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Review Article

Iron Bioavailability from Cereal Foods Fortified with Iron

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Abstract

Cereals are a staple and healthy food, providing a good source of carbohydrates, fiber, and phytochemicals, and are low in fat. They are considered the major supplier of energy in the human diet with starchas the main component of the grain. At the same time iron anemia is the most common nutritional deficiency, affecting 1.62 billion people globally. Not all dietary iron, heme or non-heme, will be available for absorption, and a negative balance between iron requirement and absorption may lead to iron deficiency and/or anemia. The recommended iron values are usually based on genetics and dietary iron-bioavailability, which can be considered the principal factor that varies between cultures and influences the differing recommendation levels between countries. Iron food fortification is considered more cost-effective and economically more attractive than iron supplementation and/or dietary interventions. The World Health Organization recommends iron compounds for cereal fortification purposes and the choice of the compound should be made considering local regulations, sensory properties and its bioavailability. Ferrous sulfate is the principal iron compound used in cereal fortification studies, often used in association with ascorbic acid and NaEDTA. However, iron bioavailability from ferrous sulfate is lower than from other compounds. The level of fortification, storage conditions, level of extraction, baking and the interaction with other chemical compounds influences the iron absorption rate.

Keywords: Iron status; Food enrichment; Bioavailability; Iron fortificants; Anemia; Grains

Introduction

Over the past decades, consumer and nutritional demands in the field of processed food production have changed considerably. In the present day foods are intended to not only satisfy hunger and to provide necessary nutrients, but also to prevent nutrition-related diseases and enhance the physical and mental well-being of consumers [1]. Iron is among the essential nutrients that can influence the physical and mental well-being on a large scale. Iron deficiency anemia is the most common nutritional deficiency in humans, affecting 1.62 billion people globally. Individuals more vulnerable to iron deficiency include infants over 6 months, children, women of fertile age, pregnant women and older people (Table 1). The World Health Organization (WHO) classifies iron deficiency anemia when the hemoglobin level is under 13 g/dL in men (>15 years old), under 12 g/dL in non-pregnant women (>15 years old), and below 11 g/dL in pregnant women [2,3].

Iron deficiency anemia is a major public health issue and its severity level in a population is based on the prevalence of below normal of hemoglobin: severe (>40.0%); moderate (20.0-39.0%), mild (5.0-19.9%) and normal (<4.9%) [2,3]. Preschool-age children and pregnant women are among the groups of persons that are classified with a severe public health problem (Table 1) as both groups havean iron anemia prevalence over 40% [3].

Reduced levels of hemoglobin and myoglobin impair physical performance due to reduced activity of iron-dependent cytochromes and lower ATP production. This situation also impairs psychomotor development in children, and cognitive performance among children and adults. In cases of severe iron deficiency, body thermoregulation and cellular immune function could also be affected [4-7]. In India is estimated that about 20% of maternal deaths are directly related to anemia and another 50% of maternal deaths are associated with it [8]. In Kuwait are more likely to become anemic if their mothers are anemic [9].

The imbalance between iron requirement and absorption leads to iron overload or deficiency which, depending on severity, may lead to iron toxicity or iron anemia. In children ages 1 to 5 years, anemia, as measured by hemoglobin levels, and iron deficiency, as measured by serum ferritin, are positively associated serum retinol levels [10]. Iron overload is related to increases of cancer risk in humans, such as liver and colorectal cancers [11-13].

Homeostatic mechanisms can alter intestinal iron absorption by supplying iron preferentially to functional compartments in response to deficiency or excess. The human body is capable of adjusting

Table 1: Global anemia prevalence and number of individuals affected by population group.

Population group	Prevalence of iron anemia (%)	Population affected (millions of individuals)
Preschool-age children	47.4	293
School-age children	25.4	305
Pregnant women	41.8	56
Non-pregnant women	30.2	468
Men	12.7	260
Elderly	23.9	164

Source: Adapted from reference [2].

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Table 2: Dietary promoters and inhibitorsof iron absorption.

	Food and/or food compounds	Comments
Promoters	- Acid ascorbic	Present in fruits, juices and vegetables such as green leaves, peppers
	-Heme iron	Present in meat, poultry, fish and seafood (~40% of the total iron)
	-Muscle tissue, the digestion products of meat, fish or poultry	30g of muscle has the enhancer propertyas 25mg of ascorbic acid, possible due to the presence of cysteine-containing peptides or a multitude of small peptides
	-Fermented or germinated food and condiments	Sauerkraut and soy sauce (cooking, fermentation, or germination of food reduces the amount of phytates)
	-Caseinophosphopeptides (CPPs) -Polyoxycarbonic acids	The CPPs added to fruit beverage (grape and orange) appears to improve iron bioavailability*. Such as citrate and malate
Inhibitors	-Phytate or phytic acid	Present in cereal grains, high-extraction flour, legumes, and seeds
	-Polyphenols	Foods that contain the most potent inhibitors (e.g. tannins) resistant to the influence of enhancers include tea, coffee, cocoa, herbal infusions (tea) in general, certain spices (e.g. oregano), and some vegetables
	-Calcium	Particularly from milk and milk products found as calcium phosphate, inhibit absorption of non-heme and heme iron
	-Proteins	Animal proteins from products like milk and eggs, and albumin, casein, and soy protein (independent of the phytate content)
	- Inositol	Food with high inositol content

*Among the CPPs compounds, αs1-CN(64–74)4P, αs2-CN(1–19)4P and β-CN(1–25)4P) increased ferritin synthesis, β-CN(1–25)4P being the most effective.
Source: Adapted from references [4,12,20-22].

intestinal mucosa cells involved in iron uptake by regulating the number of the binding and transport iron proteins. This process is an essential regulatory mechanism required to prevent iron overload and to achieve iron homoeostasis [14,15].

Healthy individuals have daily iron absorption rates of 1-2 mg that is balanced by a similar amount of iron loss from the gut and skin, and from menstruation and pregnancy [16]. There is no evidence of any benefit in having iron stores higher than the minimum needed to guarantee adequate iron procurement for the functional compartments. An adult human usually contains around 45 mg/kg of iron, with females in reproductive age generally having lower levels than males due to iron loss during menses, pregnancy, and lactation [17].

Heme and non-heme iron

In the diet inorganic iron-salts (non-heme) are present in plants and animal tissues, and organic iron (heme), which comes from hemoglobin and myoglobin, is present in animal food sources. The latter contributes around 10-15% of total iron consumption in omnivorous individuals, and is absorbed by a separate pathway and more efficiently than non-heme iron. Heme iron has higher bioavailability (15-35%) than non-heme iron (add the estimated range). With the exception of a few iron fortificant compounds, all non-heme iron present in food contributes toa common iron pool in the digestive tract and is absorbed to the same extent, with the absorption efficiency linked to the balance between the presence of absorption inhibitors, enhancers, and the iron status of the individual [18].

Consequently, not all ingested heme or non-heme iron will be available to be absorbed. The fraction absorbed will be influenced by individual factors and also by the complexation reactions in the intestinal lumen [16]. However, the form of iron and the interplay of enhancers and inhibitors may be more important than total iron intake in determining iron status [19]. Table 2 exhibits the main dietary enhancers and inhibitors of iron absorption.

Heme-iron absorption is less affected by dietary compounds with the exception of calcium compounds. Calcium phosphate is the strongest inhibitor of heme and non-heme iron, compared to calcium carbonate and calcium citrate [23]. Among the enhancers, ascorbic acid positively influences non-heme iron bioavailability. Individuals consuming foods with high levels ofiron inhibitors and with low levels of promoters and also followers of vegetarian diets have reduced levels of absorption efficiency, rangeing from 18 to 10%. As the absorption of non-heme iron is lower heme iron found in meat and meat products, vegetarians need to consume twice as much iron to meet their daily requirement [24]. Vegetarian children and pregnant woman are vulnerable to iron deficiency, with rates of prevalence around 33 and 25%, respectively [25]. Teenagers following unbalanced vegetarian diets can also exhibit iron anemia. Among vegetarian students (14-18 years old) of both genders the iron anemia prevalence was reported as 31.2%, a moderate level of significance in public health management [26].

Iron bioavailability is estimated to be around 5-12% for vegetarian diets and 14-18% for mixed diets. These values are used to generate dietary reference values for all population groups [12]. Considering all factors that may influence iron bioavailabitility, the estimated average absorption iron rate for a typical western diet is between 15-18% [24,27]. The Food Agriculture Organization of the United Nations/World Health Organizationset iron bioavailability at 5% for a strict vegetarian diet, at 10% when some meat and ascorbic acid was added, and at 15% for diets rich in meat and fruits [28].

Nutritional recommendations

Countries, groups of countries and international organizations have recommended values for dietary iron intake for both genders at different ages. Table 3 exhibits some of these values. The recommended values usually are based on genetic factors of the population and also the diet iron-bioavailability, which in turn is primarily driven by cultural differences. Usually the proposed values based on body iron-losses, diet iron-bioavailability, and iron-requirements for metabolism and growth. The iron recommendations are also linked to the organic requirements which can be estimated using different approaches [15,24].

After a review ofthe definitions, data sources and methodology used by countries, groups of countries and international organizationsin creating nutritional reference values, we concluded that the bulk of the groups define major concepts in the same way, but

Table 3: Requirements for iron (Fe) (mg/day) by age and gender among different agencies and countries.

	WHO/FAO (2002)		EU Com (1992)		DACH (2002)		Nordic NNR (2004)		AU NZ[a] (2006)		Brazil (2005)		Spain (2009)		United States[b] (2001)		UK (1991)	
Age	Bioav 15%	Bioav 5%	Age	Fe	Age	Fe	Age	Fe	Age	Fe	Age	Fe	Age	Fe	Age	Fe	Age	Fe
6-12m	6.2	18.6			<12m	0.5	<6m	-	0-6m	0.2	6-11m	0.27	<6m	7	0-6m	0.27	<12m	5.4
1-3y	3.9	11.6	6-11m	6	1-4y	8	6-11m	8	7-12m	11	1-3y	9	6-12m	7	7-12m	11	1-3y	6.9
4-6y	4.2	12.6	1-3y	4	4-7y	8	12-23m	8	1-3y	9	4-6y	6	1-3y	7	1-3y	7	4-6y	6.1
7-10y	5.6	17.8	4-6y	4	7-10y	10	2-5y	8	4-8y	10	7-10y	9	4-5y	9	4-8y	10	7-10y	8.7
			7-10y	6			6-9y	9					6-9y	9				
Males																		
11-14y	9.7	29.2	11-14y	10	10-13y	12	10-13y	11	9-13y	8	≥11y	14	10-12y	12	9-13y	8	11-14y	11.3
15-17y	12.7	37.6	15-17y	13	13-15y	12	14-17y	11	14-18y	11			13-15y	15	14-18y	11	15-18y	11.3
≥18y	9.1	27.4	>18y	9	15-19y	10	18-30y	9	≥19y	8			16-19y	15	≥19y	8	15-50y	8.7
							≥31y	9					≥20y	10			>50y	8.7
Females																		
11-14*y	9.3	28	11-14y	22	10-13y	15			9-13y	8	≥11	14	10-12y	18	9-13y	8	11-14y	14.8
11-14y	12.5	37.6	15-17y	21	13-19y	15	10-13y	11	14-18y	15			13-15y	18	14-18y	15	15-18y	14.8
15-17y	20.7	62	>18y	20	≥19y	15	14-17y	15	19-50y	18			16-49y	18	19-50y	18	18-50y	14.8
≥18y	19.6	58.8					18-60y	15										
Post-menopausal*	7.5	22.6		-		10		9		8		14	Post-menopausal*	10		8		8.7
Pregnancy		***				30				27		27	Pregnancy	18		27		14.8
Lactation	10	30		10		20		15		9**		15	Lactation	18		10-9		14.8

[a]UL: 0-3y = 20mg/day; 4-13y = 40mg/day; >14y = 45mg/day [b]UL: 0-13y= 40mg/day; >14y= 45mg/day; * no menstruation; **10 in ≤18y mothers; *** iron supplement

Source: Adapted from references [24,27,29-35].

with differing terminology. It is observed that significant differences exist in the nutritional recommendations amongst countries and groups of countries; these differences included age groups, nutrients covered, methodologies used, how frequently values are re-evaluated and the values proposed [36]. Such differences can be found for iron values when it is analyzed alone among distinct countries, groups of countries oragencies (Table 3).

The highest recommended valuesfor iron are for pregnant women and women of child bearing age. The recommended values by age vary widely among countries, groups of countries and agencies The highest iron ingestion levels recommended correspond to groups of individuals with greater prevalence of anemia: preschool age children, women of child bearing age, and pregnant woman [2]. It iss important to note that some individuals have increased iron requirements, such as endurance athletes, blood donors, individuals with pathological blood loss and post-menopausal women that are using hormone replacement therapy [24,37].

To prevent adverse effects related to iron overload, assessment of risks were used in an attempt to derive an upper safe level for dietary iron intake. Not all countries or country groups present upper safe limits values for iron. Of the countries that establish upper values, the United States is noteworthy, presenting values of 40 and 45 mg of iron/day for individuals up to13 years old and all others, respectively [24]. Australia and New Zealand also present upper levels of ingestion by age [32].

Hereditary hemochromatosis, an autosomal recessive disease with estimated prevalence in the population of 0.002% in Caucasians and lower incidence in other races, represents a sub-population with risk for iron overload. These individuals are susceptible to iron overload even at normal dietary iron intakes due to an accelerated rate of intestinal iron absorption and progressive iron deposition of iron in various tissues [38].

Evaluating iron bioavailability

While bioavailability may be considered the amount of a nutrient that is available for normal metabolic and physiologic processes, there is no universally accepted definition of bioavailability. However, there is consensus that bioavailability influences the estimation of the dietary need ofa nutrient as well as affecting the nature and severity of toxicity due to excessive consumption. Although not synonymous with bioavailability, absorption and/or retention of the nutrients are often used as indicators of bioavailability. The bioavailability process integrates several steps where by an ingested nutrients becomes available: digestion, absorption, transport, utilization and elimination [39-41].

In the nutrition field, bioavailability can be considered an important factor due to its variability among different foods, food components and gastrointestinal and physiological conditions. The bioavailability of a nutrient may be affected by various factors, including the concentration of the nutrient, dietary factors, chemical form, supplement forms taken separately from meals, nutrition and health of the individual, excretory losses, and nutrient–nutrient interactions. The Dietary Reference Intake (DRI) publications

Table 4: World Health Organization suggestion for iron fortificants to be used in cereal based foods.

Iron fortificant compound	Solubility	Fe content (%)	Relative bioavailability*	Relative cost** (per mg/Fe)	Common cereal based vehicle
Ferrous sulfate (dry)	Water soluble	33	100	1.0	- Cereal-based complementary foods - Low extraction (white) wheat flour or degermed corn flour - Pasta - Rice
Ferrous sulfate plus ascorbic acid	Water soluble	20	100	1.0	- Pasta - Rice
Ferrous bisglycinate	Water soluble	20	>100	17.6	- Pasta - Rice
Ferric ammonium citrate	Water soluble	17	51	4.4	- Pasta - Rice
Sodium iron EDTA	Water soluble	13	>100	16.7	-High extraction wheat flour, corn flour, corn masa flour
Ferrous fumarate	Poorly water soluble, soluble in dilute acid	33	100	2.2	- Cereal-based complementary foods - High extraction wheat flour, corn flour, corn masa flour (x2 amount) - Low extraction (white) wheat flour or degermed corn flour
Electrolytic iron (x2 amount)	Water insoluble, poorly insoluble in dilute acid	97	75	0.8	- Breakfast cereals - Cereal-based complementary foods - Low extraction (white) wheat flour or degermed corn flour
Ferric pyrophosphate (x2 amount)	Water insoluble, poorly insoluble in dilute acid	25	21-74	4.7	- Pasta - Rice - Infant cereals
Encapsulated ferrous sulfate	The encapsulating agent must be a food-grade digestible ingredient	16	100	10.8	- Cereal-based complementary foods - High extraction wheat flour, corn flour, corn masa flour (2x amount) - Low extraction (white) wheat flour or degermed corn flour
Encapsulated ferrous fumarate (x2 amout)	The encapsulating agent must be a food-grade digestible ingredient	16	100	17.4	- High extraction wheat flour, corn flour, corn masa flour
Micronized ferric pyrophosphate	Poorly soluble	25	21-74	-	- Pasta - Rice

* to hydrated ferrous sulfate, adult humans
** to dry ferrous sulfate
Source: Adapted from reference [4].

identify three main factors that affect the bioavailability of iron: chemical form, dietary factors and concentration [24,41].

The availabledata about bioavailability was obtained using many different techniques and procedures, and under a diversity of variable conditions, and consequently comparison is in some cases impossible [39]. Considering that 80-90% of the absorbed iron is used for hemoglobin synthesis, and the fact that iron presents low daily metabolic excretion, it is possible to directly use the measured values of iron absorption to calculate the potential bioavailability [42].

In terms of the iron fortificants, bioavailability is dependent on the solubility of the compound and the composition of the diet, and in particular on the presence of inhibitors in the diet as phytates and polyphenols [4]. There are interactions with added iron inthe phytate-rich, fiber-rich fraction of wheat bran under gastrointestinal pH conditions, where most of the iron isbound to the insoluble fiber fraction [43]. However, adding ascorbic acid orNaFeEDTA [sodium iron (Fe^{3+}) ethylenediaminetetraacetic acid] and removing phytates, can be effective ways of increasing the total amount of iron absorbed from iron-fortified foods [4].

Monsen et al. (1978) did an algorithm incorporating all inhibitors and enhancers and estimated non-heme iron absorption to be between 3- 8% and estimated heme iron absorption at 23% [44]. Bioavailability estimates obtained by using single-meal studies could be less accurate and have less meaning in practical ways. Long-term studies of whole diets could be very useful to assess true bioavailability and bioefficacy of food fortificants, but the bulk of the available information is based on single-meal evaluations [45]. Analyzes that include the influence of gut microbiota and include the influence of other dietary factors (enhancers/inhibitors/micronutrient interactions), as well as the dietary patterns of the individuals (e.g., vegetarians), are preferred.

Cereals fortified with iron

Food enrichment or fortification represents the "addition of one or more essential nutrients to a food whether or not it is normally contained in the food for the purpose of preventing or correcting a demonstrated deficiency of one or more nutrients in the population or specific population groups" [46]. Food fortification increases micronutrient supply in order to reduce nutritional deficiencies in the population. It takes advantage of existing delivery mechanisms for industry-manufactured products [47] and is among the four principal strategies for minimizing nutritional iron deficiency [48].

The other three are strategies are dietary modifications and/or diversification to improve iron bioavailability, selective plant breeding or genetic engineering to increase the iron content or to reduce absorption inhibitors in dietary staples, and supplementation with pharmacological doses, usually without food [48]. The treatment for iron anemia using iron supplementation with pharmacological doses of ferrous sulfate has an estimated cost of $20,000/10,000 persons [49].

Dietary changes are the preferred method, but due to difficulties in changing food and cooking habits it presents practical limitations [50]. For example itis observed that changing domestic cookware to iron cookware has low acceptability among users. Treating iron anemia using iron cookware is estimated to cost $5,000/10,000 persons. in 5 thousand dollars/ 10 thousand persons [49]. But the value of using iron cookware as an intervention to control iron-deficiency anemia is limited if households are unconvinced of the necessity of regular use [51]. Hence, iron fortification is considered economically more attractive than iron supplementation, and appears to be more cost effective than iron supplementation, regardless of the geographic coverage of fortification [52].

Compared to the others strategies, food fortification seems to be a safe, and a more economical, flexible, socially acceptable and effective approach to improving nutrition iron status among vulnerable individuals in developed countries where people consume significant quantities of industrially manufactured foods. Milk, margarine, cheese, yogurt, condiments and seasoning powder, salt, sugar, and cereals, with emphasison wheat and maize flour and rice, are among the common staple foods used as a vehicle for iron fortification [48,53,54].

The effectiveness of the population coverage depends strongly on the food vehicle used, but the impact is also contingent upon the population's nutrient intake and its nutrient gap. Fortification is often limited by safety concerns, technological compatibility, and final cost. However, knowledge about the dietary characteristics of the target population remains essential to select the fortification program with the highest effectiveness potential. Successful programs require reliable food enforcement and monitoring systems; simply selecting efficacious products is insufficient [47].

Taking into account that cereals provide a very substantial proportion of the needs of the world's population for dietary energy, protein, and micronutrients, it is reasonably easy to understand that they are among the top target foods for fortification [55,56]. Cereals belong to the Gramineae family; they are a basic, ubiquitous and healthy raw material, a good source of carbohydrates with a good fiber and phytochemicals content and low in fat. They are considered the major suppliers of energy to the human diet, with starch being the central component of the grain [57,58].

The major cereal crops are wheat, rice, and maize, but sorghum, millet, barley, oats, and ryeare also important in some areas [55]. Wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), and rice (*Oryza sativa* L.) represent the cereal crops that arehighly prevalent in human diets. Over the past 50 years their production has increased dramatically due to factors such as increased access to farmable land and new varieties, but primarily as a result of intensified land management and the introduction of new advanced technological processes. All of these result in changes in nutritional value of food crops [55,59].

The worldwide production of cereal in 2013, sorted by type of grain, exhibit that rye production was the lowest (16.69 million metric tons), with maize being the most important grain produced with over 1.02 billion metric tons. Other cereals presented production values between corn and rye: oats (23.88 million metric tons), millet (62.30 million metric tons), barley (143.96 million metric tons), wheat (715.91 million metric tons) and rice (740.90 million metric tons) [60].

Native cereal starches are ideal sources of slowly digestible starch (SDS) (>50% of the starch content. Mechanical and thermal treatments change the structure and digestibility of starch. In cereal products the moisture level and the cooking time and temperature influences the formation of SDS [58]. Processed products derived from cereal flours (e.g. bread, cereal snacks and breakfast cereals) are also useful food vehicles, but the amount of iron provided via this route will depend on the quantity of food eaten and on the level of fortification [4]. Around 68 countries worldwide have mandatory fortification of at least a portion of their ceral flour, which supplies at a minimum iron and/or folic acid to their populations. Researchers found that more than 20 countries in Latin America have implemented programs of mass iron fortification, most of which involve the fortification of wheat or maize flours [61].

The efficiency of the physiologic mechanisms for preventing the absorption of undesirable levels of iron was investigated, resulting in mandatory wheat flour fortification with ironbeing discontinued in Denmark (1987) and Sweden (1994), in part due the possibility of adverse effects which included significant increases in body iron stores and the prevalence of iron overload among Danish men [62,63]. There is some epidemiological evidence to suggest that wheat flour fortification with iron might decrease the prevalence of iron deficiency [64-66], but the effectiveness appears to be related to the iron compound used in the fortification process [65].

Iron compounds used in cereal fortification

The World Health Organization recommends some iron compounds for cereal fortification (Table 4). Among them are ferrous sulfate, ferrous fumarate, ferric pyrophosphate, and electrolytic iron powder [4]. Heme iron is not a regular compound used as food supplement, or even in food fortification programs [42]. Unfortunately, several cereal foods are still fortified with low-cost elemental iron powders, which present lower bioavailability, and are not recommended by the World Health Organization [48].

Ferrous sulfate isused in fresh bread and bakery products, typically products with a short shelf life [53,67]. Ferric orthophosphate is used to fortify flour and cereal products due to its low interaction with the food matrix [67]. Baked wheat flour fortified with soluble iron compounds (ferrous sulfate, ferric orthophosphate, hydrogen reduced iron, electrolytic reduced iron and carbonyl iron) produces insoluble forms of iron. This is due to the fact that iron sources added to the wheat flour usually do not remain in the original chemical form after baking [68]. However, the use of citric or ascorbic acids in baked cereal base fortified products promotes iron availability [69,70].

Soluble iron compounds ferric citrate and ferric sulfate have a relative bioavailability of 31 and 34%, respectively, while dried ferrous is about 100%. Ferrous fumarate, ferrous succinate, ferrous tartrate and ferrous citrate, which are poorly soluble iron sources, have relative bioavailabilities in humans of 101, 123, 62 and 74%, respectively. The nearly insoluble ferric orthophosphate and reduced forms of iron exhibit bioavailabilities ranging from 5 to 60% and from 13 to 90%, respectively [53,67]. Compared to ferrous sulfate bioavailability of freely water soluble compounds, like ferrous gluconate and ferrous lactate, exhibit relative bioavailabilities in humans of 89 and 106% respectively [53].

Among iron fortificants used in cereal foods, the form with the highest bioavailability is NaFeEDTA [18,67]. NaFeEDTA does not enter the common pool of non-heme iron in the absorption process, but rather it dissociates in the gastrointestinal tract to form iron, which is bioavailable, and aNaFeEDTA salt. The absorption of the metal ion and NaFeEDTA occurs by independent processes [18]. Absorption levels of NaFeEDTA is considered two to three times better than those of ferrous sulfate if the phytate content of the food matrix is high. Other compounds, such as ferrous bisglycinate and various encapsulated and micronized iron compounds, were proposed in recent years as alternatives for iron fortification because they provide better protection against the inhibitors of iron absorption [4].

The effect of different iron sources on color values and sensory color perception in tortillas prepared with corn masa flour fortified with a micronutrient premix (vitamins and zinc), and one of eight iron compounds (ferrous fumarate, ferrous sulfate, ferric orthophosphate, ferrous lactate, ferrous gluconate, ferric pyrophosphate, NaFeEDTA, and A-131 electrolytic iron) were studied. The fortified tortillas were compared with control samples prepared without any iron fortificant. All iron-fortified tortillas were significantly darker than control tortillas, but the A-131 electrolytic iron had minimal effect on color and has significantly lower cost than other iron sources evaluated [71]. Among children the consumption of whole maize flour fortified with electrolytic iron or NaFeEDTA resulted in no improvement or a modest, dose-dependent improvement in their iron status, respectively, with NaFeEDTA being more suitable than electrolytic iron for fortification in high-phytate flours [65].

Researchers evaluated the sensory quality attributes of two millet flours fortified with iron. Fortification did not cause changes in the hardness, texture and aroma of the dumplings prepared from the fortified flours over a period of 60 days following preparation. However, a discoloration was perceived in the dumplings prepared from the flours. Nevertheless, the general quality of the products prepared was acceptable to the sensory panelists and the fortified flours appeared to be suitable as vehicles for fortification with iron [72]. Biscuits fortified with either ferrous sulfate or NaFeEDTA equivalent to 8.8 mg of iron per 100 g of flour, in combination with either citric and tartaric acids at 60, 80, or 100 mg/100 g levels, were evaluated for sensory attributes by 30 panelists with the help of a scorecard specially developed for biscuits. Sensory tests indicated that NaFeEDTA-fortified biscuits were more acceptable than ferrous sulfate-fortified biscuits, and that biscuits fortified with NaFeEDTA along with tartaric acid were similar to control biscuits in all sensory attributes [73].

Domestic preparation of rice in iron cookware was observed to increase the bioavailability of iron by about 300% (from 0.249 to 0.747 mg/100g) and consumption of the prepared rice on a daily basis for 12 weeks reduced the iron anemia incidence from 31.2 to 5.3% among vegetarian teenagers [26]. Geerligs et al. (2003) defends the use of iron cookware in communities as an alternative way to prevent iron deficiency and anemia in developing countries where regular iron supplementation is problematic [74]. The weight of the cookware, heat energy level and sometimes the changes in sensory properties are considered the main limitations to implementation of the use of iron cookware [26,51,74,75].

Acritical review of sensory evaluation practices in iron fortification programs point out that poor consumer acceptance, unacceptable taste, and discoloration of the iron-fortified foods were the more frequent causes of unsuccessful iron fortification programs. The authors suggest the incorporation of a thorough, organized, and unified approach to sensory evaluation practices into iron fortification programs for product optimization to improve consumer acceptance of iron-fortified foods. This latter factor is crucial for a successful iron fortification program [76].

What forticant should be used?

Despite the solubility and cost of iron fortificants used in food fortification, is important to address the fact that foods fortified with iron exhibit increased rancidity and sometimes develop unwanted color changes. The first is due to oxidation of unsaturated lipids, while the latter usually include a green to bluish coloration in cereals, a greying of chocolate and cocoa, and darkening of salt to yellow or red/brown. These sensory changes are highly variable and difficult to predict even in the same product in different situations [4].

The choice of the appropriate iron source for use in the fortification process in question is considered a critical point that in some cases requires an adjustment of the pH and/or additions of appropriate ligands to ensure iron solubilization, and by consequence its bioavailability. More reactive and potentially more bioavailable iron sources are converted to insoluble hydroxides when stored at the pH of cereals, and become refractory and not soluble even when the pH is lowered to 2.0 [77].

The selection of a specific fortificant compound should be made considering factors such as the potential for organoleptic changes to the product, the bioavailability of the fortificant, the cost, stability and the shelf-life [45]. To solve problems related to sensory aspects of iron fortified foods such unacceptable taste and color, a fortification technology that prevents the iron-mediated undesirable taste and appearance of the final product while preserving stability and bioavailability was developed. The process involves iron stabilization using colloid chemistry (encapsulation), chelation, and electrochemical chemistry (redox modulation). Results from color and sensory evaluations showed that formulation of products using the fortification technology known as “GrowthPlus” eliminated unwanted effects on taste, appearance, and product stability. Bioavailability evaluation using animals and humans showed this technology does not interfere with the bioavailability of iron from either ferrous bis-glycinate or ferrous fumarate [78]. However, the high cost of application of this technology currently limits its application in fortification programs.

Another practical barrier to effective implementation of iron food fortification programs are policy aspects. These are important for effective program management, with legislation often being required to support and sustain iron fortification programs [79]. The regulations in various parts of the world have been adjusted for this purpose. Concerns about safety regarding upper limit levels must be considered in food iron fortification programs, and foods fortified may receive a special label indicating the level of fortification in accordance with specific legislations [80].

Conclusion

Cereals are basic, ubiquitous and healthy foods, a good source of carbohydrates, fiber and phytochemicals, and low in fat. They are considered the major suppliers of energy in the human diet, with starch being the central component of the grain. At the same time iron deficiency anemia is the most common nutritional deficiency in humans, affecting 1.62 billion people globally. Part of the problem is related to the iron bioavailability.

The World Health Organization recommends some iron compounds for cereal fortification purposes and the choice of the compound should be made considering the local regulations, sensory aspects and also bioavailability of the iron compound in relation to the population requirement. Ferrous sulfate is the principal iron compound used in cereal fortification studies, and is often used in association with ascorbic acid and NaEDTA. However, iron bioavailability from ferrous sulfate is lower than from other compounds, such FeNaEDTA or ferric pyrophosphate. The s level of fortification, storage conditions, level of extraction, baking and the potential association with other chemical compounds influences the absorption efficiency rate.

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