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REVIEW PAPER

# IMPORTANCE OF IODINE FORTIFICATION IN FOOD PRODUCTION: HUMAN HEALTH AND TECHNOLOGY*

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**Abstract**

Iodine (I) is an essential element in the human diet, and the demand for it is determined by age, sex, and lifestyle. According to the World Health Organization (WHO) recommendations, the daily intake of I should be 150 μg for adults and 250 μg for pregnant and breastfeeding women. The application of new solutions in the fields of food technology, nanotechnology, encapsulation and biofortification supports the activities carried out to increase the concentration and bioavailability of I in food products. Widespread iodization of salt enabled a reduction in I deficiency in many countries. In view of changing consumer preferences and dietary guidelines, the current recommendations need to be carefully verified. The WHO also estimated the loss of iodine to be 20% from production to consumer and another 20% during cooking. A valuable, natural source of I might be raw materials and products of plant origin after applying biofortification. Multicomponent fortification of iodized salt (IS) is not easy, as the stability of the added components varies, and suitable techniques are required, e.g. encapsulation, extrusion or spray drying. The problem of iodine deficiency is still common and affects approximately two billion people, school-age children, and women during pregnancy and lactation. An inadequate supply of I results, e.g. in hypothyroidism and goiter, congenital fetal anomalies and stillbirths. Biofortified vegetables, characterized by high bioavailability and stability, can be a safe source of I for the human body and an alternative to inorganic I from IS. Problems associated with the supplementation of food products with I or IS are mainly related to its stability and possible effects on the organoleptic characteristics of products. The paper presents food products as a source of I and alternative methods of enriching foods with I. In overcoming the problem of iodine deficiency disorders (IDD), the possibility of using IS was pointed out, but also the potential difficulties and limitations of using IS in food technology.

**Keywords:** iodine, iodized salt, trace element, biofortification, food technology

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# INTRODUCTION

Iodine (I) is an essential element in the human diet, and its deficiency can lead to the development of hypothyroidism and goiter and increases the risk of thyroid cancer (Wiernicka et al. 2011, Gietka-Czernel 2015, Zimmermann 2019) as well as stomach cancer (Zdrojewicz et al. 2016). During pregnancy, inadequate iodine supply results in an increased risk of spontaneous abortions, stillbirths, and congenital fetal anomalies (Wiernicka et al. 2011, Gietka-Czernel 2015, Zimmermann, Boelaert 2015). Iodine deficiency can result in cretinism or irreversible changes in the developing fetal brain (Wiernicka et al. 2011, Choudhry, Nasrullah 2018). Low dietary iodine content also leads to a reduction in IQ (intelligence quotient) by approx. 13.5 points. The group of above disorders is referred to as iodine deficiency disorders (IDD) – Wiernicka et al. (2011), Gietka-Czernel (2015), Zimmermann, Boelaert (2015), Zdrojewicz et al. (2016), Choudhry, Nasrullah (2018) – Table 1. Comprehensive information about IDD can be obtained from

Table 1

Possible iodine deficiency disorders for selected groups of humans (WHO 2007, Estman, 2018)

| Study group | Diseases |
|---|---|
| Fetus | stillbirth / congenital anomalies/ /increased perinatal morbidity and mortality / endemic cretinism / spontaneous abortion |
| Neonate | neonatal goiter / neonatal hypothyroidism / endemic neurocognitive / / mutism / spastic diplegia / infant mortality |
| Child and adolescent | impaired mental function / delayed physical development / / iodine-induced hyperthyroidism / goiter / increased susceptibility of the thyroid gland to nuclear radiation |
| Adults | goiter with its complications / hypothyroidism / impaired mental function / spontaneous hyperthyroidism in the elderly / / iodine-induced hyperthyroidism / increased susceptibility of the thyroid gland to nuclear radiation |

the Iodine Global Network (IGN) website (http://www.ign.org). Despite the wealth of data and preventive measures, IDD affects close to two billion people worldwide, of which approximately 50 million exhibit clinical manifestations and it is a major public health concern in many countries (Biban Lichiardopol 2017).

Iodine can be absorbed into the human body through the mucous membranes of the respiratory organs and through the skin. However, almost 90% of this element is supplied through the digestive tract (Wiernicka et al. 2011, Antonyak et al. 2018) – Figure 1. Inorganic compounds, such as potassium iodide, are absorbed from the stomach and upper small intestine very quickly and almost completely, while the absorption of the organic forms is limited and requires a reduction to iodide before or after the absorption. Absorbed I

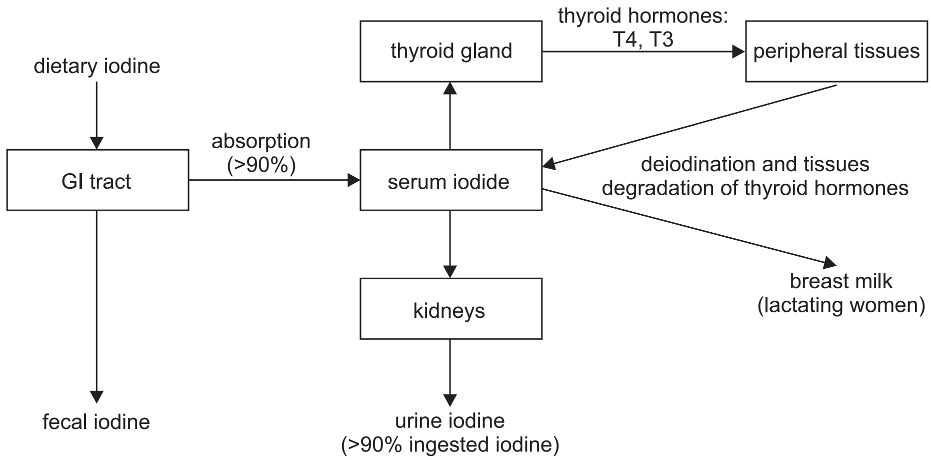


Fig. 1. Simplified metabolism of iodine: T4 – thyroxine, T3 – triiodothyronine (Bertinato, 2021)

is quickly removed from the blood plasma through the thyroid gland, kidneys, salivary glands, gastric mucosa, or lactating mammary glands, and any excessive amounts are excreted in the urine. Iodine in the form of iodide is transported from the blood to the thyroid gland thanks to the sodium/ /iodine symported protein (NIS), whose activity is controlled by the thyroid-stimulating hormone (TSH). Iodide is then oxidized to iodine by thyroid peroxidase (TPO), and incorporated into the thyroglobulin molecule (Tg). Thyroid hormones, thyroxine (T4), and triiodothyronine (T3) are then secreted into the bloodstream.

The demand for I is determined by age, gender, and lifestyle, and according to the World Health Organization (WHO) recommendations, its daily intake should be as follows: for children under 5 years of age – 90 μg, for children aged 6-12 – 120 μg, for children ≥ 12 years old and the adults – 150 μg, and for pregnant and breastfeeding women – 250 μg.

The Polish model of iodine prophylaxis, introduced in 1996 pursuant to a decision by the Ministry of Health, involves the obligatory iodization of table salt for domestic use (20-40 mg $kg^{-1}$), obligatory iodization of baby foods for infants (10 μg 100 $cm^{-3}$ milk), and the supplementation of pregnant women and breastfeeding mothers (150-200 μg $day^{-1}$) – Brzóska et al. (2015), Gietka-Czernel (2015).

The prevention of the under-supply of iodine is to be supported by databases that enable monitoring changes in I concentration in food products and the supply of iodine. One such database is Euthyroid (https://www.euthyroid.eu), the first European initiative of this type. The data provided online are for 2018, and the current data can be obtained after completing a form. The data were acquired from 22 EU Member States, which accounts for approximately 94% of the EU population, and from five other countries, i.e. Iceland, Israel, Macedonia, Norway, and Switzerland. Ershow et al. (2018)

draw attention to the importance of establishing databases concerning the I content in foods, beverages, and supplements, taking into account the factors associated with the variability of its concentration. Such databases would facilitate the composition of diets to ensure that I levels are controlled and maintained.

Three institutions in the United States: the U.S. Department of Agriculture (USDA), the U.S. Food and Drug Administration (FDA), and the Office of Dietary Supplements-National Institutes of Health (ODS-NIH), have prepared and shared data concerning the Iodine Content of Common Foods (https://www.ars.usda.gov/mafcl).

What happens, however, when the intake of I is higher than the required dose, for example in Japan, where it amounts to 5-14 mg per day or even more in the coastal areas? This is 5-14 times higher than the maximum recommended I intake level in the United States. The Japanese phenomenon generally indicates the lack of toxic effects of I on humans, while there are noted problems related to I deficiency when Japanese migrate to the United States. These observations, however, cannot be regarded as true in all circumastances. There are known cases of adverse effects of high I concentrations on humans, in particular those suffering from thyroid diseases, sensitive to I, or with endemic goiter.

Excessive fortification of foods with I should be avoided, as the element can cause diseases, e.g. autoimmune thyroiditis (Doh et al. 2018). Weng et al. (2014) point out that excessive intake of I may also cause adverse effects on humans, such as hyperthyroidism or Hashimoto's thyroiditis.

Most iodized salts contain KI for reasons of stability, although according to recent data, iodate can cause adverse effects on human health. The data extrapolated from animal experiments show that the maximum dose of iodate that humans can safely consume is 300 μg $day^{-1}$ (Doh et al. 2018). Liu et al. (2017) demonstrated that after cooking food for 2-15 min, almost all of the iodate added to it was converted into iodide (86.8%±14.5%) and molecular iodine (9.6%±6.2%), as a result of the reduction by vitamin C, glutathione and thiol protein groups.

Cohort studies show that for fortified foods other than NaCl, there is no clear evidence of the effect of the intervention on reducing the proportion of people with goiter, improving physical growth, or adverse events (Santos et al. 2019). However, results show that adding iodine to foods is likely to increase the urinary iodine concentration. Additional studies to better quantify the effect of the intervention on these outcomes, as well as other outcomes, are needed. A range of issues not described in this publication, such as medical aspects, metabolism, methods of assessment with a focus on urinary iodine concentration (UIC), can be expanded by analyzing the information recently presented by Hatch-Mcchesney and Lieberman (2022).

## IODINE SOURCES AND SUPPLEMENTATION

Iodine is found in nature (soil, algae, seaweed, seawater) in various forms: inorganic sodium ($NaIO_3$, $NaIO_4$) and potassium salts (iodides and iodates), inorganic diatomic iodine (molecular iodine or $I_2$), and organic monoatomic iodine (Patrick 2008). Chemical nomenclature could cause problems because the iodine atom (I) and the di-iodine molecule ($I_2$) are named iodine. Free iodine ($I_2$) does not occur in nature.

Iodine occurs in seawater at concentrations of approximately 45-60 μg $dm^{-3}$, in fresh water at 0.5-5 μg $dm^{-3}$, while in the soil, its concentration varies and ranges from 0.5 to 50 mg $kg^{-1}$. The average I concentration in the air is 10-20 ng $m^{-3}$, and the concentration of this element in the air and soil decreases with the increasing distance from the sea, which may result in IDD symptoms (Antonyak et al. 2018). The concentrations of I in selected food products are provided in Table 2.

Iodine (in the iodide form) in the aquatic environment is naturally incorporated into marine organisms at high concentrations. Therefore, fish and seafood are widely regarded as the richest iodine source in the human diet, and they also provide other essential nutrients beneficial to health and development. It is recommended to consume at least two portions of polyene--rich fish per week as part of a healthy balanced diet, which can ensure sufficient iodine intake. The recently published data on the concentrations of I in the available fish in England show the variation in their I content, and the I concentration being higher in wild fish than in farmed fish (Sprague et al. 2022). The I concentration in food products varies and is determined, for example, by geographical conditions. Therefore, general data on the popular food products and the recommended I intake may be useful, e.g. 1.5 g IS accounts for 47% of the recommended daily intake, 1 g seaweed accounts for 11-1989%, and an average-sized banana accounts for only 2% (Choudhry, Nasrullah 2018).

Based on meta-analysis data, the bioavailability of iodine from seaweeds (total I: 32-31 000 μg $g^{-1}$ dry weight) *in vitro* was low (2%-28%), but bioavailability *in vivo* was high (31%-90%), indicating an inadequate *in vitro* methodology (Blikra et al. 2022). Processing (blanching, soaking, drying, freeze-drying) may reduce the iodine content of brown algae from 3% to 99%, but the iodine content in algae is still high. The bioavailability of I from the cooked egg white or yolk was 33% and 10%, respectively (Lipiec et al. 2012).

Censi et al. (2022) point out that for as many as 26% of the subjects, urine iodine concentration (UIC, determined using the colorimetric ceric ion arsenious acid method) in the Vento region in Italy was <50 μg $dm^3$ for school students (aged 11-16 years). Similar problems were demonstrated in Norway for a study group of vegans, vegetarians and pescatarians (aged 18-60 years). Approximately 50% of subjects had an I intake of less than 50% per day of the recommended level, and the authors point to the need for urgent measures to be taken in order to determine the dietary guidelines for this group (Groufh-Jacobsen et al. 2020).

Table 2

Iodine concentrations in food products

| Food product | I concentration (μg g$^{-1}$)$^a$ | I concentration (μg kg$^{-1}$)$^b$ |
|---|---|---|
| Fish (marine) | 163-3180 | 1456 |
| Fish (freshwater) | 17-40 | 103 |
| Shellfish | 308-1300 | - |
| Tuna | - | 180 |
| Salmon | - | 140 |
| Shrimp | 35 | - |
| Nori | 16-43 | - |
| Kombu kelp | 2984 | - |
| Wakme | 66 | - |
| Eggs | 93 | - |
| Milk | 35-56 | 84 |
| Skimmed milk pasteurised | - | 300 |
| Whole milk pasteurised | - | 310 |
| Cheese | - | 77 |
| Cheddar cheese | - | 300 |
| Whey cheese | - | 803 |
| Yogurt, low fat, fruit-flavored | - | 410 |
| Meat | 27-97 | 68 |
| Cereal grains | 22-72 | 56 |
| Legumes | 23-36 | - |
| Vegetables | 12-201 | 89$^{\#}$<br>80$^{\#\#}$ |
| Fruits | 10-29 | |
| Banana | - | 97 |
| Apple, oranges, grapes, | - | <5 |
| Oils and fats | - | 36 |
| Fresh fruit | - | 31 |
| Bread | - | 17 |
| Nuts | - | 89 |

$^a$ –the geometric mean (FAO/WHO 2001), $^b$ – Fordyce (2003), $^{\#}$ – leafy vegetable, $^{\#\#}$ – other vegetable

Despite the data presented in Table 2, the I concentrations in food are different and range from 11 to 193 μg 100 g$^{-1}$ in sea fish and from 1.5 to 80 μg 100 g$^{-1}$ in freshwater fish (Szymandera-Buszka et al. 2008), and approximately 92 μg 100 g$^{-1}$ in seafood, shrimps, crabs and lobsters (Bouga et al. 2018).

The level of I in seaweed is highly variable and ranges from 11 to 6118 μg $g^{-1}$ seaweed dry matter weight (Bouga et al. 2018). Similarly, the content of I in vegetables, fruit, and cereal grains varies significantly and depends on the content of I in the soil and water (Wiernicka et al. 2011, Weng et al. 2014).

A good source of I can be cow's milk and hen's eggs (Brzóska et al. 2015, Krzepiłko et al. 2015), but its concentration in these products depends on the content of this element in the feed consumed by animals (Haldimann et al. 2005, Flachowsky, Franke 2014). According to Reijden et al. (2017), I derived from cow's milk can cover from 13% to 64% of the adult daily requirement for this element. However, since the iodine content in milk and dairy products varies (33-534 mg $dm^{-3}$), the determination of the recommended milk intake in order to provide the body with an appropriate amount of I is very difficult.

Milk sourced during the summer period contains 50% less I than winter milk (Payling et al. 2015). Analyses conducted in the UK showed that organic milk and UHT milk contained less I than pasteurized milk by approximately 44% and 27%, respectively (Stevenson et al. 2018), and these observations are consistent with those obtained by Payling et al. (2015) and Walther et al. (2018). The average I concentration in drinking milk in Poland, taking into account its losses due to the pasteurization process, is approximately 100-200 μg $dm^{-3}$ (Brzóska et al. 2015). The concentration of I in milk also increases with the use of feed supplementation with I compounds, although the results of these studies are inconclusive. Most experiments noted an increase in the I concentration after the use of its feed additive. Objections may be raised by the use of milk with an increased I concentration in the production of fermented drinks and cheeses. Shirone et al. (2018) obtained, from milk sourced from the cows fed with a feed with the I content of 10 mg $kg^{-1}$, pasta filata cheese produced with no starter cultures added, whose physicochemical parameters (the microorganism composition after 90 days of maturation) were the same as in the cheese produced from control milk. However, despite the lack of differences in the microorganism composition, and their biochemical parameters, the proteolytic enzyme activity depended on the I concentration. Moreover, higher concentrations of biogenic amines and propionic acid in the experimental cheese were noted. Unfortunately, the I concentrations in the obtained control cheeses and cheeses obtained from milk with an increased I concentration were not monitored.

In Switzerland and worldwide, IS is very rarely used in cheese production. Experiments demonstrated the possibility of increasing the I concentration by 402 μg $kg^{-1}$ after placing the cheeses in a brine containing $KIO_3$, even though I diffused in cheese more slowly than $Cl^-$ (Haldimann et al. 2019). At the same time, it was estimated that 10% of the recommended demand for I can be satisfied in Switzerland through the consumption of cheeses following dietary recommendations.

An analysis of the microorganism composition in sauerkraut with and without the addition of IS demonstrated no qualitative differences in the bacterial composition. However, differences were observed in the yeast and mold composition (Müller et al. 2018) – Table 3.

Table 3

Influence of iodized salt on quality of food products

| Food product | Effect of the use of IS | References |
|---|---|---|
| Bologna sausage | Iodine at a concentration of 25 mg $kg^{-1}$ had no effect on sensory characteristics, while at concentrations of 50 and 100 mg $kg^{-1}$, it caused minor changes in texture and color. | Greis et al. (2018) |
| Turkey mince cutlets | A 6% increase in the decomposition of free and bound thiamine during frying and storage. | Szymandera-Buszka, Waszkowiak (2003) |
| Pork meatballs | During storage, no effect on lipid oxidation was demonstrated. However, a reduction in the available lysine and methionine concentrations, and protein digestibility, was noted. | Hęś et al. (2012) |
| Sauerkraut | Yeast and mold growth during fermentation was inhibited with no starter culture added. No effect of IS on LAB. | Müller et al. (2018) |
| Edamer cheese | Uneven distribution of iodine in cheese. Iodate, when added to cheese, can be converted into iodide and bound to proteins. | Wiechen, Hoffman (1994) |
| Pork burger | No effect on the burger quality. | Szymandera-Buszka, Waszkowiak (2004) |

Drinking water can be an I source as well. However, its mineral content is determined, *inter alia*, by the distance between the water intake point and the sea. In many countries, very little information on the I content in drinking water and bottled water is available (Voutchkovai et al. 2014, Ershow et al. 2018). It is important that products containing essential nutrients are consumed in appropriate quantities ensuring that the body's demand for these components is satisfied. I deficiency is still a global problem. Moreover, the use (for health or worldview reasons) of diets that exclude or limit the I sources, e.g. a vegan diet, a low-salt diet, or a dairy-free diet due to lactose intolerance, can also be a reason for insufficient I intake (Ershow et al. 2018). Despite the recommendation, the actual supply of I with fish in the UK amounts to 10-20% and is greater for men than for women.

## ENRICHMENT OF TABLE SALT WITH IODINE

Many countries carry out iodine prophylaxis, which involves the introduction of I into the diet in the form of IS (Elsayed et al. 2015, Krzepiłko et al. 2015, Codling et al. 2017). Salt is regarded as a suitable carrier for the enrichment of foods with iodine as it is commonly accepted by consumers and consumed by virtually all population groups in all countries (WHO, 2014). Salt iodization technology is inexpensive and well-understood, and the production of salt is reduced to several plants, which facilitates the monitoring of the quality and quantity of I being introduced (Bouga et al. 2018).

The production of IS involves a sequence of simple processes, such as washing raw materials, draining, iodizing, heating or drying, cooling, and packaging. What is important is the cost of process implementation and the environmental effects of the technology applied. The main problem is the large volume of water used in the process, i.e. approximately 1.5 $m^3$ per 500 kg of salt, or 10 tons of rinsed salt. Of the three main salt iodization methods, i.e. dry mixing, drip feeding, and spray mixing, the latter is the only method suitable for coarse- and fine-grained salt and is easy to implement and effective (McGee et al. 2017). In the traditional technology of sea salt production, an important role is served by halophilic microorganisms. The role of microorganisms in the table salt production process is not fully understood, but it can be assumed that three microorganism types are of importance: extremely halophilic *Archaea* (family *Halobacteriaceae*), unicellular green flagellate algae *Dunaliella salina*, and the red halophilic bacterium *Salinibacter ruber* (Oren 2010). All of these microorganisms produce dye compounds, including carotenoids, which absorb quanta of sunlight and thus increase the temperature and efficiency of water evaporation. It is also thought that halophilic *Archaea* may be involved in halite crystallization. Nilawati et al. (2022) noted the following effects of the consortium of halophilic microbiota and *Haloferax* spp. on the possibility of obtaining purer NaCl characterized by larger rectangular and harder crystals: the bacteria can exchange the accumulated $Na^+$ for $K^+$ via the ion pump on the cell wall; NaCl crystallization is supported because when the process of exchange between $K^+$ (which reaches the bacteria) and $Na^+$ (being released) occurs, the Na+ and $Cl^-$ saturation around the bacterial cells initiates the formation of regular salt crystals. Therefore, the proposed technology involves the application of an *in situ* iodization technology combined with the enrichment of *Halophilic* bacteria consortium and *Haloferax* spp. to produce bio-based NaCl salt.

The enrichment of salt with micronutrients is an effective way to reduce their deficiency in developing countries because table salt is consumed commonly and at a constant level, irrespective of one's socio-economic status. The most common I salts added to foods include $KIO_3$ or KI. The levels of table salt fortification with iodine vary and in Europe range from 8 to 69 mg I $kg^{-1}$ table salt (NaCl). The highest I concentration in table salt is provided in Spain (51-69 mg $kg^{-1}$). In Poland, table salt is enriched with I in the form of KI (30±10 mg $kg^{-1}$ or $KIO_3$ (39±13 mg $kg^{-1}$ (Regulation of the Minister of Health 2002, Stoś et al. 2002, 2009), the I concentration in salt amounts to 20-40 mg I $kg^{-1}$ and, according to the information from the Global Fortification Data Exchange database, it amounts to 23 mg $kg^{-1}$, i.e.

115% of the maximum WHO recommended level (https://fortificationdata.org/ /country-fortification-dashboard/?alpha3_code=POL&lang=en). In certain African countries, e.g. in Kenya, Cameroon, Eritrea, and Guinea-Bissau, 1 kg of table salt contains 100 mg of I (Winger et al. 2008). The iodine content in raw iodized salt is usually unstable, and the actual I concentration in IS can differ by 8-49% from the declared concentration, especially when salt is stored in open containers and in a highly humid environment (Patel et al. 2012, Karim, Kargbo 2017, Ershow et al. 2018). Additionally, the impurities occurring naturally in salt, e.g. magnesium chloride, contribute to an increase in its moisture content and, consequently, to a loss of a significant amount of I added (Diosady et al. 2002). The iodine content can gradually decrease to 0.2-1.3 ppm over four months of storage (Nilawati et al. 2022). To stabilize the iodine content, 50 mg of iodine and 1000 mg of iron per kg of NaCl salt are introduced. This enrichment retains more than 75% I at 40°C and in 100% relative humidity.

An interesting proposal to solve the problem of widespread deficiency of folic acid, could be the simultaneous enrichment of table salt with these components (DFS, double fortified salt). A preparation containing 1-3% (w:v) I as KI, and 1-2% (w:v) of folic acid, was characterized by high stability of the components added, and after 12 months of storage under ambient conditions, it contained >80% of folic acid, and >90% of iodine (McGee et al. 2017).

Romita et al. (2011) obtained DFS with I and iron, stable for six months at 40°C and with a relative humidity of 40-60%. In order to minimize the interaction between the elements, the authors developed a method for the spray drying of iron fumarate, which allowed them to obtain sufficiently small (<20 μm) microcapsules that they then mixed with IS. The innovative salt can, at the same time, prevent IDD and iron deficiency anemia. However, a recent cohort analysis results showed that DFS only had a slight positive effect on the hemoglobin concentration and the incidence of anemia as compared to IS (Baxter et al. 2022).

Multicomponent fortification of IS is not easy, as the stability of the added components varies, and suitable techniques are required, e.g. encapsulation, extrusion or spray drying. Quadruple fortified salt was obtained with the solid iron-vitamin B12 premix and sprayed I and folic acid solution (Modupe, Diosady 2021). The salt contained 1,000 ppm iron, 50 ppm I, 25 ppm folic acid, and 0.25 ppm B12. The production required the stabilization of folic acid and the coextrusion of vitamin B12 and iron. Quintuple fortified salt (Q5FS), i.e. iodized salt (IS) fortified with an additional four micronutrients: iron, folic acid, vitamin B12 and zinc, were comparable to IS and DFS with iron (Puri et al. 2022). Examples of multicomponent fortification with IS are provided in Table 4.

Since iodine derived from natural sources is widely regarded as safe, Doh et al. (2018) proposed a new IS (kombu salt) obtained by the method

Table 4

Examples of fortified salt preparations

| Compounds added | Technique used | Reference |
|---|---|---|
| I, Fe | microencapsulation | Modupe et al. (2022) |
| I, Fe, vitamin A | spray-cooling technique | Zimmermann et al. (2004) |
| I, Fe, vitamin A | encapsulation, granulation | Raileanu, Diosady (2006) |
| I, Fe, folic acid | encapsulation, spraying | Modupe et al. (2019) |
| I, Fe, folic acid, vitamin B12 | encapsulation, coextrusion, spraying | Modupe, Diosady (2021) |
| I, Fe, folic acid, vitamin B12, Zn | microencapsulation | Puri et al. (2022) |
| I, Fe, folic acid, vitamin B12, Zn | extrusion (cold), encapsulation, spraying | McDonald et al. (2022) |

of spray drying of a mixture of sea salt and an I-rich aqueous extract of the seaweed *Laminaria ochroleuca (*kombu). The salt properties were similar to, or better than, those of commercial IS, and according to the authors, kombu salt could find application in the food industry.

## POSSIBILITIES AND LIMITATIONS OF THE USE OF IODINE SUPPLEMENTS IN THE FOOD INDUSTRY

At the beginning of the 20th century, IS was introduced in many countries. Currently, it is assumed that approximately 86% of the global population has the option of using IS (Ershow et al. 2018). In 169 countries, obligatory IS use programs, and in 194, voluntary IS use programs are known. However, in the majority of these countries, there are no databases informing of the I content in food products ("Map: Fortification Legislation." Global Fortification Data Exchange. [Accessed 23/08/2022.] http://www.fortificationdata.org.). Iodine stability in salts is quite high and affected by storage and processing conditions, e.g. loss of I was 41.16% after heating at 200°C for 24 h and 58.46% when IS was heated with an oxidized agent. At room temperature and relative humidity of 30-45%, in sealed paper bags, 58.5% of iodine was lost in approximately 3.5 years (Biber et al. 2002). Fallah et al. (2020) demonstrated that to protect iodine in salt, the ambient temperature, darkness, and non-humidity were the best conditions for storing IS.

It can be assumed that the iodine stability is high and that the addition of I to foods, in various forms, will bring about no significant changes to its quality (West, Merx 1995, Blankenship et al. 2018). Doubts relate to the analytical methods used, the organization of experiments, and the interpretation of results, as there are no standards in this area. However, the World Health Organization (WHO, 2007) estimated the loss of iodine to be 20%

from production to consumer and another 20% during cooking, but without presenting any confirming data. A very interesting discussion on the issues related to the introduction of I into foods, its stability and bioavailability were presented by Winger et al. (2008). The presented information can be interpreted in different ways and, as the authors indicated, for such an important issue, further discussion is necessary.

Szymandera-Buszka and Waszkowiak (2004) presented data according to which the losses of total I and inorganic I after frying burgers were approximately 20-30%. Beneficial effects of fat-free frying and the addition of soy hydrolyzate to pork mince on the I retention were demonstrated. The beneficial effects of plant proteins on the I retention were noted when successfully using dietary wheat fibers and soy proteins as the carriers of I added in the form of KI or $KIO_3$ in order to satisfy the requirements of the Polish government (approximately 23 mg I $kg^{-1}$ which is equivalent to 30 mg KI $g^{-1}$ or 39 mg $KIO_3$ $kg^{-1}$) – Szymandera-Buszka (2021). Vegetable homogenates (pumpkin, cauliflower, broccoli, carrot) after enrichment with I in a KI or $KIO_3$ solution, followed by spray drying, also appeared to be good iodine carriers (Zaremba et al. 2022). At the same time, the authors pay attention to the critical process parameters, i.e. the need for verification of the enrichment conditions and immediate freezing (76°C) of the intermediate product before lyophilization. However, the interesting results and new products, particularly in view of changes to consumer preferences, require further analyses, e.g. the determination of the interaction between components and an analysis of I release and bioavailability. At the same time, it is worth paying attention to information on the possible adverse effects occurring when obtaining pickled vegetables in IS, e.g. a reduction in the vitamin C concentration in vegetables, or a change in their texture (Amr et al. 2004)

Blankenship et al. (2018) presented data on the effect of the use of IS on the organoleptic properties of processed foods. Only six experiments observed slight changes in the organoleptic properties of processed foods with IS added: a bitter taste of lemon-flavored cake (KI); an improved color of the Mortadella sausage and dried meat products ($KIO_3$); darkening and softening of vegetable marinades, darkening of potherb mustard pickle, and a minor change in the flavor of cucumber pickles.

Several meat and fish products were prepared with IS ($KIO_3$), and the I stability was determined through the production process. The processes applied included heating, fermenting, freezing, hot smoking, ripening by enzymes and storing (Meinhardt et al. 2022). Irrespective of the processes being carried out and unit operations, the I concentration in food products did not change significantly (Table 3).

However, examples are known of adverse changes in food caused by the addition of I compounds (Table 3). Even though the NaCl environment appears to be very unfriendly to microorganisms, as salt is used in food production as a preservative decreasing the water activity coefficient value, it was demonstrated that it is a source of halophilic bacteria and archaea (Satari et al. 2021). The microorganisms found in products containing I compounds should be subject to monitoring, and preparations containing I compounds have an effect on the microbiota of both food products and the gastrointestinal tract. Lanza et al. (2020) demonstrated that fermentation of olives in a brine containing 0.006% $KIO_3$ significantly increased the I concentration in olives as compared to a brine containing only sea salt (Sale marino di Trapani). The I concentration in olives was also determined by their cultivar and amounted to 109 and 38 µg in 100 g for *Carolea* cv. and *Leucocarpa* cv. olives, respectively. No significant effect of the addition of I salt on the organoleptic characteristics, or the color of olives was noted. A significant reduction in the population, and a reduction in the diversity, of yeast to the *Candida* genus were noted in a brine obtained with the addition of $KIO_3$. The presence of yeast and hydrolytic enzymes, e.g. cellulases and pectinases, can contribute to a reduction in the hardness of olives.

The most common chemical compounds of I added to table salt are KI or $KIO_3$. KI is a strong reducing agent, while $KIO_3$ is an oxidizing agent, which is why food producers are concerned that I and its salts can cause oxidation, e.g. of lipids, ascorbic acid, oxidation of ferrous ions to ferric ions, or reduction of ferric ions to ferrous ions, and changes in protein functions due to the formation of disulfide bonds between amino acids.

Analyses were conducted to determine the stability of I in products with IS added during the implementation of technological processes and storage (Table 5). Of all the commonly used I salts, $KIO_3$ is much more stable than KI. Goindi et al. (1995) concluded that during the preparation of 50 different Indian dishes, the average loss of I in the products depended on the applied thermal processing method and amounted to: 22% for pressure cooking, 37% for cooking, 27% for shallow frying, 20% for deep frying, 6% for baking, and 205 for steaming. Rana et al. (2013), when preparing Indian dishes as well, applied the following methods of cooking: baking, shallow frying, deep frying, pressure cooking and microwave cooking, and demonstrated that the losses of I fell within a range of 6.58-51.08%. According to Longvah et al. (2012), the lowest retention of I was obtained when preparing Indian dishes using shallow frying in oil (52±23%), and the highest retention was obtained during pressure cooking (82.2±6.2%). The retention of I in the same dishes with no IS added ranged from 27.8% to 98%, and the I concentration in 100 g of the product was 3.7 and 10.0 µg, respectively (Longvah et al. 2013). The results presented in Table 5 indicate an increase in the loss of I with an increase in the temperature used and the duration of its use. The factors important for the loss of I also included the exposure of a product to sunlight and a change in acidity through the addition of acetic acid. Chavasit et al. (2002) demonstrated that a considerable loss of I was caused by spices, i.e. garlic, ground dried pepper, ground dried chili, fresh chili, green curry paste, and the addition of sugar. Ascorbic acid caused a complete loss of I immediately after addition.

Table 5

The effect of technological processes on I retention in food products

<table>
<tr><th>Process or unit operation</th><th>Product type</th><th>Iodine salt type</th><th>Iodine retention (%)</th><th>References</th></tr>
<tr><td>Cooking</td><td rowspan="6">chilled Turkey meatballs</td><td rowspan="2">KI</td><td>55</td><td rowspan="6">Waszkowiak, Szymandera-Buszka (2000)</td></tr>
<tr><td>Frying</td><td>59</td></tr>
<tr><td>Cooking</td><td rowspan="2">KI, collagen isolate</td><td>84</td></tr>
<tr><td>Frying</td><td>90</td></tr>
<tr><td>Cooking</td><td rowspan="2">KI, collagen isolate enriched</td><td>70</td></tr>
<tr><td>Frying</td><td>85</td></tr>
<tr><td rowspan="2">Boiling</td><td>carrots</td><td>KI</td><td rowspan="2">0</td><td rowspan="3">Comandini et al. (2013)</td></tr>
<tr><td>potatoes</td><td>KI</td></tr>
<tr><td>Baking</td><td>mashed potatoes</td><td>KI</td><td>~100</td></tr>
<tr><td rowspan="2">Roasting (15 min)</td><td rowspan="4">pork meatballs</td><td>$KIO_3$</td><td>95</td><td rowspan="4">Szymandera-Buszka, Waszkowiak (2007)</td></tr>
<tr><td>KI</td><td>95</td></tr>
<tr><td rowspan="2">Roasting (30 min)</td><td>$KIO_3$</td><td>88</td></tr>
<tr><td>KI</td><td>79</td></tr>
<tr><td rowspan="2">Frying</td><td rowspan="4">pork burgers</td><td>KI</td><td>70</td><td rowspan="4">Szymandera-Buszka, Waszkowiak (2004)</td></tr>
<tr><td>KI, soy hydrolyzate</td><td>71</td></tr>
<tr><td rowspan="2">Frying (without fat)</td><td>KI</td><td>74</td></tr>
<tr><td>KI, soy hydrolyzate</td><td>81</td></tr>
<tr><td>Baking</td><td>bread</td><td>KI</td><td>83</td><td rowspan="3">Greis et al. (2018)</td></tr>
<tr><td>Parboiling</td><td>sausage</td><td>KI</td><td>86</td></tr>
<tr><td>Pasteurization</td><td>pickled cucumber</td><td>KI</td><td>49</td></tr>
<tr><td>Fermentation</td><td>fish</td><td>$KIO_3$</td><td>84</td><td rowspan="3">Chanthilath et al. (2009)</td></tr>
<tr><td>Fermentation (sunlight)</td><td rowspan="2">fish sauce</td><td>$KIO_3$</td><td>45</td></tr>
<tr><td>Fermentation (shade)</td><td>$KIO_3$</td><td>87</td></tr>
<tr><td>Steaming and drying</td><td rowspan="2">fish crackers</td><td rowspan="2">$KIO_3$ $(ZnO+Fe_4(P_2O_7)_3)$</td><td>92.7</td><td>Pinkaew et al. (2015)</td></tr>
<tr><td>Storage (four months)</td><td>72.7</td><td></td></tr>
<tr><td>Storage (one year)</td><td>biofortified fish</td><td>iodine-rich macroalgae</td><td>83</td><td>Barbosa et al. (2022)</td></tr>
<tr><td rowspan="3">Cooking</td><td>potatoes</td><td rowspan="3">$KIO_3$</td><td>109</td><td rowspan="3">Meinhardt et al. (2019)</td></tr>
<tr><td>pasta</td><td>118</td></tr>
<tr><td>rice</td><td>150</td></tr>
</table>

cont. Table 5

| Process or unit operation | Product type | Iodine salt type | Iodine retention (%) | Reference |
|---|---|---|---|---|
| Pressure cooking | various products | no supplemented | 22 | Geetanjali et al. (1995) |
| Boiling | | | 37 | |
| Shallow frying | | | 27 | |
| Deep frying | | | 20 | |
| Roasting | | | 6 | |
| Steaming | | | 21 | |
| Boiling | various Indian recipes | KI | 40 | Rana, Raghuvanshi (2013) |
| Roasting | | | 10 | |
| Shallow frying | | | 6 | |
| Deep frying | | | 10 | |
| Pressure cooking | | | 51 | |
| Microwave cooking | | | 47 | |

Meinhardt et al. (2019) demonstrated, in contrast to the WHO analyses, that I in the form of $KIO_3$, when added to water while cooking pasta, potatoes, or rice, was very stable and no losses of I, previously observed mainly due to its volatility, were noted. After cooking the products, their I concentration was even higher than the theoretical maximum concentration. Attention was drawn, however, to the need for additional experiments to verify the results obtained.

The addition of IS is also used in fish processing, and during the production of fermented fish and fish sauce, where no significant differences were noted in the organoleptic evaluation as compared to control products (Chanthilath et al. 2009). The I retention in these products ranged from 45% to 87% (Table 5). Multi-micronutrient fortified fish crackers (a popular snack in South-East Asia) with I, Fe and Zn were considered a potential food vehicle to improve I, Fe and Zn statuses, especially for children (Pinkaew, Karrila 2015). The retention of I in the triple-fortified product was as high as after the production processes as well as after 4-month storage (Table 5). Despite the positive organoleptic rating of products containing different micronutrient compositions, statistically significant I losses were noted during storage, which were induced by ZnO and $C_4H_2FeO_4$. In particular, the addition of Fe in the form of ferrous fumarate resulted in significant oxidative changes, to which attention should be paid after the application of multi-component supplementation of food products. An increase in the micronutrient concentration, including in I in fish, can also be obtained by feeding fish with iodine-rich macroalgae (*Laminaria digitata*) – Barbosa et al. (2020, 2021). It was demonstrated that after obtaining fortified farmed fish: gilthead seabream (*Sparus aurata*) and common carp (*Cyprinus carpio*), the consumption of 150 g of steamed fortified seabream or carp contributes to a significant daily intake of I, respectively, up to 12% and 19-23% (Barbosa et al. 2021). Other experiments using feeds containing iodine-rich algae demonstrated no significant increase in the I concentration in the tissues of gilthead seabream as compared to the control material (Ferreira et al. 2022).

According to the WHO, the intake of sodium chloride should not exceed 5 g $day^{-1}$; numerous measures are being taken to reduce the salt concentration in foods (Wachowska, Adamczak 2019). Excess salt in the diet can lead to arterial hypertension, atherosclerosis or strokes. However, since the recommended reduction in the table salt amount in the diet can significantly reduce the effectiveness of preventing I deficiency, it is necessary to search for other sources of this element (Hęś et al. 2012, Pyka et al. 2019).

Alternative carriers of I were proposed, e.g. collagen (Waszkowiak, Szymandera-Buszka 2008*a*), dietary fiber derived from wheat (Waszkowiak, Szymandera-Buszka 2008*b*) or soy protein preparations (Waszkowiak, Szymandera-Buszka 2008*b*, Hęś et al. 2012).

Collagen can be used as the carrier of I, in particular for people who should avoid the intake of sodium chloride (Waszkowiak, Szymandera-Buszka 2008*b*). The use of collagen isolate as the carrier of KI in fried meatballs and cooked meatballs reduced the I loss, as compared to the I losses when IS was used and during cold storage, by 26% and 27%, respectively, and during deep-frieze storage, by 15% and 27% (Waszkowiak et al. 2000).

The use of dietary wheat fiber and soy proteins reduced the I losses during thermal processing and storage of meat products, especially for the fortification of products with KI. The use of high-protein and fiber-rich preparations as the carriers of I can inhibit lipid oxidation (Hęś et al. 2012). Sensory analysis of products containing iodized soy isolate and wheat fiber showed no significant differences in the color, flavor, aroma, or overall acceptability of meat products containing or devoid of I. The only difference was the less intense aroma of products with wheat fiber added. In products with a higher I concentration, in particular, those containing soy isolate, there was an increase in thiamine stability during thermal processing and storage, as compared to products enriched with iodized table salt (Waszkowiak, Szymandera-Buszka 2008*a*).

In Sudan, sucrose was used as the carrier of I, which was obtained by adding an I salt to a sugar solution prior to crystallization, or spraying sugar before drying. It was demonstrated that the enrichment of sugar with I could help eliminate IDD in endemic areas (Eltom et al. 1995).

Tomaszewska et al. (2016) suggest that mineral water could be a good I source. However, in view of the high rate of I release from water, i.e. more than 10% of its initial amount per hour, it would be advisable to increase, pursuant to the WHO Directive (2011), the concentration of I added to water up to 0.15 mg $dm^{-3}$. Bottled water “Jodica” from Nieszawa in Poland is one of the few examples of water enriched with I. The iodine concentration in "Jodica" amounts to 150 µg $dm^{-3}$, which satisfies the adult daily requirement for this element. Mineral waters "Zuber", "Franciszek", "Józef" and "Henryk" contain a significant amount of I, and can be used in the diet of people at risk of its deficiency (Krzepiłko et al. 2015). It should be noted that mineral waters enriched with I are still wholesome sources of other elements beneficial to human health, e.g. Mg and Ca.

Eggs, which are the second largest source of I of animal origin, when additionally enriched with I, can be a food product that is important in the prevention of IDD in humans. Supplementation of laying hen feed with I offers an easy possibility for obtaining eggs with an increased content of this element. Feed supplementation with I has no effect on the sensory characteristics of the eggs if the I concentration in a feed is less than 5 mg $kg^{-1}$ (Opaliński 2017). Moreover, the intake of eggs enriched with I lowers blood cholesterol levels and is recommended for people with cardiovascular diseases (Kurosad et al. 2005).

A valuable, natural source of I might be raw materials and products of plant origin after applying biofortification (Weng et al. 2014). Biofortification is an upcoming, promising, cost-effective and sustainable technique of delivering micronutrients to a population that has limited access to diverse diets and other micronutrient interventions. In order to obtain them, it is suggested that a fertilizer with the addition of *Laminaria japonica* algae with the I content of approximately 734 mg $kg^{-1}$ be used. Landini et al. (2011), Cerretani et al. (2014) and Nath et al. (2018) note that biofortified vegetables can be a safe source of I for the human body and an alternative to inorganic I from IS. The I sources of plant origin, as compared to I derived from IS, are characterized by high bioavailability and stability, e.g. celery, after cooking for 2 and 5 min, retained 93% and 86% I, respectively. The high stability of I in biofortified vegetables was confirmed by Li et al. (2018). After cooking for 5 min, celery contained 85% of the initial I content, while only approximately 30% of the initial I content remained in the IS cooked with the celery. The loss of I from the biofortified celery leaves after soaking for 8 h was only 3.5-10.4%, and the bioavailability of I from the biofortified celery after *in vitro* digestion was 74.08-68.28%. Voogt et al. (2009) cultivated hydroponic lettuce an intake of 5 g of which provides 25% of the dose of I recommended for adults. Even low I compound concentrations (I $<0.25$ mg $dm^{-3}$ or $IO^{3-}<0.50$ mg $dm^{-3}$) promoted strawberry growth, had a beneficial effect on I retention and the biofortification of crops with exogenous I is a noteworthy strategy to control IDD.

# SUMMARY

An inexpensive and relatively simple treatment that involves the introduction of I compounds to foods prevents severe human health problems. The application of new solutions in the fields of food technology, nanotechnology, encapsulation and biofortification supports the activities carried out to increase the concentration and bioavailability of I in food products. Widespread iodization of salt enabled a reduction in I deficiency in many countries. However, the issue is still present and leads to very serious problems relating to IDD. The omission or disregard of the procedure for adding I compounds to foods, spices or food additives, but primarily to table salt, results in severe health, social and financial complications. In view of changing consumer preferences and dietary guidelines, the current recommendations need to be carefully verified. Probably, in view of the WHO recommendations concerning the reduction in salt intake, it would be appropriate to consider increasing the I concentration in table salt, also because of a possible I loss during the performance of technological processes. It would also be advisable to add IS to dishes – if possible, at the end of thermal processing. It is also justified to introduce iodination of mineral water and milk, as well as biofortification of selected vegetables and feeding flock and cattle with food rich in I to provide adequate I intake in the setting of coexisting recommendations to reduce salt intake. However, attention should be paid to the potential link between the supplementation with I and the occurrence of thyroid diseases in some populations. It is necessary to monitor the concentration of I in food products, its bioavailability and possible deficiencies, as well as excessively high concentrations. The problem of too high I concentration poses little hazard that is offset by the elimination of the consequences of its deficiency.

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