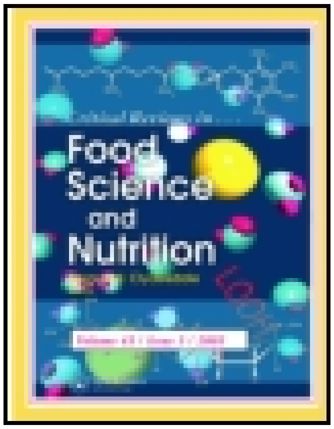

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Bioavailability of Micronutrients from Plant Foods: An Update

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Bioavailability of Micronutrients from Plant Foods: An Update

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Abstract

Deficiencies of iron, zinc, iodine and vitamin A are widespread in the developing countries, poor bioavailability of these micronutrients from plant-based foods being the major reason for their wide prevalence. Diets predominantly vegetarian are composed of components that enhance as well as inhibit mineral bioavailability, the latter being predominant. However, prudent cooking practices and use of ideal combinations of food components can significantly improve micronutrient bioavailability. Household processing such as heat treatment, sprouting, fermentation and malting have been evidenced to enhance the bioavailability of iron and β-carotene from plant foods. Food acidulants *amchur* and lime are also shown to enhance the bioavailability of not only iron and zinc, but also of β-carotene. Recently indentified newer enhancers of micronutrient bioaccessibility include sulphur compound-rich *Allium* spices ī onion and garlic, which also possess antioxidant properties, β-carotene-rich vegetables ï carrot and amaranth, and pungent spices ī pepper (both red and black) as well as ginger. Information on the beneficial effect of these dietary compounds on micronutrient bioaccessibility is novel. These food components evidenced to improve the bioavailability of micronutrients are common ingredients of Indian culinary, and probably of other tropical countries. Fruits such as mango and papaya, when consumed in combination with milk, provide significantly higher amounts of bioavailable ϐ-carotene. Awareness of the beneficial influence of these common dietary ingredients on the bioavailability of micronutrients would help in devising dietary strategies to improve the bioavailability of these vital nutrients.

Key words: Bioavailability, Plant foods, Micronutrients, Iron, Zinc, ϐ-carotene, Newer enhancers of bioavailability

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INTRODUCTION

Deficiency of micronutrients, especially iron, iodine, vitamin A and zinc, are widely prevalent not only in developing countries, but also in the developed countries. Micronutrient deficiencies are often known as ôhidden hungerö, since they are less visible than deficiencies of macronutrients such as protein and energy. Micronutrient deficiencies, especially nutritional anemia, iodine deficiency disorders and vitamin A deficiency have been a cause for concern in developing countries.

The prevalence of iron deficiency in India is widespread, and almost 79% of children between 6 and 35 months and women between 15 and 49 years of age are anemic (Krishnaswamy, 2009). Although the prevalence of severe forms of vitamin A deficiency such as corneal xerophthalmia has declined in India over the past 2ï 3 decades, sub-clinical deficiency of this vitamin is reported to be prevalent in around 60% of preschool children, indicating that this deficiency is indeed widespread in the country (Vijayaraghavan, 2009). The universal iodization of salt in India has brought about a decline in iodine deficiency to a large extent. The prevalence of Iodine Deficiency Disorders (IDD) among children in 15 districts studied recently in India has shown a significant decline; the overall prevalence of goiter being 4.8% (Toteja et al., 2004). However, the deficiency of iodine continues to be a problem in some parts, especially the hilly regions and the sub-Himalayan regions of India. The overall prevalence of goiter in the Jammu region was nearly 12% (Bhat et al., 2008); while the sub-Himalayan Tarai region of Uttar Pradesh had a high prevalence of goiter (30%) (Chandra et al., 2008).

Although not fully assessed, zinc deficiency is believed to be as widespread as that of iron, and is a cause for concern especially in the developing countries (Prasad, 2003). A recent study on the prevalence of zinc deficiency among children aged 6 months to 5 years from five representative states of India revealed that the overall prevalence of zinc deficiency was 43.8% (Kapil and Jain, 2011). Deficiency of zinc has been included as a major risk factor to the global burden of diseases along with deficiencies of iron, iodine and vitamin A (Ezzati et al., 2002).

While inadequate intake of iron is an important cause for this high prevalence, the poor bioavailability of iron from plant-based foods contributes significantly to this problem (Purushothaman, et al., 2008; Rao and Prabhavathi, 1983). Minerals and trace elements such as calcium, iron and zinc are inefficiently absorbed from the diet, and the absorption could be as low as less than 1% for iron (Fairweather-Tait, 1997). The bioavailability of iron from a typical cereal-pulse based diet, as commonly consumed in India, is rather low, i.e., nearly 3%, and the intake of foods rich in iron absorption promoters is inadequate (Rao and Prabhavathi, 1983). Apart from inherent factors such as phytate, tannin, and fibre that negatively influence the bioavailability of minerals from food grains, the same may also be influenced by processing, such as cooking, that these food grains undergo before their consumption.

A majority of the population in India is dependent on plant foods, which provide carotenes, especially ϐ-carotene, to meet their requirement of vitamin A. ϐ-Carotene is abundantly found in green leafy and yellow-orange vegetables (Gopalan et al., 1999). Several factors such as diet composition and methods employed for food processing affect the bioavailability of ϐ-carotene from foods. Dietary factors such as fat, fibre and protein are documented to influence β-carotene bioavailability (Yeum and Russel, 2002).

The diets commonly consumed in India and probably other developing countries contain a variety of food grains and vegetables, and the daily culinary practices involve several domestic processing methods such as heating, sprouting and fermentation. The combination of various food ingredients as well as the culinary practices may thus have a significant influence on the bioavailability of micronutrients from plant-based diets. Based on the available knowledge, it would be prudent to evolve food-based strategies to maximize the bioavailability of micronutrients from these diverse diets. The present review focuses on the bioavailability of micronutrients from plant-based foods.

Iodine

Under normal conditions, the absorption of dietary iodine is >90%. Bioavailability of iodine from diets rich in dairy products is reported to be around 95% as indicated by a balance study in women with adequate iodine status (Jahreis et al., 2001). The high prevalence of iodine deficiency in the sub-Himalayan region of India, which was a moderately iodine deficient zone as indicated by the iodine content of drinking water, was attributed to the high consumption of cyanogenic foods such as cabbage, cauliflower, radish, etc, which could be an additional factor contributing to the high prevalence of iodine deficiency (Chandra et al., 2008). Thus, bioavailability of dietary iodine does not seem to be of concern; rather, deficient intakes of iodine and / or high intake of cyanogenic foods seem to be risk factors for iodine deficiency.

Iron and zinc

Bioavailability of micronutrients, particularly iron and zinc, is low from plant foods, being influenced by various dietary components, which include both inhibitors and enhancers of their absorption. Among inhibitors, phytic acid, tannins, dietary fibre and calcium are the most potent, while organic acids are known to promote iron absorption (Gibson, 1994; Sandberg, 2002). Recent studies have shown that the bioavailability of zinc from food grains is similarly influenced by the above dietary factors (Hemalatha et al., 2007a).

Bioavailability of iron and zinc from plant foods and composite meals

In an early study, several foods commonly consumed in India were screened for iron bioavailability using an *in vitro* method (Rao and Prabhavathi, 1978). The percent iron bioavailability ranged from 7.1 in pearl millet (*Pennisetum glaucum*) to 15.0 in rice (*Oryza sativa*) among the cereals and millets, and from 7.6 in cowpea (*Vigna catjang*) to 22.0 in chickpea (*Cicer arietinum*) among the pulses. These values differed greatly from those subsequently reported by Annapurani & Murthy (1985), using the same *in vitro* procedure. Recently, several commonly consumed cereals and pulses were screened for the bioaccessibility of iron, employing the simulated gastrointestinal digestion method, involving equilibrium dialysis (Hemalatha et al., 2007a). The values obtained from these three studies (Table 1) vary widely. These differences could probably be attributed to the procedure employed for determination, and regional differences in the food grains examined.

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Data on the bioavailability of zinc from foods commonly consumed in India is limiting. Hemalatha et al. (2007a) determined the bioaccessibility of zinc from several cereals and pulses using the equilibrium dialysis method with simulated gastrointestinal digestion. The bioaccessibility of zinc from cereals ranged from 5.5% in sorghum (*Sorghum vulgare*) to 21.4% in rice, while that from pulses ranged from 27% in whole green gram (*Phaseolus aureus*) to 56.5% in decorticated chickpea. Bioaccessibility of zinc from pulses was generally higher than that from cereals. This was attributed to the lower negative influence of the various inherent factors such as phytate, calcium and dietary fibre on zinc bioaccessibility from pulses (Hemalatha et al., 2007a). These researchers also observed that the bioaccessibility of zinc from food grains was higher than that of iron, this difference being more prominent in the case of pulses; while the bioaccessibility of iron from cereals ranged from 4% in sorghum to 8% in rice, zinc bioaccessibility ranged from 5.5% in sorghum to 21% in rice. Iron bioaccessibility in pulses was between 1.8% (cowpea; *Vigna catjung*) and 10.2% (French bean; *Phaseolus vulgaris*) and that of zinc ranged from 27% in whole green gram to as high as 56.5% in decorticated chickpea. This indicates that bioaccessibility of zinc is probably less influenced by dietary factors than that of iron.

Cereals and pulses are often consumed as a part of a complex meal which also consists of various ingredients such as common salt, food acidulants, vegetables, fat and spices. It is possible that these ingredients might have an influence on bioavailability of minerals from the meal. It would thus be more appropriate to examine the bioaccessibility of minerals from composite meals, in addition to constituent food grains individually.

Early iron absorption studies from traditional Indian diets using the extrinsic tag method in adult men revealed that the mean iron absorption from a single meal ranged from 0.8 to 4.5% depending on the type of staple. The absorption of iron from millet-based diets was the lowest (0.8 ï 0.9%), while it was highest from rice-based diets (4 ï 5%) (Rao et al., 1983). Pushpanjali and Khokhar (1996) determined the *in vitro* iron and zinc availability from sixty vegetarian diets consumed by Indian children, adolescents, adults and older adults. They reported that the availability of these minerals from the diets was very poor, ranging from 3.3 to 4.4% in the case of iron, and from 7.8 to 8.7% for zinc. The poor mineral availability was attributed to the high content of phytates and dietary fibre in these diets, which were predominantly based on cereals.

More recently, the bioaccessibility of iron and zinc from representative composite meals based on the staple grains commonly consumed in India was determined employing the simulated gastrointestinal digestion method with equilibrium dialysis [Bhavyashree et al., 2009]. Finger millet (*Eleucine coracana*)-based meal had the lowest bioaccessibility of iron (1.5%), followed by rice- (2.5%), sorghum- (3.5%) and wheat (*Triticum aestivum*)-based (4.7%) meals. On the contrary, bioaccessibility of zinc was the lowest in the sorghum-based meal, being as low as 0.31%, and highest in the rice-based meal (8.5%), followed by wheat- and finger millet-based meals (5.8 and 1.6%, respectively). Despite similar concentration of iron and zinc in both the rice-based and finger millet-based meals, bioaccessibility of both these minerals was lower from the finger millet-based meal. The authors attributed this to the higher tannin content in finger millet, which could be the only variation in these two meals, their composition being almost similar. The composition of all the four meals was similar to that commonly used in Indian households (Bhavyashree et al., 2009).

Influence of domestic food processing on bioavailability of iron and zinc from plant foods

Any food that we consume is normally subjected to some form of processing; the exceptions being fruits and certain vegetables. Processing generally brings about alterations in the food matrix as well as in the inherent components of foods, thus probably affecting the bioavailability of nutrients, including minerals. Processing methods commonly employed at the domestic level include heat processing, sprouting and fermentation.

Heat processing

Food processing by heat is generally known to improve the digestibility of macronutrients such as carbohydrates and proteins, by softening and loosening the food matrix, thereby increasing the accessibility of these nutrients to the digestive enzymes. Softening of the food matrix is also believed to release the protein-bound minerals such as iron, thereby facilitating their absorption (Lombardi-Boccia et al., 1995). Moreover, heat processing is also likely to alter the inherent factors that inhibit mineral absorption such as phytate and soluble dietary fibre, thus improving the bioavailability of minerals.

Prabhavathi and Rao (1979) reported that boiling rice and pulse and roasting whole wheat on a griddle without fat did not have any effect on ionisable iron. These authors also observed that the ionisable iron content of parboiled rice was lower than that of raw rice, despite a higher content of inherent iron in the former. Thus, parboiling does not seem to have affected the bioavailability of iron.

Heat processing of food grains has been reported to produce contrasting effect on the bioaccessibility of iron and zinc (Hemalatha et al., 2007b). Pressure-cooking and microwave -heating improved the bioaccessibility of iron from cereals and pulses, while that of zinc was significantly reduced. The bioaccessibility of iron from pressure-cooked cereals ranged from 7% in wheat to 12% in the case of rice, these values being significantly higher than those of the corresponding raw cereals. Microwave-heating brought about an even greater increase in iron bioaccessibility. Similar trends were observed in the pressure-cooked and microwave-heated pulses (Hemalatha et al., 2007b). On the other hand, zinc bioaccessibility from food grains was considerably reduced upon pressure-cooking, this effect being more prominent in the case of pulses. Pressure-cooking decreased zinc bioaccessibility by 63% and 57% in finger millet and rice, respectively, while such a decrease in zinc bioaccessibility was evident in the case of almost all the pulses examined, the percent decrease ranging from 11.4 in whole chickpea to 63 in cowpea (Hemalatha et al., 2007b). This is probably the only report on the influence of heat processing on bioaccessibility of zinc.

Sprouting and fermentation

Idli, dosa and *dhokla*, the products prepared from combinations of cereals and pulses that are ground and fermented overnight are popular breakfast items in India. Similarly, legumes such as chickpea, green gram, etc. are germinated and consumed in either the cooked or raw form in most parts of India. Thus, germination and fermentation are the two commonly employed domestic food processing methods.

Germination and fermentation are known to improve mineral bioavailability by reducing the inherent factors such as phytic acid, which inhibit mineral bioavailability (Gibson and Hotz, 2001; Kaur and Kawatra, 2002; Duhan et al., 2004). Besides reducing such factors, fermentation probably has the added advantage of the formation of organic acids, which form soluble ligands with the minerals, thus rendering them more bioavailable.

Soaking of the grains is a prerequisite for germination. Kaur and Kawatra (2002) reported higher retention of zinc in bone, liver, spleen and kidney of rats fed dehulled, soaked and pressure-cooked ricebean (*Vigna umbellata*), followed by germinated and pressure-cooked grain, compared to raw grain. Soaking horse gram (*Dolichos biflorus*) and moth bean (*Phaseolus aconitifolius*) was reported to significantly reduce phytate and tannin levels and thus bring about a significant increase in *in vitro* iron availability. Degradation of the phytate and tannins was more pronounced after germination of the same grains for 24 h (Chopra and Sankhala, 2004). Soaking of pigeon pea (*Cajanus cajan*) for 12 h brought about the maximum increase in HCl-extractability of zinc, followed by germination (48 h), and germination (36 h) and pressure-cooking (Duhan et al., 2004). Hemalatha et al. (2007c), however, did not find any improvement on the bioaccessibility of iron and zinc from green gram, chickpea and finger millet upon soaking of these grains. Germination of these grains for 48 h, on the other hand, produced contrasting effects on iron and zinc bioaccessibility. While iron bioaccessibility was increased by 62% (green gram), 39% (chickpea) and 20% (finger millet), concomitant with a reduction in tannin content, zinc bioaccessibility from these grains was significantly decreased as a result of germination. The absence of any increase in zinc bioaccessibility upon germination of the tested food grains in this study was consistent with a lack of significant reduction of phytate content of these grains (Hemalatha et al., 2007c). Ghadivel and Prakash (2007) reported that germination brought about significant increase in *in vitro* iron availability from green gram, cowpea, lentil (*Lens esculenta*) and chickpea. Dehulling of the germinated legumes further increased iron availability. The beneficial effect of germination was attributed to the decrease in phytate and tannin content as a result of germination and dehulling (Ghadivel and Prakash, 2007).

In one of the earlier studies on the influence of food processing on *in vitro* iron availability, Prabhavathi and Rao (1979) have reported that fermentation of rice and black gram (*Phaseolus mungo*) mixture and subsequent cooking (as in the preparation of *idli*) did not result in any change in the ionizable iron content. More recent studies in our laboratory revealed that the fermented batter of rice: black gram 2:1 and 3:1 as in the preparation of *idli* and *dosa*, respectively, had higher bioaccessibility values for zinc (71 and 50%, respectively), while iron bioaccessibility values were increased in these cases of fermentation to an even greater extent (277 and 127%, respectively) (Hemalatha et al., 2007c). However, zinc and iron bioaccessibility was not improved by fermentation of the combination of chickpea, green gram, black gram and rice (1:1:0.5:0.5) as in the preparation of *dhokla*. A fermentation of cerealï legume combinations of *idli* and *dosa* batter significantly reduced both phytate and tannin, while such a reduction was not evident in the case of *dhokla* batter (Hemalatha et al., 2007c).

Malting

Malted grains are extensively used in weaning and geriatric foods as malting generally improves the nutrient content and digestibility of foods. Roasting and malting of wheat, barley (*Hordeum vulgare*), and green gram in the preparation of weaning foods was found to increase the bioavailability of iron by 16-32%. This effect was more pronounced in malted weaning foods compared to roasted ones {Gahlawat & Sehgal, 1994). It has been reported that using a malting process to decrease phytic acid in oats resulted in increased zinc and iron absorption in adult subjects (Larsson et al., 1996).

We recently evidenced a significant increase in the bioaccessibility of iron as a result of malting wheat and finger millet (Platel et al., 2010). Malting increased the bioaccessibility of iron by >3-fold from two varieties (brown and white) of finger millet and by >2-fold from wheat, whereas such a beneficial influence was not seen in malting of barley. The bioaccessibility of zinc, on the other hand, was increased to an extent of 234 and 100% from wheat and barley, respectively. However, the bioaccessibility of zinc was decreased from the malted finger millet varieties. The beneficial effect of malting on the bioaccessibility of iron and zinc was attributed to the combined effects of soaking, germination and heat treatment (Platel et al., 2010).

Influence of inherent dietary factors on iron and zinc bioavailability

Bioavailability of iron is known to be influenced by various dietary components, which include both inhibitors and enhancers of absorption. Among inhibitors, phytic acid, tannins, dietary fibre and calcium are the most potent, while organic acids are known to promote iron absorption (Gibson, 1994; Sandberg, 2002). These factors coexist along with the mineral in foods. It is possible that the bioavailability of zinc from food grains is similarly influenced by such diverse factors coexistent in them. Cereals and pulses are known to contain high concentrations of one or more of the above inhibitors of iron absorption. A majority of the Indian population are vegetarian; hence plant-based foods are the major providers of important minerals such as iron and zinc. However, these foods also contain substantial amounts of inhibitors of mineral absorption such as phytates and tannins. It would therefore be relevant to discuss the influence of these factors on the bioavailability of iron and zinc from plant foods.

Iron and phytate content are reported to be negatively correlated to *in vitro* iron availability from representative Indian composite diets. Diets containing rice as the staple were found to have higher iron availability than those that contained pearl millet as the staple. This was attributed to the high phytate content of pearl millet, compared with that of rice (Nair and Iyengar, 2009).

Extensive studies in our laboratory on the influence of inherent factors on the bioaccessibility of iron and zinc revealed a significant negative correlation between inherent phytate content and zinc dialyzability value in the case of pulses, while this negative effect was not significant in the case of cereals (Hemalatha et al., 2007a). However, when the negative influence of phytic acid on zinc bioaccessibility was viewed in terms of the phytate: zinc molar ratio present in the grain, a negative correlation of zinc bioaccessibility was apparent with an increase in this ratio from 14.7 in rice to 23.9 in finger millet, while a further increase in this ratio, even up to 37.5 in wheat, had no corresponding negative effect. A similar trend was observed in pulses up to a phytate: zinc molar ratio of 22.8, beyond which the negative trend was not seen. In the case of iron, phytic acid content of the cereal grains produced a significant negative influence on its bioaccessibility; however, a similar negative influence of phytate on iron bioaccessibility from pulses was not evident (Hemalatha et al., 2007a).

A decreasing trend in zinc bioaccessibility from cereals was observed with an increase in inherent calcium concentration of these grains. However, this trend was not significant, and it was inferred that the calcium levels normally found in mixed diets are unlikely to bring about a phytate-induced decrease in zinc bioaccessibility (Hemalatha et al., 2007a). When zinc bioaccessibility from various food grains was viewed in terms of molar ratio: [phytate] X [calcium]/[zinc], a slight decrease in zinc bioaccessibility from both cereals and pulses was generally evidenced, as this ratio increased. Such an inverse relationship of calcium was, however, not evident for iron bioaccessibility values when the same were viewed in relation to calcium inherent in the grain, as well as the [phytate] X [calcium]/ [iron] molar ratio [Hemalatha et al., 2007a]. A [phytate] X [calcium]/[iron] molar ratio between 150 and 200 has been suggested as being critical in inhibiting the bioavailability of zinc from human diets (Cossack & Prasad, 1983). The [phytate] X [calcium]/[zinc] ratios of the food grains employed in the study by Hemalatha et al. (2007a) were below 65, except in finer millet which had a ratio of 190. Zinc and iron dialyzabilities were enhanced when the phytate was partially removed from grains by treatment with fungal phytase, which supported the negative correlation of inherent phytic acid with dialyzability of these minerals (Hemalatha et al., 2007a).

Tannin did not have any significant influence on either zinc or iron dialyzability from both cereals and pulses. Insoluble dietary fibre interfered with iron dialyzability, while both the insoluble and soluble fractions of dietary fibre had this negative effect on zinc dialyzability (Hemalatha et al., 2007a).

Influence of exogenous factors on iron and zinc bioavailability

Indian culinary involves the use of additives to enhance the organoleptic properties of the foods. These additives include acidulants such as lime (*Citrus aurantifolia*), *amchur* (dry mango powder (*Mangifera indica*), tamarind (*Tamarindus indica*), kokum (*Garcinia indica*), etc. Spices are an inseparable part of Indian diets, being used as food adjuncts since times immemorial. It is possible that these components added exogenously could influence the bioavailability of iron and zinc from the diets.

Organic acids such as citric, malic, tartaric, and ascorbic acid are well known to have a significant enhancing influence on iron bioavailability. Information on the effect of organic acids on zinc bioavailability is limiting. The food acidulants that are commonly employed in Indian culinary, namely lime, *amchur*, tamarind and kokum are sources of one or the other organic acid. Hemalatha et al. (2005) examined the effect of these common acidulants on the bioaccessibility of zinc and iron from food grains. Among the four acidulants examined, amchur and citric acid (the major acid present in lime) generally enhanced the bioaccessibility of zinc and iron from all the food grains studied. The increase in zinc bioaccessibility produced by citric acid ranged from 11 to 44%; citric acid brought about a higher increase in the bioaccessibility of iron from the food grains examined, the percent increase ranging from 30 to 86%, in both raw and cooked grains (Hemalatha et al., 2005). The acidulants were included at a level that decreased the pH of the medium by 1 unit. Tamarind and kokum, which are also sources of organic acids (tartaric acid in tamarind and hydroxycitric acid in kokum), however did not produce a similar increase in iron and zinc bioaccessibility; on the other hand, these two acidulants significantly lowered the bioaccessibility of these minerals from the food grains. This negative effect was attributed to the high content of tannin in both tamarind and kokum, which dominated over the beneficial effect of the constituent acids.

A similar dominating effect of tannin was evidenced when the fruit of *Emblica officinalis*, a rich source of ascorbic acid, was studied for a beneficial effect on mineral accessibility (Gowri et al., 2001). Representative cereals, pulses and combinations of these grains were examined for a possible effect of amla fruits on the bioaccessibility of iron. *Emblica* fruits did not exert any beneficial enhancing effect on iron bioaccessibility from any of the food grains studied, while an equivalent amount of pure ascorbic acid brought about a significant increase in the same. This absence of any beneficial effect of *Emblica* fruit was attributed to the high tannin content (which was nearly half the concentration of ascorbic acid) in these fruits, which countered any beneficial effect of the inherent ascorbic acid (Gowri et al., 2001). Thus, the acidulants citric acid, the constituent acid of lime, and *amchur* seem to be potential enhancers of iron and zinc bioaccessibility.

In view of a report that vitamin A and β-carotene can enhance non-heme iron absorption from food grains (Gracia-Casal et al., 1998), we recently examined carrot (*Daucus carota*) and amaranth (*Amaranthus gangeticus*), rich sources of β-carotene, for a possible effect on the bioaccessibility of iron and zinc from food gains. Curcumin, the principal phytochemical of turmeric (*Curcuma longa*), which is structurally somewhat similar to β-carotene, was also evaluated for its influence on zinc and iron bioaccessibility from food grains (Gautam et al., 2010a). Addition of carrot or amaranth at two levels (2.5 g and 5 g per 10 g of grain) significantly enhanced the bioaccessibility of iron and zinc from the food grains, the range of percent increase being 13.8ï 86.2 in the case of carrot and 11ï 193 in the case of amaranth. The magnitude of this positive effect was maximal with the level of vegetable sources corresponding to 200 µg β-carotene per 10 g of grain. This is the first report on the beneficial influence of β-carotene on iron and zinc bioaccessibility. Curcumin, on the other hand, exerted a beneficial enhancing effect only on iron bioaccessibility (Gautam et al., 2010a).

Dietary sulfur-containing amino acids have been reported to improve the mineral status of experimental animals (Greger and Mulvaney, 1985). In view of this, *Allium* spices onion (*Allium cepa*) and garlic (*Allium sativum*), which are rich in sulphur-containing compounds, were examined for a possible beneficial influence on the bioaccessibility of iron and zinc from food grains (Gautam et al., 2010b). Two representative cereals and pulses were studied in this context, employing two levels of dehydrated garlic (0.25 and 0.5 g/10 g of grain) and dehydrated onion (1.5 and 3 g/10 g of grain). These two spices generally enhanced iron bioaccessibility from both cereals and pulses, the percent increase in iron bioaccessibility ranging from 9 to 66 in cereals, and from 10 to 73 in pulses. A similar enhancing effect was also seen on zinc bioaccessibility, the extent of increase in cereals ranging from 10 to 159% and in pulses from 10 to 50%. Thus, both garlic and onion were evidenced to have a significant promoting influence on the bioaccessibility of iron and zinc from food grains, when included at levels normally encountered during cooking. This effect was evident even when the grains were cooked in the presence of the two *Allium* spices (Gautam et al., 2010b).

As mentioned earlier, foods are often consumed in combination in the form of composite diets. Hence it is possible that such diets would contain combinations of different enhancers, or of inhibitors and enhancers of mineral bioavailability together. These components are not only inherent in the food grains used in the preparation of the diets, but could also be added exogenously in the form of adjuncts. It would thus be meaningful and relevant to know the effect of combinations of these modulators of mineral availability. In this context, we recently examined specific combinations of promoters of iron and zinc bioaccessibility, namely, *amchur*, β-carotene-rich vegetables and *Allium* spices for a possible additive/synergistic effect on the bioaccessibility of iron and zinc from food grains (Gautam et al., 2011a). The positive influence on the bioaccessibility of iron was additive in the case of combinations of *amchur* with carrot, and with garlic, and combinations of onion with carrot, and with amaranth in a few specific grains. A synergistic influence was evidenced in a few grains for combinations of *amchur* with onion and with garlic. In the case of zinc bioaccessibility, the influence of *amchur* + garlic and *amchur* + onion was additive while the combination of *amchur* + amaranth and *amchur* + garlic produced a synergistic promoting influence on zinc bioaccessibility in a few instances (Gautam et al., 2011a). Cooking of vegetables along with onion or garlic is a common practice in Indian households, thus this could be encouraged as a prudent means of increasing mineral bioavailability.

In another study, we verified whether promoters of mineral bioavailability would counter the negative effects of phytate and tannin on the same from grains, when present together (Gautam et al., 2011b). Combinations of promoters ï *amchur*, carrot and onion with phytic acid and tannin exogenously added individually were examined for their influence on iron and zinc bioaccessibility from the food grain. The beneficial effect of the promoters was generally dominant in the presence of either phytic acid or tannic acid. The negative effect of the inhibitor was not only annulled, but also the positive influence of the promoter was fully retained. This beneficial effect of the promoters in countering the negative effect of the inhibitors was evidenced in both raw and cooked grains (Gautam et al., 2011b). Thus, it would be desirable to include promoters of mineral bioavailability such as acidulants, β-carotene-rich vegetables or *Allium* spices liberally, in dishes that require the addition of components such as tannin-rich tamarind or in diets rich in phytate-containing food grains.

It is reported that addition of vegetables rich in ascorbic acid and β-carotene (cabbage, tomato and carrot) to mung bean preparations improved the iron status of anaemic women. The addition of these vegetables significantly increased *in vitro* iron availability from these preparations, which was attributed to the improved iron status of women (Purushothaman et al., 2008).

Apart from inherent inhibitors of mineral absorption such as phytate, tannin and insoluble dietary fibre, minerals that are similar in chemical configuration are likely to compete with each other at the site of absorption, thus coming in the way of their bioavailability (Gibson, 1994). The use of supplements of iron and of calcium is common among pregnant women in developing countries. In such a situation, there would be an imbalance in the ratios of zinc to iron and calcium. Iron supplements have been reported to decrease zinc absorption in pregnant women (Simmer et al., 1987), and it is possible that supplemental levels of calcium too would hinder zinc absorption. It has been recently reported that exogenous iron included at therapeutic levels (5 mg per 10 g of cerealï legume combination) along with a combination of cereal and pulse significantly reduced (32% reduction) the bioaccessibility of zinc from the food grains (Hemalatha et al., 2009). In the same study, exogenous calcium equivalent to therapeutic levels (83 mg per 10 g of the cerealï legume combination) was also evidenced to significantly reduce (by 27%) the bioaccessibility of zinc from the tested food grains. This negative influence of exogenous iron and calcium was seen in both raw and cooked grains. Such negative influences on the bioaccessibility of zinc were however not evident when exogenous iron and calcium were added at levels up to four times the intrinsic level (Hemalatha et al., 2009). In view of the observed negative influence of supplemental iron and calcium on zinc bioaccessibility, zinc supplementation is probably necessary along with that of iron and calcium, especially in the Indian context, to compensate for the reduction in zinc bioaccessibility.

The bioaccessibility of zinc from pulses has been documented to be higher than that from cereals, in spite of a generally higher concentration of phytate, tannin, calcium and insoluble dietary fibre in the former (Hemalatha et al., 2007a). The overall negative effect of such inherent inhibitory factors was more prominent in cereals than in pulses, suggesting that protein, of which pulses are richer sources, may have a modulatory role on zinc bioaccessibility. This hypothesis was corroborated in an investigation that examined the effect of exogenous protein added to cereals on their zinc bioaccessibility (Hemalatha et al., 2009). Soy protein isolate added to rice and sorghum at a level that raised their protein content to 20% (roughly corresponding with the protein content of pulses), significantly enhanced zinc bioaccessibility from sorghum, the extent of increase being 50 and 90% in the raw and cooked grain, respectively. Soy protein isolate, on the other hand, significantly decreased iron bioaccessibility from both the food grains examined (Hemalatha et al., 2009). Addition of sodium chloride at 5% level potentiated the positive effect of soy protein on zinc bioaccessibility, and, at the same time, effectively countered its negative effect on iron bioaccessibility. Thus, sodium chloride, which is an inevitable ingredient of our diets, seems to beneficially modulate zinc and iron bioaccessibility (Hemalatha et al., 2009).

Calcium

Millets such as finger millet and legumes, especially whole-grain legumes form important sources of calcium in vegetarian diets. However, these grains also contain significant amounts of absorption inhibitors such as phytates, tannins and dietary fibre. Although these dietary components are known to inhibit the bioavailability of iron and zinc, it is possible that they also

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negatively influence the bioavailability of calcium. A negative correlation between the content of phytate, tannin and dietary fibre of legumes (chickpea, lentil, green and cowpea) and the bioaccessibility of calcium from these grains has been found (Ghadivel and Prakash, 2007). The percent bioavailability of calcium ranged from 15.7 in green gram to 29.3 in lentil. Germination and dehulling of these legumes brought about a significant increase in the bioavailability of calcium, which was attributed to a decrease in the anti-nutritional factors as a result of the processing methods (Ghadivel and Prakash, 2007). A study on the bioaccessibility of calcium from representative Indian meals based on rice, wheat, finger millet and sorghum revealed that rice-and finger millet-based meals provided higher amounts of bioaccessible calcium as compared to sorghum- or wheat-based meals (Bhavyashree et al., 2009).

Other trace minerals

Trace minerals such as copper, manganese, chromium and selenium are probably as important as iron zinc and calcium, in view of their physiological functions. The bioavailability of these minerals from dietary sources, although less explored, is likely to be influenced by the same dietary factors that influence the bioavailability of iron, zinc and calcium. Amino and keto acids and ascorbic acid have been reported to form chromium complexes of low molecular weight, thereby enhancing the bioavailability of this element (Fairweather-Tait and Hurrell, 1996). Chelating substances such as oxalate have been reported to enhance chromium bioavailability, while EDTA and citrate were without effect. Inhibitors of chromium bioavailability include phytates, zinc and iron. It is reported that chromium, zinc and iron share a common gastro-intestinal transport mechanism (Fairweather-Tait and Hurrell, 1996).

Unlike their negative effect on the bioavailability of other trace minerals, phytate and dietary fibre do not seem to negatively affect the bioavailability of copper (Lonnerdal, 1996). Studies in experimental animals as well as in humans found that fibre and phytate had no effect on copper absorption, although zinc absorption was decreased (Lonnerdal, 1996). Some Amino acids are known to form complexes with divalent cations such as copper. Histidine is known to chelate copper; and copper-histidine complex may be an effective way of providing available copper (Lonnerdal, 1996).

Ascorbic acid is known to have a negative effect on copper absorption in laboratory animals; this effect is attributed to the reduction of cuprous ions to cupric ions, the latter being less well absorbed (Lonnedal, 1996). The negative effect of ascorbic acid on copper bioavailability is less pronounced in humans (Lonnerdal, 1996; Fairweather-Tait and Hurrell, 1996). Excessive zinc has been reported to impair bioavailability of copper, at levels that exceed normal dietary intakes. Therapeutic levels of zinc (150 mg/day) taken over extended periods of time have been reported to produce symptoms of copper deficiency (Fairweather-Tait and Hurrell, 1996). Animal studies have revealed that high amounts of calcium, fibre and phytate inhibit the availability of manganese, probably by the formation of insoluble manganese complexes (Fairweather-Tait and Hurrell, 1996).

The dietary factors that are reported to influence selenium bioavailability are methionine, thiols, heavy metals and ascorbic acid. Dietary methionine affects the absorption of selenium-

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methionine because of the common absorption mechanism for both of them (Fairweather-Tait and Hurrell, 1996). Certain thiols in the gastrointestinal tract enhance selenite absorption probably owing to formation of selenocomplexes with thiol compounds which are more rapidly absorbed by the intestinal epithelium (Fairweather-Tait & Hurrell, 1996). Guar gum, a soluble fibre, is reported to reduce selenium absorption from the gastrointestinal tract (Fairweather-Tait and Hurrell, 1996).

β-Carotene

Bioavailability of β-carotene from green leafy vegetables and yellow-orange fruits and vegetables

Deficiency of vitamin A is of public health concern, being the leading cause for childhood blindness. The other serious consequence of vitamin A deficiency is lowered immunity, leading to increased morbidity and childhood mortality. The prevalence of severe forms of vitamin A deficiency such as corneal xerophthalmia in India has declined, but sub-clinical deficiency of this vitamin is still prevalent in almost 60% of preschool children (Vijayaraghavan, 2009).

Dietary sources of preformed vitamin A such as animal foods being expensive, a majority of the population in India and other developing countries is dependent on ϐ-carotene derived from plant foods, to meet their requirement of vitamin A. However, the RDA for ϐ-carotene is eight times that of vitamin A, owing to its poor bioavailability and incomplete conversion to retinol (Indian Council of Medical Research, 2010). Similar to iron and zinc, the bioavailability of ϐ-carotene is influenced by factors such as diet composition and methods employed for food processing. Dietary factors such as fat, fibre and protein are also documented to influence the bioaccessibility of β-carotene (Veda et al, 2006; Yeum and Russel, 2002). While green leafy and yellow-orange vegetables are abundant sources of β-carotene, information on the bioavailability of this provitamin from these plant foods is limiting.

Our study (Veda et al, 2006) has revealed that the bioaccessibility of β-carotene is independent of its content. Among the green-leafy and yellow-orange vegetables examined in this study, fenugreek, which had the highest amount of β-carotene (9.15 mg / 100 g), had the lowest bioaccessible amount of this provitamin (6.7% bioaccessible). Amaranth and carrot had similar amounts of total β-carotene (around 8 mg/100 g), but the bioaccessibility of β-carotene from the latter was nearly twice that from the former (20.3 and 10.6%, respectively). (Veda et al., 2006). These findings were further corroborated in another study (Veda et al., 2010). The total β-carotene content of drumstick leaves was reported to be 15.7 mg/100 g, while that of spinach, coriander and mint leaves was similar (4.8, 4.9, and 5.3 mg/100 g, respectively). However, despite the high total content of β-carotene in drumstick leaves, its bioaccessibility from the same was only 11.5%, not much different from that of the other green leafy vegetables (11.4 ï 14%) (Veda et al., 2010).

The matrix in which the carotenoids are embedded is an important factor determining their bioavailability. The carotenoids in dark green leafy vegetables are present in the chloroplasts as complexes with proteins within the cell structures. This may be the reason for their relatively poor bioavailability from green leafy vegetables. Carotenoids in fruits, on the other hand, are present as oil droplets in the chloroplasts, and hence may be more easily extractable during digestion (West and Castenmiller, 1998).

Fruits such as mango (*Mangifera indica*) and papaya (*Carica papaya*), which are rich sources of β-carotene, are grown abundantly and consumed in the tropical countries. Mango is a seasonal fruit, and several varieties of this fruit are available during the season. Papaya is available throughout the year, and can easily be grown in the backyards of households. Information on the varietal differences in the content and bioavailability of β-carotene from mango and papaya is limiting. Veda et al. (2007) reported significant differences in the content and bioavailability of β-carotene from six common varieties of mango grown in India. The β-carotene content of the mangoes ranged from 0.55 mg/100 g (*Malgoa* variety) to 3.21 mg/100 g (*Badami* variety), while the bioaccessibility ranged from 24.5% (*Badami*) to 39% (*Raspuri*). As in the case of vegetables, the bioaccessibility of β-carotene from the different varieties of mango was independent of the total content. The *Badami* variety, which had the highest content of β-carotene (3.21 mg/100 g), had the lowest percent bioaccessibility (24.5) of this provitamin. Considering both the total content and percent bioaccessibility of β-carotene, the *Mallika* variety provided the highest amount of bioaccessible β-carotene (0.89 mg/100 g), followed by the *Badami* variety (0.79 mg/100 g) (Veda et al., 2007). Such varietal differences, however, were not evident in the case of papaya. The two varieties of papaya examined, namely, *Surya* and *Honey dew,* had similar content of β-carotene, which was around 0.70 mg/100 g, and the percent bioaccessibility of β-carotene from these two varieties was also similar (around 34%).

Addition of milk to the pulp of these fruits significantly enhanced the bioaccessibility of ϐ-carotene from all the varieties of mango and papaya, the extent of increase ranging from 12 to 56% in the case of mango, and 19 and 38% in the two varieties of papaya (Veda et al., 2007). Thus, consumption of mango and papaya in the form of milk shake seems to be advantageous in deriving more of ϐ-carotene. This is the only report on the varietal differences in the content and bioavailability of ϐ-carotene from fruits.

Influence of heat processing on the bioavailability of β-carotene from vegetables

Heat treatment in the form of mild cooking is reported to enhance the absorbability of ϐ-carotene (Rodriguez and Irwin, 1972). We have recently reported the influence of domestic heat treatment on the bioaccessibility of ϐ-carotene from green leafy and yellow-orange vegetables (Veda et al., 2010). Heat treatment of these vegetables by pressure-cooking, stir-frying and open-pan boiling significantly enhanced the bioaccessibility of ϐ-carotene. Stir-frying the vegetables in a small quantity of oil brought about an enormous increase in ϐ-carotene bioaccessibility, the extent of increase ranging from 67 to 191%. Pressure-cooking increased the bioaccessibility of ϐ-carotene by 21 to 84%, while open-pan boiling enhanced the same to an extent of 23 ï 36% from the vegetables examined. It was observed that the beneficial influence of heat processing on the bioaccessibility of ϐ-carotene was more pronounced in the case of green leafy vegetables, as compared to fleshy vegetables (carrot and pumpkin). This difference was attributed to the differences in the alteration of the matrices of these vegetables as a result of heat processing

(Veda et al., 2010). The use of suitably heat-processed vegetable sources of ϐ-carotene could thus form a dietary strategy to derive this micronutrient maximally by the population dependent on plant foods.

Influence of exogenous factors on the retention and bioavailability of β-carotene

The food acidulants commonly used in Indian cuisine are *amchur* (dry mango powder), lime juice, tamarind and kokum. Turmeric and onion are the spices that are known to possess antioxidant property and are also commonly used in Indian households. These common food ingredients were examined in our laboratory for a possible beneficial influence on the bioaccessibility of ϐ-carotene from representative vegetables. The acidulants *amchur* and lime juice generally enhanced the bioaccessibility of ϐ-carotene from the vegetables examined, both raw and heat-processed, the effect of lime juice being more pronounced than that of *amchur* (Veda et al., 2008). The antioxidant spices turmeric and onion had a similar enhancing effect on the bioaccessibility of ϐ-carotene from the test vegetables, especially when they were heat processed. ϐ-Carotene is highly heat-labile; heat treatment especially in the presence of light and oxygen causes isomerisation of carotene as well as its oxidative destruction, thus decreasing its biological activity (Ogulensi and Lee, 1979). In our study, we observed that the acidulants lime juice and antioxidant spices minimized the loss of ϐ-carotene during heat processing, in addition to improving its bioaccessibility from the vegetables (Veda et al., 2008). Our observation that the effect of the antioxidant spices on the bioaccessibility of ϐ-carotene was more prominent in heat-treated vegetables was attributed to the role of these spices in preventing the oxidative destruction of ϐ-carotene, thereby minimizing its loss in addition to enhancing the bioaccessibility. Thus, cooking ϐ-carotene- rich vegetables in the presence of acidulants such as lime juice or *amchur*, and antioxidant spices turmeric and onion is a feasible food-based strategy to maximize the bioaccessibility of this provitamin.

Dietary spices as enhancers of micronutrient bioavailability

Spices are extensively used in Indian culinary, as well as in other tropical countries to enhance the taste and flavor of foods. Certain spices are known to alter the intestinal ultrastructure and permeability characteristics; piperine, the active principle of black pepper is known to increase bioavailability of drugs and other phytochemicals, as a result of an alteration in membrane lipid dynamics and change in the conformation of enzymes in the intestine (Veda and Srinivasan, 2009). The lipophilic spice compounds ï capsaicin (red pepper), and gingerol and gingerone (phytochemicals of ginger) are similar to piperine with respect to the structural homology. These dietary spices that have the potential to alter the ultrastructure and permeability of intestinal brush border were examined for a possible beneficial influence on the absorption of ϐ-carotene. Higher *ex vivo* uptake of ϐ-carotene from the intestines of rats fed black pepper (*Piper nigrum*), red pepper (*Capsicum annuum*), ginger (*Zinziber officinale*), piperine and capsaicin was evidenced (Veda and Srinivasan, 2009). Piperine had the highest stimulating effect on the uptake of ϐ-carotene, the increase being to an extent of 147%, while the parent spice black pepper increased the same by 59%. Dietary capsaicin increased the uptake of ϐ-carotene by 50%, while red pepper brought about an increase to an extent of 27%. The spice ginger increased the uptake of ϐ-carotene by 59%. (Veda and Srinivasan, 2009). Thus, significantly enhanced intestinal uptake of ϐ-carotene as a result of consumption of pungent spices was evidenced.

The results of this study were further authenticated in elaborate animal studies employing the dietary spice compounds piperine, capsaicin and ginger. The influence of these dietary spices on the absorption of orally administered β-carotene and its conversion to vitamin A was studied in rats maintained on diets containing these spices for a period of 8 weeks (Veda and Srinivasan, 2011). The concentration of β-carotene in the serum, liver and intestine of piperine- and ginger-fed rats significantly increased 4 h after a single oral administration of β-carotene, which suggested improved absorption. However, retinol concentration was not significantly changed in these animals, suggesting that the bioconversion of β-carotene to vitamin A was not similarly influenced. The test spices did not affect the activity of any of the enzymes involved in the bioconversion of β-carotene to retinol (Veda and Srinivasan, 2011). Although the bioconversion of β-carotene was not promoted, increased absorption and tissue levels of β-carotene by the dietary spices may contribute to a higher antioxidant protection by this provitamin.

The pungent spices piperine (of black pepper), capsaicin (of red pepper) and ginger, were also evidenced to improve the uptake of iron, zinc and calcium by the intestines of rats pre-fed these spices (Prakash and Srinivasan, 2012). After maintaining experimental rats on diets containing these spices for a period of 8 weeks, everted segments of duodenum, jejunum and ileum of small intestines isolated from these rats were examined for *ex vivo* uptake of iron, zinc and calcium from incubations containing digesta of finger millet. Higher uptakes of iron, zinc and calcium in the intestines was evidenced in all spice-fed animals, the positive influence of dietary spices on the mineral uptake being highest for calcium. Dietary capsaicin increased the uptake of zinc to a greater extent than that of iron. The beneficial influence of these spices on the uptake of minerals by the intestinal segments was attributed to an increase in the absorptive surface of the intestine by them (Prakash and Srinivasan, 2011). Thus, spices, especially pungent spices, could play an important role in enhancing mineral bioavailability, which would be a feasible strategy to improve their intake.

Conclusions

Deficiencies of iron, zinc, iodine and vitamin A are widespread in the developing countries, the major reason for their wide prevalence being poor bioavailability of these micronutrients from plant-based foods. Diets predominantly vegetarian are composed of components that enhance as well as inhibit mineral bioavailability, the latter being predominant. However, prudent cooking practices and use of ideal combinations of food components can significantly improve micronutrient bioavailability. Heat treatment has been evidenced to enhance the bioavailability of iron and ϐ-carotene from plant foods. Cooking practices normally adopted for plant-based foods, which involve boiling in water (ca 100ºC), or pressure-cooking (ca 115 ºC), at 15 p.s.i. for about 5 to 15 min depending on the type of food, will suffice to bring about this desired effect. Similarly, household processes such as sprouting, fermentation and malting bring about significant improvement in the bioavailability of iron and zinc from food grains. Sprouting of grains for 24 to 48 h after overnight soaking as in the preparation of salads is recommended for improving the bioavailability of iron from pulses. Malting of the grains thus sprouted involving brief roasting, which additionally provides heat is also a good strategy, wherever feasible, to improve mineral bioavailability. Fermentation of the batter of cereal-pulse combinations overnight, as in the preparation of *idli* and *dosa* improves the bioavailability of both iron and zinc.

Food acidulants *amchur* and lime are also evidenced to enhance the bioavailability of not only iron and zinc, but also of ß-carotene. Presence of these food acidulants at amounts normally used in household cooking will provide sufficient organic acid to bring about the beneficial improvement in mineral and ß-carotene bioavailability. Newer enhancers of micronutrient bioaccessibility have recently been identified, and these include sulphur compound-rich spices ï onion (at the dietary level of 15 g / 100 g of the staple grain) and garlic (2.5 g/100 g of staple grain), which also possess antioxidant properties, ß-carotene rich vegetables ï yellow-orange or green leafy, at 2.5 g/100g of staple grain, and pungent spices red pepper (3 g/100 g grain), black pepper (0.5 g/100 g) as well as ginger (50 mg/100 g). In food grains rich in phytates and tannins, inclusion of any one or more of enhancers of mineral bioavailability (among food acidulants, ß-Carotene-rich vegetables, and *Allium* spices) at the optimal levels would counter the negative effects of the inherent inhibitors.

The spices onion and garlic are also evidenced to prevent the oxidative destruction of ß- carotene during heating, in addition to improving its bioavailability. ß-Carotene-rich vegetables carrot and amaranth were also found to be potent enhancers of iron and zinc bioaccessibility. The pungent spices red pepper, black pepper and ginger, which are known for their digestive stimulant property, also significantly improve the uptake of micronutrients by the intestinal segment of rats pre-treated with these spices. Information on the beneficial effect of these dietary compounds on micronutrient bioaccessibility is novel. These food components evidenced to improve the bioavailability of micronutrients are commonly used in Indian culinary, and probably in other tropical countries. Fruits such as mango and papaya, when consumed in combination with milk (50 ml milk / 10 g fresh pulp), provide significantly higher amounts of bioavailable ß-carotene. Thus, awareness of the beneficial influence of these common dietary ingredients on the bioavailability of micronutrients would help in devising dietary strategies to improve the bioavailability of these vital nutrients. Such strategies would be easily adaptable, since there in no need to drastically change food habits. Prudent choice of food combinations would go a long way in improving the bioavailability of micronutrients, thereby eliminating their deficiencies.

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Table 1. Bioavailability of iron from foods commonly consumed in India

Food grain	Percent iron bioavailability		
	Rao & Prabhavathi, 1983	Aannapurani & Murthy, 1985	Hemalatha et al., 2007a
Rice	15.0	5.2	8.1
Wheat	7.1	12.9	5.1
Finger millet	7.4	11.3	6.6
Sorghum	9.0	18.8	4.1
Pearl millet	7.1	10.0	-
Cowpea	7.6	30.4	1.8
Pigeon pea (Decorticated)	19.8	-	3.1
Horse gram	-	14.8	-
Chickpea (Whole)	22.0	36.9	6.9
Chickpea (Decorticated)			4.8
Green gram (Whole)	20.9	8.2	2.3
Green gram (Decorticated)	-	-	7.9
Field bean	-	17.2	-
Lentil	18.8	-	-
Soybean	18.6	25.0	-
French bean	-	-	10.2
Black gram (W)	-	-	2.8

Table 2. Influence of domestic food processing methods on the bioaccessibility of iron and zinc from food grains (Cereals and pulses)

Process	Iron bioaccessibility	Zinc bioaccessibility
Food processing methods		
Pressure-cooking	Enhanced	Decreased
Microwave cooking	Enhanced	Decreased
Germination	Enhanced	Decreased
Fermentation	Enhanced	Enhanced
Malting	Enhanced	Enhanced
Exogenous factors		
Amchur	Enhanced	Enhanced
Citric acid	Enhanced	Enhanced
Soy protein isolate (SPI)	Decreased	Enhanced
Sodium chloride	Effect of SPI countered	Effect of SPI potentiated
Therapeutic levels of Fe & Ca	ī	Decreased

(Source: Hemalatha et al., 2007b, 2007c, 2009; Platel et al., 2010)

Table 3. Negative influence of inherent factors on iron and zinc bioaccessibility from food grains

	Negative correlation with inherent factors
Iron bioaccessibility	Phytic acid in cereals
	Insoluble dietary fibre
Zinc bioaccessibility	Phytic acid in pulses
	Calcium in cereals
	Insoluble & soluble dietary fibre

(Source: Hemalatha et al., 2007a)

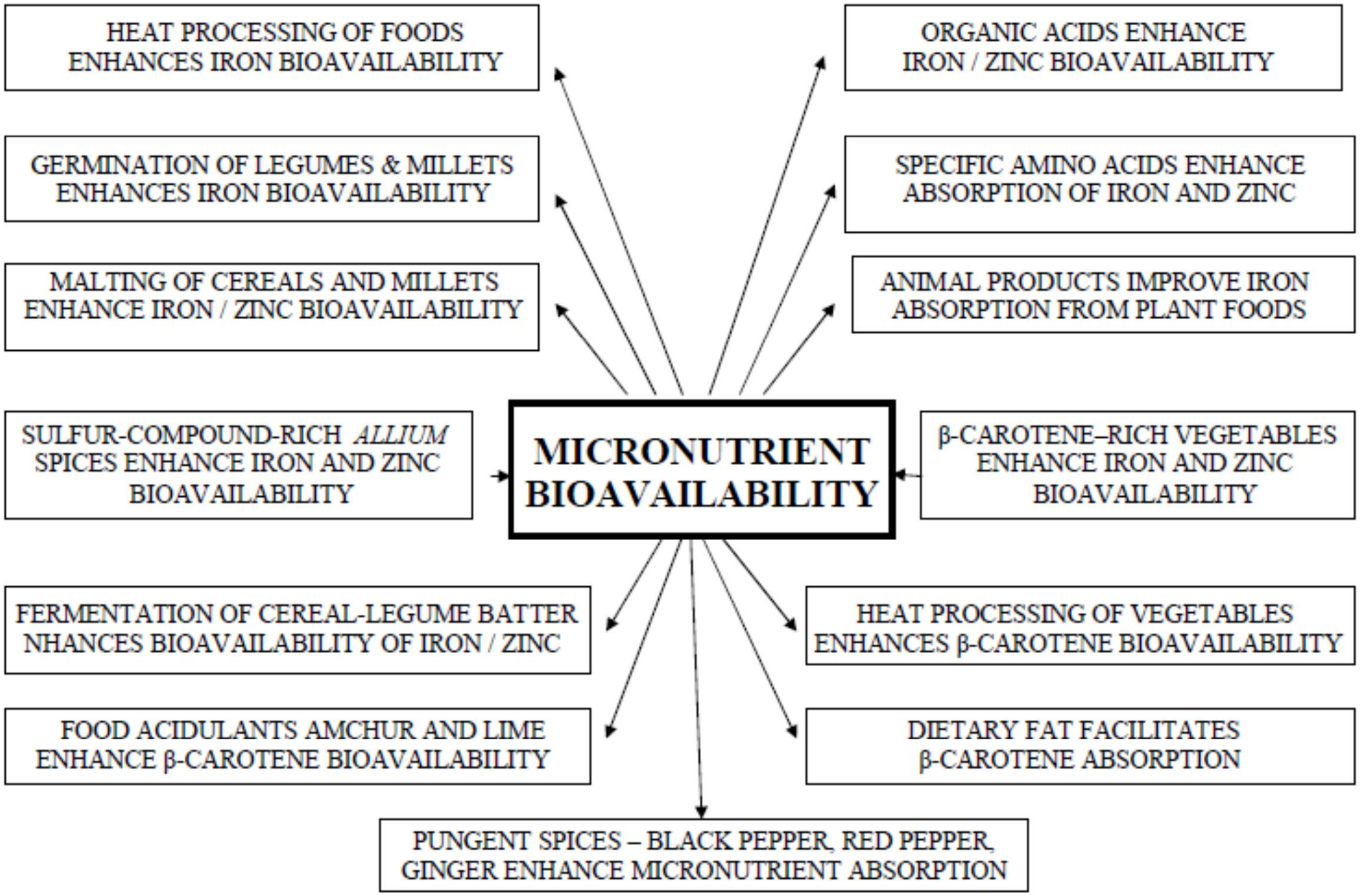

Fig.1 Promoters of micronutrient bioavailability

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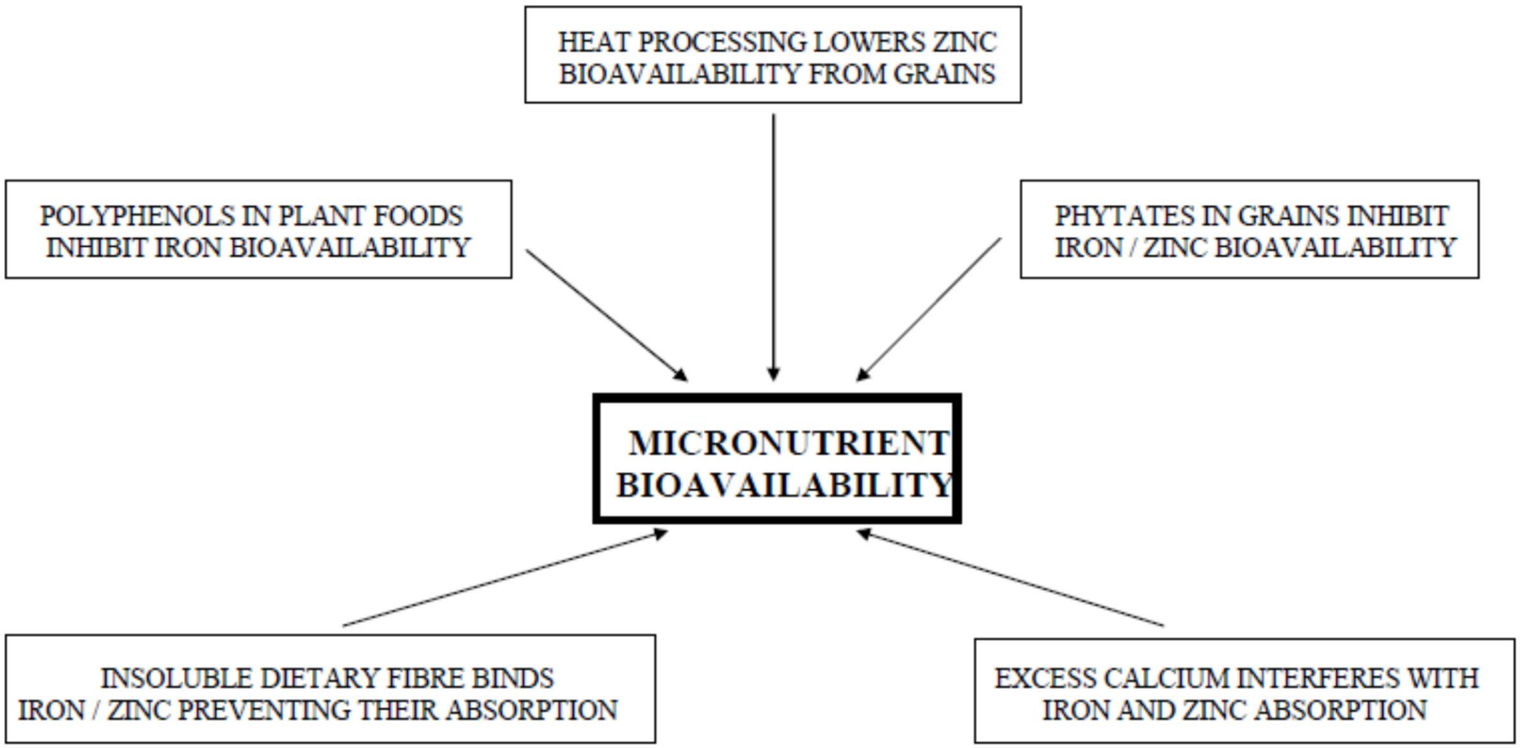

Fig.2 Inhibitors of micronutrient bioavailability

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