *Enterococcus*	Zinc 50 mg/kg Probiotics 6×10^{9}CFU/g. 35 days	*In vivo* (Japanese quail)
Magnesium[61]	*Lactobacillus rhamnosus* (LGG®) *Bifidobacterium animalis* subsp. *Lactis* (BB-12®)	Magnesium 125 mg/day Probiotics 1.8×10^{10}CFU/cap. 9 wk	*In vivo* (Adult human)
Potassium[62]	*Lactobacillus acidophilus*	Potassium 5 g/kg and 10 g/kg Probiotics 1.47×10^{7}CFU/kg. 84 days	*In vivo* (Nile tilapia)
Iron[63]	*Lactobacillus plantarum* *Lactobacillus curvatus*	Iron 120 mg/kg Probiotics 5×10^{9}CFU/dose. 8 wk	*In vivo* (Rats)

Dosage of probiotic strains

Probiotics can adhere to the intestinal lining, compete with pathogenic bacteria for nutrients including minerals. However, the effectiveness of a probiotic strain in mineral absorption is dependent on the dosage of that probiotic strain. The ideal dose can change based on particular probiotic strains and individuals. While a higher dose of probiotics can inhibit pathogenic bacterial growth, influence gut mobility and transit time, and hence improve mineral absorption, a lower dose of probiotics reduces mineral absorption as certain metabolites like short chain fatty acids (SCFAs) are less produced. SCFAs facilitate mineral absorption by breaking down minerals into more soluble forms. The role of probiotic dosage on mineral absorption is not completely understood, and it depends on various factors like strain specificity, gut microbial composition, and type of minerals[37,65].

Probiotic administration timing

The efficacy of mineral absorption also depends on the timing of probiotic administration. For instance, taking probiotics with meals, on an empty stomach, or alongside antibiotics yields different benefits with respect to mineral absorption. The presence of food may provide a favourable environment for probiotic strains to survive and thus enhance mineral absorption. Taking probiotics on an empty stomach or with antibiotics may not give similar results. In addition, mineral metabolism and absorption can be dependent on circadian rhythms, a 24 h biological clock governing various body functions[67].

Efficacy across unique individuals

Individual differences, encompassing genetic factors, gut microbiota composition, and overall health status, contribute to the unique response to probiotics. Every individual has a unique gut microbiota that influences mineral absorption by a particular probiotic strain. Similarly, pre-existing genetic disorders, medication, and food habits also influence the metabolism and absorption of minerals. Moreover, recent studies revealed that nanoscale metal oxides induce Feton-like effects and oxidative stress, which may interfere with gut microbiota harmony and inhibit mineral absorption[68].

Conclusion

The clinical significance of probiotics in mineral absorption lies in their potential to address mineral deficits and improve nutritional outcomes. Probiotics, through their enzymatic activities and modulation of the gut environment, enhance the bioavailability of essential minerals. This has implications for bone health, particularly in populations vulnerable to osteoporosis. Probiotics could play a supportive role in clinical settings where mineral supplementation is prescribed, potentially optimizing nutrient therapy effectiveness. Individuals with gastrointestinal disorders affecting nutrient absorption may benefit from probiotics due to their ability to modulate the gut microbiota and reduce inflammation. Tailoring probiotic interventions to individual needs and characteristics is crucial. However, standardized protocols, guidelines, and further research are essential to fully harnessing the therapeutic potential of probiotics in preventing and treating mineral deficiencies across diverse populations. This comprehensive review underscores the pivotal role of essential minerals, including Ca, Se, Zn, Mg and K, in maintaining human health. The intricate involvement of the gut microbiota (GM) in mineral absorption is thoroughly examined, shedding light on the indispensable contribution of these microorganisms. Furthermore, the study delves into the potential impact of probiotics, presenting promising avenues to enhance mineral absorption. Specific sections dedicated to individual minerals and their connection to probiotics offer valuable insights, suggesting the incorporation of these beneficial bacteria into our diets. The research significantly contributes to unraveling the intricate interplay among GM, probiotics, and mineral absorption, deepening our understanding of how these factors collectively influence human health and nutrition. These findings hold substantial promise for developing strategies to address mineral deficiencies and promote optimal nutritional outcomes, paving the way for future exploration and research in this dynamic field. Besides, fermented foods that contain multi-strain food grade microbes and bioavailable minerals could be a useful alternative approach for co-supplementation of both probiotics and minerals. The review encourages continued investigation into the nuanced mechanisms underlying mineral absorption and the potential of probiotics to positively influence overall health and vitality.

Conflict of Interest

Authors declare no competing interests.

References

1 Das TK, Pradhan S, Chakrabarti S, Mondal KC & Ghosh K, Current status of probiotic and related health benefits. *Appl Food Res*, 2 (2022) 100185.

2 Ray M, Hor P, Singh SN & Mondal KC, Multipotent antioxidant and antitoxicant potentiality of an indigenous probiotic Bifidobacterium sp. MKK4. *J Food Sci Technol*, 58 (2021) 4795.

3 Hor PK, Ghosh K, Halder SK, Mondal S & Mondal KC, Evaluation of some effective potentialities of newly formulated rice fermented food using *Elephantopus scaber* L. rhizome as herbal starter. *Indian J Exp Biol*, 60 (2022) 701.

4 Banik A, Ghosh K, Pal S, Halder SK, Ghosh C & Mondal K, Biofortification of multi-grain substrates by probiotic yeast. *Food Biotechnol*, 34 (2020) 305.

5 Weyh C, Krüger K, Peeling P & Castell L, The role of minerals in the optimal functioning of the immune system. *Nutrients*, 14 (2022) 644.

6 Islam MR, Akash S, Jony MH, Alam MN, Nowrin FT, Rahman MM, Rauf A & Thiruvengadam M, Exploring the potential function of trace elements in human health: a therapeutic perspective. *Mol Cell Biochem*, 478 (2023) 2141.

7 Parua S, Ghosh K, Hor PK, Samanta S & Mondal KC, Dietotherapeutic potency of ornamental lentil dumpling, a traditional food preparation from South West Bengal, India. *Indian J Exp Biol*, 60 (2022) 713.

8 Jomova K, Makova M, Alomar SY, Alwasel SH, Nepovimova E, Kuca K, Rhodes CJ & Valko M, Essential metals in health and disease. *Chem Biol Interact*, 367 (2022) 110173.

9 Uddin SN, Rahaman MZ, Thammi TJ, Islam MR, Masud MI, Uddin MG & Islam MS, Low serum concentration of zinc, selenium, calcium, potassium and high serum concentration of iron, sodium are associated with myocardial infarction. *Aging Health Res*, 2 (2022) 100063.

10 Chen L, Min J & Wang F, Copper homeostasis and cuproptosis in health and disease. *Signal Transduct Target Ther*, 7 (2022) 378.

11 Rahman MM, Rahaman MS, Islam MR, Rahman F, Mithi FM, Alqahtani T, Almikhlafi MA, Alghamdi SQ, Alruwaili AS, Hossain MS & Ahmed M, Role of phenolic compounds in human disease: current knowledge and future prospects. *Molecules*, 27 (2021) 233.

12 Mandal M, Mishra NP, Chatterjee P, Bhattacharyya S, Mondal KC & Acharya S, A longitudinal study on the prevalence of iron deficiency anemia in the multiethnic communities of Jhargram, West Bengal. *Acta Biol Szeged*, 66 (2023) 180.

13 Ciosek Ż, Kot K, Kosik-Bogacka D, Łanocha-Arendarczyk N & Rotter I, The effects of calcium, magnesium, phosphorus, fluoride, and lead on bone tissue. *Biomolecules*, 11 (2021) 506.

14 Office of Dietary Supplements - Calcium. Available from: https://ods.od.nih.gov/factsheets/Calcium-Consumer/

15 Office of Dietary Supplements - Selenium. Available from: https://ods.od.nih.gov/factsheets/Selenium Consumer.

16 Minich WB, Selenium metabolism and biosynthesis of selenoproteins in the human body. *Biochemistry* (Moscow), 87 (2022) S168.

17 Office of Dietary Supplements - Zinc. Available from: https://ods.od.nih.gov/factsheets/Zinc-Consumer/

18 Praharaj S, Skalicky M, Maitra S, Bhadra P, Shankar T, Brestic M, Hejnak V, Vachova P & Hossain A, Zinc biofortification in food crops could alleviate the zinc malnutrition in human health. *Molecules*, 26 (2021) 3509.

19 Office of Dietary Supplements - magnesium. Available from: https://ods.od.nih.gov/factsheets/Magnesium-HealthProfessional/

20 Office of Dietary Supplements - Potassium. Available from: https://ods.od.nih.gov/factsheets/Potassium-Consumer/

21 Office of Dietary Supplements - Iron. Available from: https://ods.od.nih.gov/factsheets/Iron-Consumer/

22 Mondal S, Halder SK, Mondal KC, Revisiting soil-plant-microbes interactions: Key factors for soil health and productivity. *Trends of Applied Microbiology for Sustainable Econom*, (2022)125.

23 Karakan T, Tuohy KM & Janssen-van Solingen G, Low-dose lactulose as a prebiotic for improved gut health and enhanced mineral absorption. *Front Nutr*, 8 (2021) 672925.

24 Joudaki H, Aria N, Moravej R, Rezaei Yazdi M, Emami-Karvani Z & Hamblin MR, Microbial Phytases: Properties and Applications in the Food Industry. *Curr Microbiol*, 80 (2023) 374.

25 Hor PK, Pal S, Mondal J, Halder SK, Ghosh K, Santra S, Ray M, Goswami D, Chakrabarti S, Singh S & Dwivedi SZ, Takó M, Bera D & Mondal KC, Antiobesity, antihyperglycemic, and antidepressive potentiality of rice fermented food through modulation of intestinal microbiota. *Front Microbiol*, 13 (2022) 794503.

26 Fonseca HC, de Sousa Melo D, Ramos CL, Dias DR & Schwan RF, Probiotic properties of *lactobacilli* and their ability to inhibit the adhesion of enteropathogenic bacteria to Caco-2 and HT-29 cells. *Probiotics Antimicrob Proteins*, 13 (2021) 102.

27 Suliburska J, Harahap IA, Skrypnik K & Bogdański P, The impact of multispecies probiotics on calcium and magnesium status in healthy male rats. *Nutrients*, 13 (2021) 3513.

28 Myeong JY, Jung HY, Chae HS, Cho HH, Kim DK, Jang YJ & Park JI, Protective effects of the postbiotic *Lactobacillus plantarum* MD35 on bone loss in an ovariectomized mice model. *Probiotics Antimicrob Proteins*, 16 (2024) 541.

29 Skrypnik K, Schmidt M, Olejnik-Schmidt A, Harahap IA & Suliburska J, Influence of supplementation with iron and probiotic bacteria *Lactobacillus plantarum* and *Lactobacillus curvatus* on selected parameters of inflammatory state in rats on a high-fat iron-deficient diet. *J Sci Food Agric*, 104 (2024) 4411.

30 Gunawan DC, Juffrie M, Helmyati S & Rahayu ES, Synbiotic (*L. plantarum* Dad-13 and Fructo-oligosaccharide) powder on gut microbiota (L. plantarum, Bifidobacterium and Enterobacteriaceae) on stunting children in Yogyakarta, Indonesia. *Curr Res Nutr Food Sci J*, 10 (2022) 371.

31 MCiszewski A, Jarosz ŁS, Michalak K, Marek A, Grądzki Z, Wawrzykowski J, Szymczak B & Rysiak A, Proteome and Peptidome Changes and Zn Concentration in Chicken after In Ovo Stimulation with a Multi-Strain Probiotic and Zn-Gly Chelate: Preliminary Research. *Curr Issues Mol Biol*, 42 (2024) 1259.

32 García-Rodríguez A, Stillwell AA, Tochilovsky BV, Tanzman JV, Limage R, Kolba N, Tako E, Marques CN & Mahler GJ, The mechanistic effects of human digestion on magnesium oxide nanoparticles: implications for probiotics *Lacticaseibacillus rhamnosus* GG and *Bifidobacterium bifidum* VPI 1124. *Environ Sci Nano*, 9 (2022) 4540.

33 Zubareva OE, Dyomina AV, Kovalenko AA, Roginskaya AI, Melik-Kasumov TB, Korneeva MA, Chuprina AV, Zhabinskaya AA, Kolyhan SA, Zakharova MV & Gryaznova MO, Beneficial Effects of Probiotic *Bifidobacterium Longum* in a

Lithium–Pilocarpine Model of Temporal Lobe Epilepsy in Rats. *Int J Mol Sci*, 24 (2023) 8451.
34 Cao X, Tang L, Zeng Z, Wang B, Zhou Y, Wang Q & Zou P, Effects of probiotics BaSC06 on intestinal digestion and absorption, antioxidant capacity, microbiota composition, and macrophage polarization in pigs for fattening. *Front Vet Sci*, 7 (2020) 570593.
35 Chen Y, Xu J & Chen Y, Regulation of neurotransmitters by the gut microbiota and effects on cognition in neurological disorders. *Nutrients*, 13 (2021) 2099.
36 Zhou J, Cheng J, Liu L, Luo J & Peng X, *Lactobacillus acidophilus* (LA) Fermenting astragalus polysaccharides (aps) improves calcium absorption and osteoporosis by altering gut microbiota. *Foods*, 12 (2023) 275.
37 Varvara RA & Vodnar DC, Probiotic-driven advancement: Exploring the intricacies of mineral absorption in the human body. *Food Chem*, 21 (2023) 101067.
38 Srivastava RK, Sapra L & Mishra PK, Osteometabolism: metabolic alterations in bone pathologies. *Cells*, 11 (2022) 3943.
39 Callejón-Leblic B, Selma-Royo M, Collado MC, Abril N & García-Barrera T, Impact of antibiotic-induced depletion of gut microbiota and selenium supplementation on plasma selenoproteome and metal homeostasis in a mice model. *J Agric Food Chem*, 69 (2021) 7652.
40 Meng Y, Liang Z, Yi M, Tan Y, Li Z, Du P, Li A, Li C & Liu L, Enrichment of zinc in *Lactobacillus plantarum* DNZ-4: Impact on its characteristics, metabolites and antioxidant activity. *LWT - Food Sci Technol*, 153 (2022) 112462.
41 Krausova G, Kana A, Vecka M, Hyrslova I, Stankova B, Kantorova V, Mrvikova I, Huttl M & Malinska H, *In vivo* bioavailability of selenium in selenium-enriched *Streptococcus thermophilus* and *Enterococcus faecium* in CD IGS rats. *Antioxidants*, 10 (2021) 463.
42 Hu Y, Gao F, Kan S & Chen D, Selenium-enriched *Bifidobacterium longum* DD98 effectively ameliorates dextran sulfate sodium-induced ulcerative colitis in mice. *Front Microbiol*, 13 (2022) 955112.
43 Iqbal Z, Ahmed S, Tabassum N, Bhattacharya R & Bose D, Role of probiotics in prevention and treatment of enteric infections: A comprehensive review. *3 Biotech*, 11 (2021) 242.
44 Zhang S, Li Y, Wang P, Zhang H, Ali EF, Li R, Shaheen SM & Zhang Z, Lactic acid bacteria promoted soil quality and enhanced phytoextraction of Cd and Zn by mustard: A trial for bioengineering of toxic metal contaminated mining soils. *Environ Res*, 216 (2023) 114646.
45 Maares M, Keil C, Pallasdies L, Schmacht M, Senz M, Nissen J, Kieserling H, Drusch S & Haase H, Zinc availability from zinc-enriched yeast studied with an *in vitro* digestion/Caco-2 cell culture model. *J Trace Elem Med Biol*, 71 (2022) 126934.
46 Cai Y, Wang X, Li C, Li F, Yan Z, Ma N & Sun M, Probiotics combined with zinc and selenium preparation in the treatment of child rotavirus enteritis. *Am J Transl Res*, 14 (2022) 1043.
47 Suliburska J, Harahap IA, Skrypnik K & Bogdański P, The impact of multispecies probiotics on calcium and magnesium status in healthy male rats. *Nutrients*, 13 (2021) 3513.
48 Nogal A, Valdes AM & Menni C, The role of short-chain fatty acids in the interplay between gut microbiota and diet in cardio-metabolic health. *Gut Microbes*, 13 (2021) 1897212.
49 Lim AW, Talley NJ, Walker MM, Storm G & Hua S, Current status and advances in esophageal drug delivery technology: influence of physiological, pathophysiological and pharmaceutical factors. *Drug Deliv*, 30 (2023) 2219423.
50 Fan Y & Pedersen O, Gut microbiota in human metabolic health and disease. *Nat Rev Microbiol*, 19 (2021) 55.
51 Mazziotta C, Tognon M, Martini F, Torreggiani E & Rotondo JC, Probiotics mechanism of action on immune cells and beneficial effects on human health. *Cells*, 12 (2023) 184.
52 Włodarczyk M & Śliżewska K, Obesity as the 21st Century's major disease: The role of probiotics and prebiotics in prevention and treatment. *Food Biosci*, 42 (2021) 101115.
53 Cunningham M, Azcarate-Peril MA, Barnard A, Benoit V, Grimaldi R, Guyonnet D, Holscher HD, Hunter K, Manurung S, Obis D & Petrova MI, Shaping the future of probiotics and prebiotics. *Trends Microbiol*, 29 (2021) 667.
54 Khasheii B, Mahmoodi P & Mohammadzadeh A, Siderophores: Importance in bacterial pathogenesis and applications in medicine and industry. *Microbiol Res*, 250 (2021) 126790.
55 Goswami D, Halder SK & Mondal KC, Characterization of siderophore from probiotic Bacillus spp. strain isolated from traditional fermented food of the Himalaya. *Syst Microbiol Biomanufacturing*, 2024 (2024)
56 Goswami D, Mondal S, Hor PK, Santra S, Jana H, Gauri SS, Halder SK & Mondal KC, Bioprospecting of probiotic bacteria from traditional food of high-altitude Himalayan region. *Food Biosci*, 57 (2024) 103257.
57 Skrypnik K, Bogdański P, Sobieska M, Schmidt M & Suliburska J, Influence of multistrain probiotic and iron supplementation on iron status in rats. *J Trace Elem Med Biol*, 68 (2021)126849.
58 Setiawan EA, Rianda D, Kadim M, Meilianawati, Susanto F, Kok FJ, Shankar AH & Agustina R, Tenth year reenrollment randomized trial investigating the effects of childhood probiotics and calcium supplementation on height and weight at adolescence. *Sci Rep*, 11 (2021) 11860.
59 Norouzi S, Daneshyar M, Farhoomand P, Tukmechi A & Tellez-Isaiasc G, *In vitro* evaluation of probiotic properties and selenium bioaccumulation of lactic acid bacteria isolated from poultry gastrointestinal, as an organic selenium source. Res *J Vet Sci*, 162, (2023) 104934.
60 Saeeda K, Chand N, Khan NU, Saeed M & Khan RU, Dietary organic zinc and probiotic alleviate induced *Eimeria tenella* infection in Japanese quails model of coccidiosis. *Trop Anim Health Prod*, 55 (2023) 37.
61 Mahboobi S, Ghasvarian M, Ghaem H, Alipour H, Alipour S & Eftekhari MH, Effects of probiotic and magnesium co-supplementation on mood, cognition, intestinal barrier function and inflammation in individuals with obesity and depressed mood: a randomized, double-blind placebo-controlled clinical trial. *Front Nutr*, 9 (2022) 1018357.
62 Hassaan MS, El-Sayed AM, Mohammady EY, Zaki MA, Elkhyat MM, Jarmołowicz S & El-Haroun ER, Eubiotic effect of a dietary potassium diformate (KDF) and probiotic (*Lactobacillus acidophilus*) on growth, hemato-biochemical indices, antioxidant status and intestinal functional topography of cultured Nile tilapia Oreochromis niloticus fed diet free fishmeal. *Aquaculture*, 533 (2021) 736147.

63 Barkhidarian B, Roldos L, Iskandar MM, Saedisomeolia A & Kubow S, Probiotic supplementation and micronutrient status in healthy subjects: A systematic review of clinical trials. *Nutrients*, 13 (2021) 3001.

64 Manzoor S, Wani SM, Mir SA & Rizwan D, Role of probiotics and prebiotics in mitigation of different diseases. *Nutrition*, 96 (2022) 111602.

65 Sandroni A, House E, Howard L & DellaValle DM, Synbiotic supplementation improves response to iron supplementation in female athletes during training. *J Diet Suppl*, 19 (2022) 366.

66 Bielik V & Kolisek M, Bioaccessibility and bioavailability of minerals in relation to a healthy gut microbiome. *Int J Mol Sci*, 22 (2021) 6803.

67 Karakan T, Tuohy KM & Janssen-van Solingen G, Low-dose lactulose as a prebiotic for improved gut health and enhanced mineral absorption. *Front Nutr*, 8 (2021) 672925.

68 Fuloria S, Mehta J, Talukdar MP, Sekar M, Gan SH, Subramaniyan V, Rani NN, Begum MY, Chidambaram K, Nordin R & Maziz MN, Synbiotic effects of fermented rice on human health and wellness: a natural beverage that boosts immunity. *Front Microbiol*, 13 (2022) 950913.