January – March, 2026
Literature Review
DOI: http://dx.doi.org/10.30867/action.v11i1.3074
Pages: 352 – 363
AcTion: Aceh Nutrition Journal
p-issn 2527-3310; e-issn 2548-5741

The role of iodine in cognitive development through thyroid hormones: Impacts during pregnancy, childhood, and adolescence

Peran yodium dalam perkembangan kognitif melalui hormon tiroid: Dampak pada masa kehamilan, anak-anak, dan remaja

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Article History:
Received: December 20, 2025; Revised: January 06, 2026; Accepted: January 19, 2026; Published: March 08, 2026.

Publisher:
Politeknik Kesehatan Aceh
Kementerian Kesehatan RI

Abstract

Iodine deficiency has been reported to re-emerge in developed countries, such as the United States and Taiwan, with significant cognitive consequences, despite inconsistencies in the existing body of evidence. Meanwhile, Indonesia lacks up-to-date data on population iodine status. This literature review aimed to examine the role of iodine in cognitive development and the impact of iodine deficiency at different life stages. The review employed a literature-based approach by searching English-language articles published between 2016 and 2025 using the Scopus, Google Scholar, PubMed, and ScienceDirect databases and the PRISMA analytical framework. The included studies were original research and review articles involving pregnant women, children, and adolescents. The findings indicate that iodine deficiency is associated with impaired cognitive function, particularly when exposure occurs during pregnancy. Adequate iodine intake through food fortification programs, supplementation, and consumption of iodine-rich foods supports optimal cognitive development. Therefore, continuous monitoring and strengthening of iodine fortification interventions are required to support human capital development. In addition, enhanced iodine supplementation programs for pregnant women, improved education on iodized salt consumption, and ongoing monitoring and evaluation of fortification programs are needed to update and strengthen iodine status data in Indonesia.

Keywords: Iodine deficiency, cognitive development, pregnancy, children

Abstrak

Defisiensi yodium muncul kembali di negara maju seperti Amerika Serikat dan Taiwan dengan dampak kognitif signifikan meski terdapat ketidakkonsistenan hasil penelitian, sementara Indonesia kekurangan data status yodium terkini. Tinjauan literatur ini bertujuan untuk mengkaji peran yodium terhadap perkembangan kognitif serta dampak defisiensi yodium pada berbagai tahap kehidupan. Metode yang digunakan adalah tinjauan literatur dengan penelusuran artikel berbahasa Inggris yang dipublikasikan pada tahun 2016–2025 melalui basis data PubMed dan ScienceDirect dengan menggunakan metode analisis PRISMA. Studi yang disertakan meliputi penelitian asli dan artikel tinjauan yang melibatkan kelompok ibu hamil, anak-anak, dan remaja. Hasil kajian menunjukkan bahwa defisiensi yodium berkaitan dengan penurunan fungsi kognitif, terutama bila terjadi sejak masa kehamilan. Pemenuhan asupan yodium yang adekuat melalui program fortifikasi pangan, suplementasi, dan konsumsi pangan sumber yodium terbukti mendukung perkembangan kognitif yang optimal. Oleh karena itu, diperlukan penguatan program suplementasi yodium bagi ibu hamil, peningkatan edukasi mengenai konsumsi garam beryodium, serta pemantauan dan evaluasi berkelanjutan terhadap program fortifikasi guna memperbaharui dan memperkuat data status yodium di Indonesia.

Kata Kunci: Defisiensi yodium, kehamilan, perkembangan kognitif

Introduction

Brain development is related to the quality of human resources (HR), which determines productivity and competitiveness. Disorders in the brain during the early stages of life can cause a decline in cognitive function. One factor that can affect cognitive development is the lack of essential micronutrients, such as iodine. Iodine deficiency is a major preventable cause of brain damage during pregnancy and impedes child growth and development (Ma & Brough, 2025). Data from Northern Taiwan show that 54% of pregnant women experience iodine deficiency. Similarly, in the United States, the iodine status of pregnant women remains below the WHO threshold (Daniel & Mangano, 2025). However, in Indonesia, there are still no recent data on deficiencies across all age groups.

The effects of iodine deficiency include hypothyroidism, goiter, fetal death, and impaired cognitive function in children (Olivieri et al., 2021; Zhao et al., 2019). Iodine deficiency also increases the risk of infant mortality and is a leading cause of preventable brain damage during early development (Bath, 2019). Studies have shown that severe iodine deficiency experienced during early pregnancy causes permanent neurological damage that cannot be reversed by iodine supplementation from an early age (Li et al., 2022).

Universal Salt Iodization (USI) is the most effective intervention program for addressing iodine deficiency. One of the main programs for combating iodine deficiency is Universal Salt Iodization (USI) to ensure that all salt consumed contains iodine in accordance with the standards of the. The equitable use of iodized salt is one of the main interventions for addressing iodine deficiency. Iodized salt is considered an effective solution because it is easily accessible to the public and reasonably priced (Indriana et al., 2021).

Salt is an ideal commodity for fortification because it is inexpensive to produce, and almost everyone consumes a relatively similar amount. Aside from salt, the main source of iodine-rich foods is the sea. For example, pollock is high in iodine (Nerhus et al., 2018).

Although extensive research has been conducted on iodine deficiency, previous literature reviews have significant limitations, such as a limited focus on early childhood or pregnant women without integrating evidence across the life cycle. Thus, there has been no recent review providing evidence of iodine deficiency and cognitive function in pregnant women, children, and adolescents.

This review is novel in that it integrates the mechanisms of iodine intake and cognitive function during pregnancy, childhood, and adolescence. This literature review is supplemented with epidemiological evidence mapping across the life cycle to support food fortification policies in Indonesia. These findings are relevant given that data on iodine deficiency in Indonesia are still very limited and can contribute to the development of cognitive function to improve human resources.

Therefore, this literature review aims to present information on the impact of iodine intake on cognitive function by exploring the effects of iodine deficiency on cognition in pregnant women, children, and adolescents through thyroid hormone mechanisms and examining sources of iodine intake and the effectiveness of sustainable iodine deficiency control efforts.

Methods

This study used a literature review approach with a narrative design to summarize the evidence on the role of iodine in cognitive development during pregnancy, childhood, and adolescence. A narrative design was chosen to combine the results of different studies based on the impact of iodine deficiency.

The reference search will be conducted from September to November 2025. English-language articles published in reputable journals between 2016 and 2025 were searched through the main databases, PubMed and Science Direct, which identified relevant publications on the role of iodine in growth and cognitive function throughout the life cycle.

All searches were conducted without any restrictions on country or time. The search strategy used Boolean operators with the keywords "iodine deficiency OR iodine status OR iodine intake AND neurodevelopment OR children's cognitive OR pregnancy." The inclusion criteria were as follows: 1) research articles showing that iodine deficiency can affect cognition. 2) The population included pregnant women, children, and adolescents.

The literature search was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, as shown in Figure 1. In the initial stage, 1,450 articles were identified, covering various types of publications, including qualitative studies, theses, and dissertations. However, only articles with full texts will be analyzed to evaluate the role of iodine in cognition during pregnancy, childhood, and adolescence.

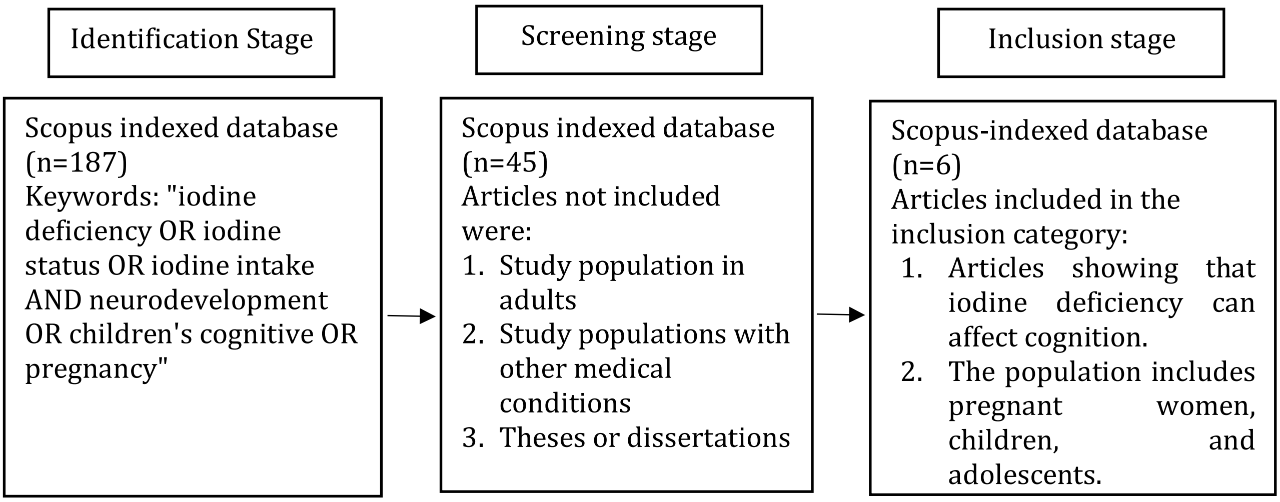

Figure 1. PRISMA diagram for article selection

The study results are organized based on age groups from pregnancy, children, and adolescents with a maximum age of 18 years to understand the role of iodine in cognitive development. The sample size used was > 100 participants, which was used as the criterion for study quality. This grouping allows for the analysis of differences in the effects of iodine deficiency throughout the life cycle. Adjustments for confounding factors, such as family socioeconomic status, were also considered in this study.

Result and Discussion

Iodine as a Component of Thyroid Hormones

The thyroid gland plays a crucial role in regulating metabolism in almost all tissues. Thyroid hormone activity originates from two iodine-containing hormones: T3 and T4. Iodine is the primary nutrient that determines the body's ability to produce both thyroid hormones.

The thyroid gland, which is small in size, is located at the front of the neck and consists of two lobes connected by an isthmus (Vatavu et al., 2024). The essential role of iodine is to support thyroid hormone production. In the digestive tract, iodine is converted into iodide, which is absorbed by the stomach and duodenum and then eliminated by the thyroid gland (Milanesi & Brent, 2017). In individuals with normal thyroid function, iodine absorption takes approximately 10 h, but it can be faster in cases of overactive thyroid (Farebrother et al., 2019).

Adults who receive adequate iodine intake use approximately 150-250 μg per day for thyroid function (Leo & Braverman, 2019). The body stores 15-20 μg of iodine, with 70-80% stored in the thyroid gland (Nazeri & Delshad, 2022). The breakdown of T3 and T4 hormones releases iodine back into circulation, which is primarily excreted through urine (Li et al., 2024). The mammary glands also collect iodine for secretion into breast milk, and small amounts are found in the gastric mucosa, salivary glands, and choroid plexus (Dold et al., 2017).

The thyroid gland produces T3 and T4 by absorbing iodine and combining it with tyrosine, which is then released into the bloodstream to regulate the metabolism of all cells in the body (Shahid et al., 2023; Pompa et al., 2024). Iodide regulates thyroid function by decreasing the response to TSH and inhibiting its oxidation and uptake. Even small changes in iodine intake can affect TSH levels through negative feedback mechanisms (Moreno-Reyes et al., 2025). The thyroid gland converts iodine into hormones T3 and T4 (Sorensen & Gauger, 2015). Thyroid cells absorb iodine and combine it with the amino acid tyrosine to form T3 and T4, which are then released into the bloodstream (Carvalho & Dupuy, 2017).

Iodide, a component of iodine, controls thyroid function by reducing the thyroid gland's response to TSH and preventing iodide oxidation (Shahid et al., 2023). Changes in iodine intake can alter thyroid function and affect the TSH levels. If iodine intake decreases, the thyroid gland cannot produce sufficient thyroid hormones (T3 and T4); therefore, the body responds by increasing TSH production to stimulate the thyroid to work harder. Thus, iodide plays a role in the feedback mechanism by modulating the thyroid response to TSH (Wenzek et al., 2022).

Iodine and Cognitive Function

Iodine is the primary component in the formation of thyroid hormones T3 and T4, which regulate gene expression in brain tissue (Calzà et al., 2015). Brain development occurs in several stages. The first and second trimesters are referred to as the critical phases, as this is when neuron multiplication, migration, and cell organization occur (Paladini & Birnbaum, 2019) . Meanwhile, the third trimester until the age of 3 years involves glial cell multiplication and migration, as well as the process of myelination (Ortinau & Neil, 2015).

In the early stages, the fetus depends on the mother's thyroid hormones, as the fetal thyroid gland is not yet functioning optimally (Landers & Richard, 2017; Ramezani & Nazarpour, 2021). Maternal T4 hormone is converted into active T3 in the fetal brain by the deiodinase enzyme, which supports normal development (Bárez-López et al., 2018). Thyroid function in the fetus becomes active during the second trimester and at birth. The T4 hormone in umbilical cord blood originates from the mother, indicating the importance of the mother's iodine status for the baby's brain development (Bath, 2019). Thus, iodine deficiency in the mother during pregnancy can cause long-term or permanent damage to the fetal brain and increase the risk of cognitive impairment (Moleti et al., 2016).

Thyroid hormones play a role in visual development, motor skills, memory, and language (Anderson 2008; Bocheva et. The critical period for preventing brain damage is between the 12th and 30th week of pregnancy. This occurs during neuronal proliferation, migration, and neuropil formation. Iodine deficiency causes a decrease in brain weight, changes in the number of cells in the brain, and cognitive impairment (Bath, 2019; Velasco et al., 2018). Therefore, iodine supplementation is recommended during 12–30 weeks of pregnancy.

Children with iodine deficiency exhibit lower learning abilities and cognitive performance, including reduced IQ. Decreased T4 hormone levels are associated with impaired memory function, leading to poor learning outcomes. A study in Portugal showed that children with adequate iodine status had higher IQs than those with iodine deficiency (Bailote et al., 2022). Studies in Indonesia have also shown that children in areas endemic for iodine deficiency mostly have average performance (Alfa et al., 2015).

Impact of Iodine Deficiency on Cognitive Function

Iodine deficiency during pregnancy disrupts the balance of thyroid hormones in both the mother and fetus. A fetal brain that does not receive sufficient thyroid hormones is at risk of long-term cognitive impairment. This is because thyroid hormones play a role in the growth and development of the fetal brain, and disruption of thyroid hormones will have an impact on cell differentiation and gene expression (Giannocco et al., 2021). During the fetal period and early infancy, various genes in the brain are expressed through T3 binding, which depends on the production of T3 and T4 within cells by the D2 enzyme (Bárez-López et al., 2018). Therefore, iodine supplementation in pregnant women is necessary to reduce fetal mortality and improve children's cognitive function.

During the first 1000 days of life, brain development is at risk if the baby experiences iodine deficiency. The risk of cognitive impairment in babies with severe iodine deficiency can lead to cretinism (Lee, 2021). To maintain normal thyroid hormone levels, an increase in the rate of iodine turnover in babies is essential for those with iodine deficiency. As children enter childhood, iodine deficiency, which causes impaired motor skills and problem-solving abilities, can be addressed through iodine supplementation. The occurrence of mild iodine deficiency in children, which can hinder cognitive optimization, has been overcome by iodine supplementation in mothers during pregnancy (Al Rahmad, 2023; Bath, 2019).

Table 1 presents a comparison of research findings from various studies examining the relationship between iodine deficiency and cognitive function, as measured by learning outcomes or knowledge tests across different age groups. These effects were observed from early childhood to adolescence, as evidenced by prospective cohort studies showing the long-term effects of iodine deficiency during pregnancy. Although the indicators of iodine status used varied, the direction of the findings remained consistent, confirming that iodine affects cognitive growth.

Table1 . Comparison of studies on the role of iodine in cognitive growth

Research Title	Sample	Design	Results
Effect of Inadequate Iodine Status on Academic Performance of Secondary School Girls in Sokoto State, Nigeria (Umar et al., 2018).	248 adolescent girls (14-17 years old)	Quasi-Experimental Design	35% of adolescents with mild to moderate iodine deficiency, as measured by serum T3, T4, and TSH levels, had lower academic performance in English and mathematics tests.
Iodine Deficiency Associated with Adolescent Cognitive Performance in an Iodine Deficiency Endemic Area (Latifah et al., 2020).	120 adolescents (11–14 years old)	Cross-Sectional Study	Goiter caused by thyroid enlargement significantly lowered IQ ($p < 0.05$). Low levels of parental education are also associated with lower intelligence in children.
Urinary Iodine Concentrations in Preschoolers and Cognitive Development at 4 and 6 Years of Age: The Rhea Mother-Child Cohort on Crete, Greece (Kampouri et al., 2024).	304 children	Longitudinal mother-child cohort	Children with urinary iodine concentrations < 100 µg/L (n = 10) showed lower motor development scores at age 4 and lower intelligence (IQ) scores at age 6. UIC levels ≥ 300 µg/L (n = 101) were also associated with decreased cognitive scores in children aged 4 and 6 years. In addition, a higher maternal body mass index (BMI) at the beginning of pregnancy was associated with lower UIC levels in children.
Effect of Iodine Deficiency on Academic Performance of School Children in Dawro Zone, Southwest Ethiopia: A Prospective Cohort Study (Asfaw & Belachew, 2020).	692 primary school children (6-12 years old)	Prospective Cohort Study	Children with iodine deficiency were 4.49 times more likely to have low academic scores than those with adequate iodine status. Attendance in class contributed to a 1.10 point

		decrease in scores. Meanwhile, children from low-income families are 2.57 times more likely to have low academic performance.

The thyroid gland adapts to mild iodine deficiency by increasing its activity to maintain euthyroid conditions and keep TSH levels ideal during pregnancy (Límanová & Svačina, 2015). This is evident in a cohort study by Kampouri et al. (2024), which showed that UIC results < 100 μg/L in children resulted in lower IQ scores at age 6. However, another study found no significant difference in intelligence test results between the mild and moderate deficiency groups, although there was a tendency toward lower IQ scores (Bailote et al., 2022).

This adaptation process begins with increased iodine absorption mediated by increased TSH secretion in response to decreased T4 levels (Moleti et al., 2016). This has been proven epidemiologically by Asfaw and Belachew (2020), who reported that iodine deficiency increases the risk of low academic performance by 4.49 times. This represents a long-term mechanism originating from the decline in maternal iodine status, which affects the optimization of fetal brain function.

The most severe impact of low iodine intake occurs in cases of severe iodine deficiency. When the median iodine status in children is below average, the population is categorized as having severe iodine deficiency, characterized by a high prevalence of goiter, cretinism, and hypothyroidism (Booms et al., 2016; Ashraf, 2025).

Iodine deficiency during pregnancy can affect the fetus, leading to neurological and severe cognitive disorders in the offspring. This is because the thyroid gland can no longer maintain normal thyroid function. Maternal hypothyroidism is associated with impaired neurological development in children. Several other studies have reported that children born to mothers with thyroid dysfunction tend to show lower intelligence scores, particularly in learning and language skills (Menotti et al., 2024).

In addition to iodine deficiency, exposure to disruptive substances, such as goitrogenic compounds, inhibits iodine absorption and disrupts thyroid function (Agrawal et al., 2018). Goitrogenic compounds can inhibit the sodium-iodide symporter (NIS) during the synthesis of T3 and T4. This disruption can cause cognitive deficits, including a decrease in IQ (Demeneix, 2019). Therefore, optimal cognitive function in children is an important determinant of learning ability and quality of life in adults. Overall, the studies summarized in the table indicate that iodine deficiency is associated with impaired cognitive function, and maternal iodine deficiency during pregnancy is also linked to long-term cognitive dysfunction. In addition, sociodemographic factors, such as parental education level, influence children's cognitive development. However, to date, there are relatively few prospective cohort studies that specifically examine the effects of iodine deficiency on cognitive development across various life stages, from pregnancy to childhood and adolescence.

Sources of Iodine

The distribution of iodine sources varies across regions; iodine is commonly found in coastal areas, primarily as iodide and iodate (Carpenter et al., 2021).

Table 2. Iodine content in seafood products (Yusuf et al., 2025)

Food Type	Iodine Content (μg/g)
Yellowtail fish	5.29
Grouper	3.75
Shrimp	2.32
Milkfish	1.83
Tuna	1.43

Table 2 shows the types of iodine-containing food sources in Indonesia. Several types of land-based foods, such as tubers, spices, vegetables, and nuts, are significant sources of iodine. The following table shows the iodine content in various foods from sources other than the sea, based on Indonesian BPS Statistics.

Table 3. Iodine content in food categories (Yusuf et al., 2025)

Food Type	Iodine Content (μg/g)
Root Vegetables	6.2
Spices	6.12
Vegetables	4.91

Cereals and legumes	3.67
Eggs	2.19

In addition to the amount of iodine in food, the amount of iodine absorbed by the body also varies. Foods from the sea, such as fish and seaweed, usually contain iodine that is easily absorbed, with an absorption rate of 90% (Ristic-Medic & Glibetic, 2015). Plant-based foods have lower bioavailability because they contain goitrogenic substances that interfere with iodine absorption (Muzzaffar et al., 2022). Therefore, cooking processes such as boiling, steaming, and soaking can help reduce the levels of goitrogenic substances and improve iodine absorption (Sun et al., 2022).

Mitigation Efforts

Cognitive impairment is the main effect of iodine deficiency, which can cause cretinism. This condition can occur when iodine deficiency is prolonged and severe. Brain damage can occur as early as the second trimester; however, iodine deficiency can be corrected. At a moderate level of severity, cognitive impairment becomes a more obvious neurological problem, resulting in a decline in learning ability and academic achievement. This has an impact on human resource development in the field. Therefore, efforts to improve the quality of life through the prevention and control of iodine deficiency are important.

Iodine supplementation of 220-250 µg/day is recommended for pregnant and lactating women to meet their increased iodine requirements (Lee & Pearce, 2018). Adequate iodine intake during pregnancy is important for maintaining maternal thyroid function and supporting optimal fetal brain development. Iodine deficiency during this period can have adverse effects, including an increased risk of miscarriage and preterm birth (Toloza et al., 2020).

Research findings indicate that low Breast Milk Iodine Concentration (BMIC) (<100 µg/L) reflects inadequate iodine status and may increase the risk of neurodevelopmental disorders in infants (Jin et al., 2021). An intervention study that provided potassium iodide capsules containing 225 µg of iodine daily for 6 months showed higher BMIC compared to mothers who did not consume supplements (Gebreegziabher & Stoecker, 2017). Thus, iodine supplementation significantly contributes to increased iodine transfer through breast milk.

Mild-to-moderate iodine deficiency is associated with cognitive decline and poor academic performance. Therefore, ensuring adequate iodine intake during lactation through iodine-rich foods or supplementation is an important intervention for supporting optimal cognitive development in children. Food fortification is another way to meet iodine needs. Food fortification is the process of adding micronutrients, such as iodine, to food to prevent or correct nutritional deficiencies in a population (McNulty, 2017). Countries such as the United States and Switzerland have been fortifying salt with iodine since 1920 (Bishai & Nalubola, 2002). In India, salt fortification with iodine has been carried out since the 1960s, which has played a role in reducing the incidence of goiter (Yadav & Pandav, 2018).

In Indonesia, salt fortification with iodine has been carried out in the previous years (Thakur et al., 2023). Indonesia has implemented a mandatory salt fortification policy with iodine to ensure that the community gets adequate iodine intake, especially in areas prone to iodine deficiency. The iodine deficiency control program in Indonesia is primarily implemented through Universal Salt Iodization (USI). The equitable distribution of iodized salt is one of the main interventions because it is easily accessible to the public and is reasonably priced (Indriana et al., 2021). Iodized salt is the result of fortification with the addition of potassium iodate (KIO3) to salt in accordance with the Indonesian National Standard (SNI Number 01-3556-2016), which contains 30-80 ppmKIo3 (Niwattisaiwong et al., 2017).

Currently, the use of iodized salt in various processed food industries has begun to be widely implemented in many countries. For example, in the Republic of Moldova, the bread industry uses iodized salt in its production process. These bread products are consumed by most households and contribute to approximately 80% of the total salt intake in adults. These products have been consumed by women of childbearing age and children in socioeconomic subgroups (Salaru et al., 2023). In addition to the Republic of Moldova, Belarus also consumes baked bread with iodized salt that meets 40% to 70% of the daily iodine requirement (Salaru et al., 2023).

Biofortification of vegetables with iodine is one strategy to address iodine deficiency disorders. The biofortification strategy involves increasing the iodine content of vegetables through hydroponic cultivation or the use of iodine-rich fertilizers. Vegetables such as celery, broccoli, and pak choi have shown an increase in iodine content when grown hydroponically with iodine supplementation (Li et al., 2018). A study conducted in Germany showed that iodine-enriched fruits and vegetables attract consumers who prioritize natural food sources. Survey results showed that approximately 85% of respondents preferred iodine-enriched products over supplements to increase their iodine intake (Welk et al., 2021).

The choice of iodine-biofortified foods over supplements is also supported by people's high motivation and confidence in choosing healthy foods. In addition, iodine biofortification not only increases intake naturally but also has the potential to support cognitive development, especially in populations at risk of iodine deficiency (De Steur et al., 2015). These efforts demonstrate that iodine fortification of various daily food products can be an effective strategy for improving iodine sufficiency in the population. However, in Indonesia, few people cultivate iodine-enriched vegetables through biofortification. Therefore, pregnant women require additional iodine, and potassium iodide supplementation is often recommended.

In addition, policy strengthening is needed through the expansion of the Universal Salt Iodization (USI) program to the processed food industry with the application of iodine levels ≥ 30 ppm KIO_3 in accordance with Indonesian National Standard (SNI) Number 01-3556-2016. Iodine supplementation for pregnant women needs to be optimized and accompanied by nutritional education through campaigns to increase iodine consumption. The program targets pregnant women, elementary school children, and adolescents. Monitoring and evaluation of iodine status in the community also need to be carried out through urinary iodine concentration (UIC) surveys (Niwattisaiwong et al., 2017). UIC sampling is a sensitive marker that reflects iodine intake in the population. Iodized salt sampling can also be performed, given the limited current data on iodine status in Indonesia.

Conclusion

This literature review demonstrates that iodine deficiency can impair cognitive function by disrupting thyroid hormone synthesis. This leads to reduced IQ, motor disorders, and even cretinism, especially if it occurs during pregnancy and in early life.

Recommendations include efforts to address this issue through the provision of iodine supplementation of 220-250 μg/day for pregnant women and education on food fortification, particularly the use of iodized salt in daily life. Continuous evaluation of the salt fortification program is necessary to update the data on iodine status in Indonesia.

Acknowledgments

The author expresses his deepest appreciation to all parties who contributed to the implementation of this research. We thank the supervisors and co-authors for their input and excellent collaboration.

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