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Food science and technology for management of iron deficiency in humans: A review

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ABSTRACT

Background: Long-term consequences of insufficient amounts of essential micronutrients can be more devastating than low energy intake in human diets. As food scientists, its great challenge and important to maintain the feed for world's increasing population considering the macro and micronutrient content of food. However, it is very important to produce more nutritious food in sustainable ways by utilising proper processing and storage methodologies which should be thoroughly investigated.

Scope and approach: This review focused on different strategies to enhance the iron content and bioavailability in food crops to minimize the iron deficiency in humans. Additionally, recent development and future research challenges in this context are identified.

Key findings and conclusions: A sustainable food based approach using iron rich dietary source in adequate amount with minimum content of absorption inhibitors can be effective in controlling iron deficiency and other usual associated nutritional deficiencies. Therefore, different approaches need to be developed to increase the iron content and decrease absorption inhibitors in food crops. In addition to this, effect of certain dietary additives, such as prebiotics, probiotics and metal chelators are needed to be studied properly.

1. Introduction

Iron is essential for almost every organism due to its involvement in a wide variety of metabolic processes. The functional inter conversion of iron oxidation states is the basic mechanism whereby iron participates in a variety of functions in plants, microbes and animals, including oxygen transport and its storage, electron transfer, substrate oxidation-reduction, hormone synthesis, DNA replication, repair and cell cycle control, nitrogen fixation, and protection from reactive oxygen species (ROS) (Abbaspour, Hurrell, & Kelishadi, 2014; Dlouhy & Outten, 2013). In mammals, different types of iron-containing enzymatic and non-enzymatic proteins (haemoglobin and myoglobin) carry out the function of oxygen transport and its storage. Iron also plays an important role in neuron signaling, as its required for myelination of spinal cord and white matter of central nervous system in brain (Soetan, Olaiya, & Oyewole, 2010). Iron deficiency is one of the principal risk factors for disability and death, affecting an estimated 2 billion people, worldwide. According to the estimates of WHO, 48% of children between 5 and 14 years and 52% of pregnant women in developing countries are anaemic (Akhtar, Ismail, Atukorala, & Arlappa, 2013; Bruno de Benoist, Erin McLean, Ines Egli, & Mary Cogswell, 2008). Continuous consumption of plant-based diets is the basic cause of low iron bioavailability, due to low absorption of non-heme iron (<10%), compared with heme iron (15–35%), which is predominantly present in animal tissues (Hurrell & Egli, 2010). Cereals and legumes also contain high amount of phytic acid (phytate; inositol phosphates), iron-binding phenolic compounds, and calcium, which further inhibit the absorption of iron in animals (Kumar, Sinha, Makkar, & Becker, 2010). Iron requirements increase three-fold during pregnancy because of expansion of maternal red-cell mass and fetal-placental growth (Pavord et al., 2012). Iron deficiency particularly prevalent in developing countries, it remains a serious public health problem in the developed countries as well, as a result of malnutrition. Effective and integrated management is needed to supply the optimum amount of iron in diet to prevent adverse effect of iron deficiency (Fig. 1). It's important to manage and provide optimum supply of iron in human diet which can be achieved by planning different methods for optimization and increased supply of iron. So in this review we addressed different strategies for management of iron deficiency. This review focused

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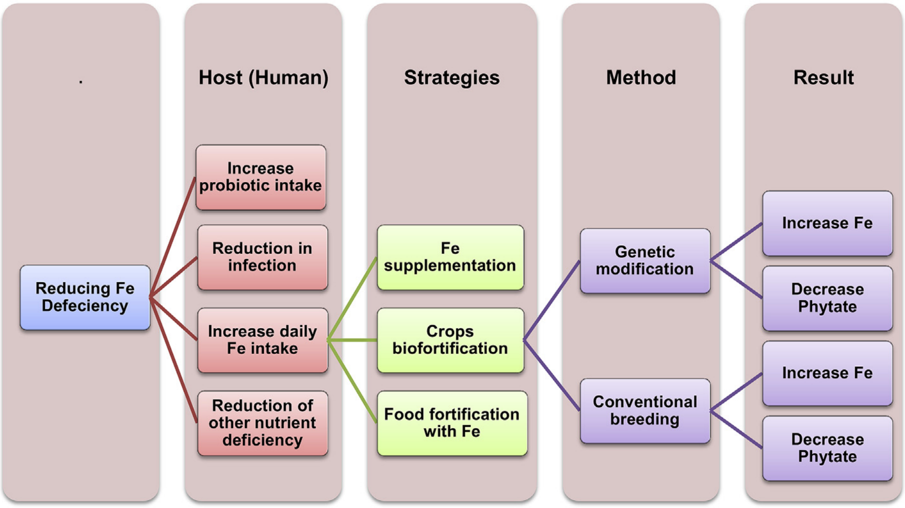

Fig. 1. Strategies to prevent the iron deficiency in human. (redrawn from Murgia et al., 2012).

on the theoretical aspects and recent progress in understanding of the role of soil in plant iron content, strategies for enhancement of iron in plants, and bioavailability in animals. Additionally, future research challenges in this context are identified.

2. Soil iron and human nutrition

Plants cannot easily acquire iron from soil although it is abundant. Therefore, iron deficiency is one of the major problems among crop plants, which limits growth and yields, and ultimately affect the food quality, quantity and nutrition. Absorption and translocation of iron in plants are highly regulated and co-ordinated processes for executing the supply of iron for normal growth and development, while also preventing excess accumulation (Saini, 2013). An excess accumulation of iron is toxic to plants and causes significant decrease in growth, biomass production and economic yield. For optimal plant growth, iron concentration in the range of 10^{-6}–10^{-5} M is required, however iron acquisition from soil is challenging due to the lower content of available iron ($<10^{-10}$ M at pH between 7 and 9) in soil solution (Marschner, 2011). Therefore, plants use different strategies to enhance the iron uptake and translocation by increasing iron solubility, including proton release in soil solution to lowering the pH, and enzymatic iron chelate reduction in soil (Fe^{+3} to Fe^{+2}) (Walker & Connolly, 2008). These two important strategies used by the plants to uptake the iron from plants are summarized in Fig. 2. The soil–-plant system or iron absorption is a contributory factor to human nutrition through sufficient micronutrient supply, and iron-deficiency in plants often limits plant growth, which indirectly affects nutritional content and agriculture productivity (Zuo & Zhang, 2010). In the last one decade, research has been focused on enhancement of iron through genetic engineering by modulating the expression of iron transporter, iron chelators, and sequestration proteins. Furthermore, effect of soil and foliar application of fertilizer on micronutrient content and quality of food crops are well understood. In coming sections, we have discussed different strategies used to enhance the iron content in crop plants.

3. Strategies used to enhance the iron content in plants

3.1. Biofortification

Development of an iron biofortified crop is largely a one-time investment that can benefit the health of millions and therefore establishes a multiplier effect. Second, biofortified crops can improve iron intake in malnourished rural populations that are unlikely to benefit from commercially fortified foods or supplements, which are often only available in cities. Therefore, an iron biofortified staple crop can help to combat iron deficiency and benefit the health of millions of peoples (La Frano, de Moura, Boy, Lönnerdal, & Burri, 2014). Overexpression of ferritin gene was initially used to increase iron content in plants. Ferritin is a universal intracellular protein that stores the excess iron and releases it in a highly controlled manner. However, increasing the level of ferritin in plants did not significantly increase the iron content; moreover, it caused symptoms of iron deficiency in the leaves of the transgenic plants (Drakakaki, Christou, & Stöger, 2000; Qu, Yoshihara, Ooyama, Goto, & Takaiwa, 2005). Qu et al., (2005) proposed that in addition to increased iron storage in seeds, enhanced iron uptake and translocation within different parts of the plant are required to further improve the iron biofortification. Suzuki et al. (2008) tested three transgenic rice lines possessing three barley genes involved in mugineic acid family phytosiderophores (MAs) synthesis in a field experiment on a calcareous soil. MAs are the metal chelators secreted by the roots of Graminaceous plants to chelate the iron. These chelated Fe^{+3}–MAs complex are absorbed from the soil through YS1 transporters (Fig. 2). These two transgenic rice lines, one with a barley gene encoding nicotianamine synthase (NAS) and the other with a barley gene encoding a dioxygenase, showed increased concentrations of iron in the grains. These results showed that introducing barley genes involved in the synthesis of MAs into rice is an effective and practical method for improvement of agricultural productivity and iron content in food crops grown in calcareous soils. Later, Masuda et al. (2013) developed iron biofortified rice by the concomitant introduction of soybean ferritin (SoyferH2) with barley genes encoding enzymes for MAs biosynthesis. The transformants exhibited 4.0 and 2.5 times more iron concentration in T_3 polished seeds compared with non-transformed (NT) plants grown in commercially supplied soil and calcareous soil, respectively. Different approaches used in biofortification of iron in rice are illustrated in Fig. 3. Transgenic plants were also developed for reduce content of inhibitors, such as phytate (phytic acid), which prevent the absorption on iron in animals. Phytate is poorly digested by humans and other monogastric animals (simple stomach with one chamber, such as in swine, rabbits, chickens, and horses) and negatively affects bioavailability of iron and other minerals. Seed phytate content was found to be