Annals of Medicine

ISSN: 0785-3890 (Print) 1365-2060 (Online) Journal homepage: www.tandfonline.com/journals/iann20

Global prevalences of erythropoiesis-associated micronutrient deficiencies (iron, folate, and vitamin B_{12}) among pregnant women: a systematic review and meta-analysis

Nhi Thi Hong Nguyen, Yang-Ching Chen, Nguyen Thanh Nhu, Hoang Bui Bao, Chien-Yeh Hsu, Arpita Das & Jane C.-J. Chao

To cite this article: Nhi Thi Hong Nguyen, Yang-Ching Chen, Nguyen Thanh Nhu, Hoang Bui Bao, Chien-Yeh Hsu, Arpita Das & Jane C.-J. Chao (2025) Global prevalences of erythropoiesis-associated micronutrient deficiencies (iron, folate, and vitamin B_{12}) among pregnant women: a systematic review and meta-analysis, Annals of Medicine, 57:1, 2602960, DOI: 10.1080/07853890.2025.2602960

To link to this article: https://doi.org/10.1080/07853890.2025.2602960

ANNALS OF MEDICINE
2025, VOL. 57, NO. 1, 2602960
https://doi.org/10.1080/07853890.2025.2602960

RESEARCH ARTICLE

OPEN ACCESS Check for updates

Global prevalences of erythropoiesis-associated micronutrient deficiencies (iron, folate, and vitamin B_{12}) among pregnant women: a systematic review and meta-analysis

Nhi Thi Hong Nguyen[a,b], Yang-Ching Chen[a,c,d,e,f], Nguyen Thanh Nhu[g], Hoang Bui Bao[b,h], Chien-Yeh Hsu[i,j], Arpita Das[a] and Jane C.-J. Chao[a,f,j,k]

[a]School of Nutrition and Health Sciences, Taipei Medical University, Taipei, Taiwan; [b]Health Personnel Training Institute, University of Medicine and Pharmacy, Hue University, Hue, Vietnam; [c]Department of Family Medicine, Wan Fang Hospital, Taipei Medical University, Taipei, Taiwan; [d]Department of Family Medicine, School of Medicine, College of Medicine, Taipei Medical University, Taipei, Taiwan; [e]Graduate Institute of Metabolism and Obesity Sciences, Taipei Medical University, Taipei, Taiwan; [f]Nutrition Research Center, Taipei Medical University Hospital, Taipei, Taiwan; [g]Faculty of Medicine, Can Tho University of Medicine and Pharmacy, Can Tho, Vietnam; [h]Department of Internal Medicine, University of Medicine and Pharmacy, Hue University, Hue, Vietnam; [i]Department of Information Management, National Taipei University of Nursing and Health Sciences, Taipei, Taiwan; [j]Master Program in Global Health and Health Security, Taipei Medical University, Taipei, Taiwan; [k]TMU Research Center for Digestive Medicine, Taipei Medical University, Taipei, Taiwan

ABSTRACT

Background: Deficiencies of iron, folate, and vitamin B12 micronutrients are considered a global public health issue. These deficiencies not only lead to anemia but are also linked to numerous short- and long-term health risks for both mothers and children. This study aimed to estimate the global prevalence of erythropoiesis-associated micronutrient deficiencies (iron, folate, and vitamin B12) in pregnant women.

Materials and Methods: We systematically searched three databases, including PubMed, Embase, and Scopus, along with a manual search for observational studies published up to August 26, 2024. Data extraction was independently screened by two reviewers. Random-effects models were employed to pool data on prevalences of iron, folate, and vitamin B12 deficiencies among pregnant women. We identified 43 studies from 28 countries.

Results: Global pooled prevalences of single iron, folate, and vitamin B12 deficiencies were 28.4% (95% CI, 21.1–37%), 11.1% (95% CI, 3.9–27.5%), and 17.1% (95% CI, 8.8–30.6%), respectively. Pooled prevalences of double micronutrient deficiencies of iron or folate were 53.1% (95% CI, 49.8–56.5%) and 49.6% (95% CI, 46.2–53%), respectively; double micronutrient deficiencies of folate or vitamin B12 were 6.2% (95% CI, 1.2–25.8%) and 11.8% (95% CI, 3.3–34.1%), respectively. Pooled prevalences of triple micronutrient deficiencies of iron or folate or vitamin B12 were 36.1% (95% CI, 13.1–68%), 34.3% (95% CI, 16.9–57.3%), and 12.6% (95% CI, 7–74.8%), respectively.

Conclusion: The findings highlight the high prevalences of erythropoiesis-related micronutrient deficiencies in pregnant women worldwide. Targeted interventions to mitigate these deficiencies during pregnancy.

ARTICLE HISTORY
Received 28 July 2025
Revised 1 December 2025
Accepted 6 December 2025

KEYWORDS
Iron deficiency; folate deficiency; vitamin B12 deficiency; pregnant women; worldwide prevalence; meta-analysis

1. Introduction

Adequate maternal nutrition during pregnancy is crucial for fetal growth and development and plays a key role in the long-term health of children [1]. The micronutrient status greatly changes during pregnancy [2]. Due to insufficient dietary intake and increased metabolic requirements, micronutrient

CONTACT Jane C.-J. Chao chenjui@tmu.edu.tw School of Nutrition and Health Sciences, Taipei Medical University, No. 250, Wuxing Street, Xinyi District, Taipei 110, Taiwan.

Supplemental data for this article can be accessed online at https://doi.org/10.1080/07853890.2025.2602960.

deficiencies are common in pregnant women [3]. Iron, folate, and vitamin B_{12} are essential micronutrients in erythropoiesis, and demands for them further increase during pregnancy [3,4]. Erythropoiesis is stimulated early in pregnancy. Direct, non-radioactive measurements of red cell mass indicate that up to 50% of the total increase occurs during the first trimester [5]. Marginal micronutrient deficiencies in the first trimester could potentially lead to more-severe deficiencies later [6]. Micronutrient deficiencies related to erythropoiesis are categorized as single, double, and triple deficiencies involving iron, folate, and vitamin B_{12} [7]. These deficiencies not only lead to anemia but also pose numerous health risks for both mothers and children [8–11]. An iron deficiency during pregnancy can lead to poor fetal growth, prematurity, and even intrauterine death due to severe anemia, along with increased maternal morbidity and mortality [12,13]. Folate is crucial during pregnancy for embryonic formation, particularly during neural tube closure, as well as for preventing birth defects and growth retardation [14–16]. Previous research indicated that inadequate folate is linked to higher risks of adverse pregnancy outcomes, including stillbirths, preterm deliveries, and low birth weights [17,18]. Vitamin B_{12} deficiency during pregnancy has been associated with adverse outcomes, including spontaneous abortion, low birth weight, intrauterine growth restriction, preterm birth, neural tube defects, developmental delays, and impaired cognitive performance in newborns [19–23].

An iron deficiency is the most prevalent nutrient deficiency worldwide and the leading cause of anemia in pregnancy, with the highest prevalence observed in South-East Asia (48.7%) [24,25]. Folate and vitamin B_{12} deficiencies are also critical public health concerns, affecting millions of people globally [17]. The previous research estimated that over 4 billion people worldwide had inadequate folate intake [26]. In addition, a pooled analysis reported that 25% of pregnant women worldwide were affected by vitamin B_{12} deficiency [27]. Micronutrient deficits frequently coexist; however, studies on their prevalence and severity are limited in the global pregnant population. Determining these deficiencies is vital to implementing effective prevention and control strategies [28].

Recent studies reported prevalences of deficiencies in iron, folate, and vitamin B_{12} among pregnant women in some countries. For instance, in India, respective prevalence rates were 67.7, 26.3, and 74.1% [4], while in Tanzania, they were 37.8, 24, and 9.7% [24]. However, these rates vary across studies. Therefore, we conducted a systematic review and meta-analysis to estimate prevalences of both single and multiple erythropoiesis-related micronutrient deficiencies (iron, folate, and vitamin B_{12}) in pregnant women worldwide.

2. Methods

This research followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) (Table S1) guidelines [29]. The review protocol was registered in PROSPERO with the registration no. CRD42024548649.

2.1. Eligibility criteria

Eligible published studies were peer-reviewed observational studies that presented the prevalences of single and multiple erythropoiesis-related micronutrient deficiencies among pregnant women during any trimester of pregnancy. Serum ferritin, folate, and vitamin B_{12} levels were evaluated using any methods to determine the prevalence of iron, folate, or vitamin B_{12} deficiency. We included late erythropoiesis-related micronutrient deficiency prevalence data from cohort studies if the original papers reported baseline and late pregnancy results.

2.2. Outcomes

For the present review, primary outcomes were estimated prevalences of single micronutrient deficiencies (iron, folate, or vitamin B_{12}), double micronutrient deficiencies (iron or folate, iron or vitamin B_{12}, and folate or vitamin B_{12}), and triple micronutrient deficiency (iron or folate or vitamin B_{12}). A secondary outcome was prevalences of micronutrient deficiencies by trimester. The erythropoiesis-related single,

double, and triple micronutrient deficiencies were defined as the presence of one, two, or three of the following: iron deficiency, folate depletion, or a vitamin B_{12} deficiency [7].

2.3. Information sources and search strategy

Three electronic databases (PubMed, Embase, and Scopus) were searched without limitations on publication year. We restricted the results to only English-language publications. Literature search terms used included "iron deficiency", "folic acid deficiency or folate deficiency", "vitamin B_{12} deficiency", "pregnant women," or "pregnancy," and "prevalence" or "incidence" (Table S2). Search results comprised papers from three databases published up to May 15, 2024, with manual searching continuing until August 26, 2024.

2.4. Study selection

Titles, abstracts, and full texts of relevant publications obtained from systematic searches of the databases and manual searches were independently screened by two authors (N.T.H.N. and A.D.) using predefined, piloted forms. Any discrepancies were resolved through discussions with N.T.N. for final inclusion in the analysis.

2.5. Data extraction

The extracted variables included the last author's name, year of publication, country, income levels, types of erythropoiesis deficiency, gestational age, mean/median age, number of participants, prevalences of erythropoiesis deficiencies of iron, folate, and vitamin B_{12}, and diagnostic criteria for erythropoiesis micronutrient deficiencies (by the World Health Organization (WHO), Centers for Disease Control (CDC), individual country, or not reported (NR)). For studies with unclear eligibility, we contacted the corresponding authors at least twice to gain detailed information on the scales used to define erythropoiesis-related micronutrient deficiencies.

2.6. Quality assessment

Two researchers independently evaluated the quality of the studies and risk of bias using the Joanna Briggs Institute Critical Appraisal Checklist for Prevalence Studies [30]. Every study was reviewed based on nine questions from the checklist. These include evaluation of the appropriateness of the sampling frame and sampling method, adequacy of the sample size, and detailed description of the study subjects and setting. The checklist also assesses the adequacy of sample coverage, the validity and reliability of methods used to identify the condition, and consistency in measurement across participants. Furthermore, it considers whether appropriate statistical analyses were conducted and whether the response rate was adequate or appropriately managed. The responses to the checklist items were categorized as "yes", "no", "not clear," or "not applicable". The overall score derived from "yes" answers ranged 0–9. An overall score of ≤ 4 in a study indicated a high risk of bias and low quality, 5 or 6 indicated a moderate risk of bias and moderate quality, and > 6 indicated a low risk of bias and high quality [30]. In cases of disagreements between evaluations, the reviewers discussed the underlying reasons to obtain a consensus, with consultation from a third independent reviewer if needed.

2.7. Data synthesis

We conducted a narrative synthesis for all studies and meta-analyses using quantitative data on prevalences of micronutrient deficiencies (iron, folate, or vitamin B_{12}) among pregnant women. Prevalences of erythropoiesis-related micronutrient deficiencies were pooled by employing random-effects models. The meta-analysis utilized a logit transformation to model variability among the studies. The "metaprop" function from the "metafor" package in R was used to pool data and calculate effect sizes (v. 4.4.1, R Foundation for Statistical Computing; Vienna, Austria). Heterogeneity was measured utilizing the I^2

statistic, with a corresponding significance Q test p value. An I^2 value of 0% implies no observed heterogeneity, while values of 25, 50, and 75% respectively reflect low, moderate, and high levels of heterogeneity [31].

2.8. Assessment of heterogeneity

To determine sources of heterogeneity across studies, subgroup meta-analyses were conducted for four pre-specified variables of three categories (age (≤ 25 and > 25 years), region (WHO subregions: Africa, America, Asia, Europe, and Western Pacific) [32], and income level (low middle income, upper middle income, and high income)) based on World Bank Data [33], and diagnostic criteria for erythropoiesis-associated micronutrient deficiencies (WHO [17,34], CDC [35], individual country, and NR). According to WHO, iron deficiency is defined as serum ferritin level of < 15 µg/L [34], and folate deficiency as serum folate level of < 4 ng/mL [17]. Vitamin B12 deficiency is defined as plasma vitamin B_{12} < 150 pmol/L (203 pg/mL) according to WHO [17], or plasma vitamin B_{12} < 148 pmol/L according to CDC [35].

2.9. Sensitivity analysis

In the sensitivity analysis, we excluded studies that did not specify diagnostic criteria for erythropoiesis-associated micronutrient deficiencies. We then reconducted the meta-analysis to evaluate the effect of their removal on the overall pooled prevalence of single micronutrient deficiencies. We further performed a sensitivity analysis by outlier removal and trim-and-fill methods, comparing the original results with the reanalyzed results to confirm the stability and robustness of our main meta-analyses of single micronutrient deficiencies.

2.10. Publication bias

Publication bias was assessed through Egger's asymmetry test [36]. A p value of < 0.05 in Egger's test suggested the presence of potential publication bias. All statistical tests with $p < 0.05$ were considered significant. Data analysis was implemented using R software (v. 4.4.1; R Foundation for Statistical Computing).

3. Results

3.1. Study selection

In total, 4962 publications were initially identified from database searches, with four additional papers found *via* a manual search. After excluding 1750 duplicated articles in the first stage, 3216 articles were screened according to the titles and abstracts. Subsequently, 3097 publications were removed, and the full text of 119 records was reviewed. Of these, 43 studies satisfied all eligible inclusion criteria for the systematic review and meta-analysis (Figure 1). For single micronutrient deficiencies, 23, 14, and 17 papers were respectively included for analyses of iron [4,24,37–57], folate [4,24,38,47,51,58–66], and vitamin B_{12} [4,24,38,48,58,60,62–64,66–73]. Regarding multiple micronutrient deficiencies, three papers were included for triple micronutrient deficiencies [4,24,38] and two, one, and six articles were respectively included for the double micronutrient deficiencies of iron or folate [47,51], iron or vitamin B_{12} [48], and folate or vitamin B_{12} [58,60,62–64,66]. For micronutrient deficiencies by trimesters, six studies reported on iron deficiency [49,52,74–77], two on folate deficiency [62,66] and two on vitamin B_{12} deficiency [62,66].

3.2. Study and participant characteristics

The 43 studies gathered data from 28 nations, with seven nations carrying out more than one study. Dates of publication ranged from 2002 to 2024. Six studies (14%) had samples collected before 2010 [4,38,43,46,59,66], 22 studies (51.1%) in 2010–2019 [37,39,42,44,45,49,52–54,56–58,60,61,65,67–69,71,73–75], and 15 studies (34.9%) from 2020 or later [24,40,41,47,48,50,51,55,62–64,70,72,76,77] (Table 1). In

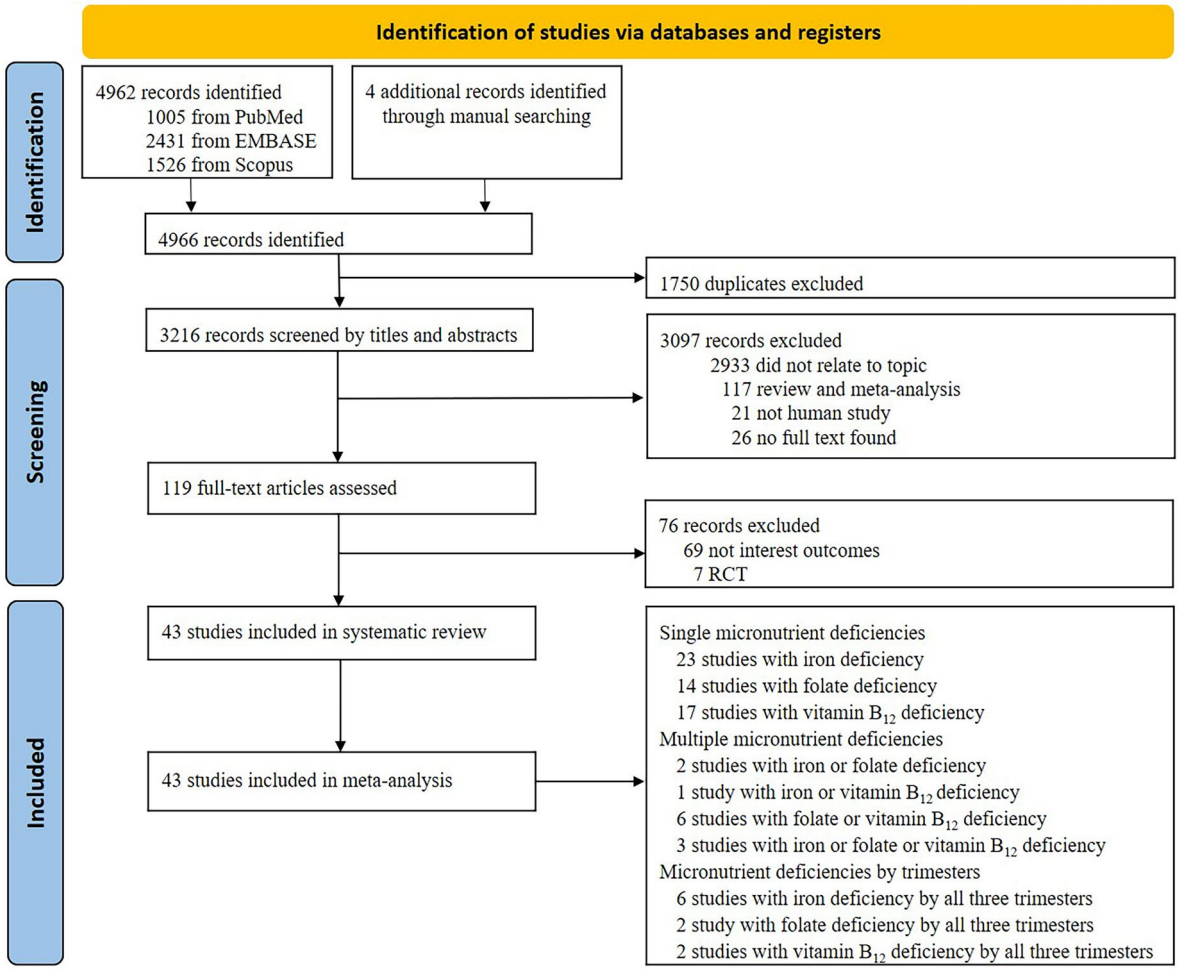

Figure 1. Flow diagram of the literature search process.

terms of study design, 26 studies employed a cross-sectional design [24,37,38,40–42,46–48,50,52,54,58,61–64,66,68–73,76,77], seven studies used a prospective cohort design [44,45,49,53,59,65,67], three studies utilized a retrospective cohort design [55,57,75], and five studies did not specify their study design [4,39,43,56,60]. Almost all of the studies provided the laboratory assays; however, six studies did not report the laboratory assays [48–50,55,75,77]. In addition, two studies did not specify the threshold values for ferritin levels [39,47], and one study did not report the threshold for folate levels [47]. Most studies ($k = 30$) reported on erythropoiesis-related micronutrient deficiencies across all three trimesters [4,24,39,40,43,45–52,54–62,66–68,70,74–77]. The mean/median age of pregnant women ranged 16–32.7 years (Table 1).

3.3. Quality assessment

The methodological quality of all included studies is summarized in Table S3. We identified seven studies with a moderate quality, all of which were incorporated into the final analysis. No research was categorized as having low quality.

3.4. Primary outcomes of meta-analysis

3.4.1. Pooled and stratified prevalence of single erythropoiesis-associated micronutrient deficiencies

Overall prevalence of single iron, folate, and vitamin B_{12} deficiencies were 28.4% (95% CI, 21.1–37%) (Figure 2), 11.1% (95% CI, 3.9–27.5%) (Figure 3), and 17.1% (95% CI, 8.8–30.6%) (Figure 4), respectively,

Table 1. Characteristics of included studies ($n = 43$).

Study	Country	Geographic region	No. of participants (n)	Study design	Erythropoiesis deficiencies	Gestational age (trimester)	Maternal mean or median* age (years)	Laboratory assays	Threshold values
Abbas et al. 2017 [37]	Sudan	Africa	423	Cross-sectional study	Iron	First trimester	26.8	Serum ferritin was measured using radioimmunoassay gamma counter (Riostad, Germany) and kits provided by Beijing Isotope Nuclear Electronic Co., Beijing, China	Serum ferritin < 0.034 nmol/L (15 µg/L)
Abdelrahim et al. 2009 [38]	Sudan	Africa	279	Cross-sectional study	Iron, folate, vitamin B_{12}	NR	25.9	Concentrations of ferritin, folate, and vitamin B_{12} were determined by immunofluorescent assay using IMMULITE kits (SIEMENS Healthcare, Los Angeles, CA, USA)	Serum ferritin < 0.034 nmol/L (15 µg/L) Serum folate < 15 nmol/L (6.6 ng/mL) Serum vitamin B_{12} < 110.7 pmol/L (150 pg/mL)
Adaikalakoteswari et al. 2015 [58]	United Kingdom	Europe	91	Cross-sectional study	Folate, vitamin B_{12}	All 3 trimesters	32.7	Serum vitamin B_{12} and folate were determined by electrochemiluminescent immunoassay using a Roche Cobas immunoassay analyzer (Roche Diagnostics UK, Burgess Hill, UK)	Serum folate < 10.5 nmol/L (4.6 µg/L) Serum vitamin B_{12} < 140.9 pmol/L (191 ng/L)
Akinbo et al. 2019 [39]	Nigeria	Africa	154	NR	Iron	All 3 trimesters	30	Serum ferritin was measured using Atomic Absorption Spectrophotometer (Buck Scientific 210 VGP, East Norwalk, CT)	NR
Akowuah et al. 2022 [40]	Ghana	Africa	220	Cross-sectional study	Iron	All 3 trimesters	30.5	Serum ferritin levels were measured using the DPC Immulite 1 ferritin assay (Diagnostic Products Corporation, Los Angeles, USA)	Serum ferritin ≤ 0.036 nmol/L (16 µg/L)
Arija et al. 2013 [74]	Spain	Europe	285	Longitudinal study	Iron	All 3 trimesters	31.1	Serum ferritin was determined by turbidimetric immunoassay. Ferritin measurements were performed in an ILab 900 (Instrumentation Laboratories)	Serum ferritin < 0.027 nmol/L (12 mg/L)
Babah et al. 2024 [41]	Nigeria	Africa	872	Cross-sectional study	Iron	Second and third trimesters	25*	Serum ferritin was measured using ARCHITECT Ferritin assay method	Serum ferritin < 0.057 nmol/L (30 ng/mL)
Baingana et al. 2015 [42]	Uganda	Africa	151	Cross-sectional study	Iron	First and second trimesters	27	Serum ferritin was measured using a commercial solid-phase ELISA method (Ramco Laboratories Inc., Stafford, TX, USA)	Serum ferritin < 0.027 nmol/L (12 mg/L)
Baker et al. 2009 [59]	United Kingdom	Europe	306	Prospective cohort study	Folate	All 3 trimesters	16	Serum folate was measured using competitive enzyme immunoassay (Bayer Diagnostics Europe Ltd, Newbery, United Kingdom)	Serum folate < 7 nmol/L (3.1 µg/L)
Barnabé et al. 2015 [60]	Brazil	America	291	NR	Folate, vitamin B_{12}	All 3 trimesters	26*	Serum folate and vitamin B12 were measured using Chemiluminescence immunoassays (Elecsys/Roche Diagnostics, Mannheim, Germany)	Serum folate < 9.1 nmol/L (4 ng/mL) Serum vitamin B_{12} < 148 pmol/L (200 pg/mL)
Bergmann et al. 2002 [43]	Germany	Europe	240	NR	Iron	All 3 trimesters	25	Serum ferritin was measured using immunoturbimetric method with a latex enhanced Kit on Hitachi 911	Serum ferritin < 0.027 nmol/L (12 µg/L)

(*Continued*)

Table 1. Continued.

Study	Country	Geographic region	No. of participants (n)	Study design	Erythropoiesis deficiencies	Gestational age (trimester)	Maternal mean or median* age (years)	Laboratory assays	Threshold values
Calje et al. 2017 [75]	New Zealand	Europe	189	Retrospective cohort study	Iron	All 3 trimesters	31*	NR	Serum ferritin < 0.045 nmol/L (20 µg/L)
Costa et al. 2016 [44]	Portugal	Europe	201	Prospective cohort study	Iron	First and second trimesters	31*	Serum ferritin was measured using Quimiluminescent assay	Serum ferritin < 0.067 nmol/L (30 mg/L)
Duffy et al. 2010 [45]	Republic of Seychelles	Africa	220	Prospective cohort study	Iron	All 3 trimesters	26.9	Serum ferritin was measured using automated enzyme immunoassay (United Hospitals H & SS Trust, Antrim, UK)	Serum ferritin < 0.034 nmol/L (15 ng/mL)
Engmann et al. 2008 [46]	Ghana	Africa	428	Cross-sectional study	Iron	All 3 trimesters	29	Serum ferritin was measured using DPC Immulite 1 ferritin assay (Diagnostic Products Corporation, Los Angeles, USA)	Serum ferritin ≤ 0.036 nmol/L (16 µg/L)
Finkelstein et al. 2019 [67]	New York	America	124	Prospective cohort study	Vitamin B_{12}	All 3 trimesters	17.3	Serum vitamin B12 was measured using IMMULITE 2000 immunoassay system (Siemens Medical Solutions Diagnostics, Los Angeles, CA, US)	Serum vitamin B_{12} < 148 pmol/L (200 pg/mL)
Fite et al. 2023 [47]	Ethiopia	Africa	397	Cross-sectional study	Iron, folate	All 3 trimesters	24.9	Serum ferritin was measured using the sandwich electrochemiluminescence principle Serum folate was measured using the competition electrochemiluminescence principle	NR
García-Casal et al. 2005 [66]	Venezuela	America	1260	Cross-sectional study	Folate, vitamin B_{12}	All 3 trimesters	20	Serum vitamin B_{12} and folate were measure using a radio immunoassay from DPC (Diag nostic Product Corporation, Los Angeles, CA, USA)	Serum folate < 6.8 nmol/L (3 ng/mL) Serum vitamin B_{12} < 148 pmol/L (200 pg/mL)
Gopal et al. 2022 [48]	India	Asia	139	Cross-sectional study	Iron, vitamin B_{12}	All 3 trimesters	24.5	NR	Serum ferritin ≤ 0.034 nmol/L (15 ng/mL) Serum vitamin B_{12} ≤ 150 pmol/L (203 pg/mL)
Harvey et al. 2016 [49]	France	Europe	605	Prospective cohort study	Iron	All 3 trimesters	29.9	NR	Serum ferritin < 0.034 nmol/L (15 µg/L)
Jeruszka-Bielak et al. 2017 [68]	Canada	America	320	Cross-sectional study	Vitamin B_{12}	All 3 trimesters	31*	Serum vitamin B_{12} was measured using microparticle Enzyme Immunoassay technology (Abbott Laboratories, Abbott Park, IL, USA)	Serum vitamin B_{12} < 148 pmol/L (200 pm/mL)

(*Continued*)

Table 1. Continued.

Study	Country	Geographic region	No. of participants (n)	Study design	Erythropoiesis deficiencies	Gestational age (trimester)	Maternal mean or median* age (years)	Laboratory assays	Threshold values
John et al. 2023 [24]	Tanzania	Africa	420	Cross-sectional study	Iron, folate, vitamin B_{12}	All 3 trimesters	25.5	Serum ferritin levels were measured by standard immunoturbidimetric assays using a Roche Cobas 400+ biochemistry analyzer (Roche Diagnostics, Germany). Serum folate was measured at the TFNC laboratory using CDC folate microbiological assay protocol. Serum vitamin B_{12} was also measured at the TFNC laboratory by using standard electrochemiluminescence immunoassay (ECLIA) based on Roche Cobas e411 immunoassay platform (Roche Diagnostics, Germany).	Serum ferritin < 0.034 nmol/L (15 µg/L) Serum folate < 10 nmol/L (< 4 ng/mL) Serum vitamin B_{12} < 203 pg/mL (150 pmol/L)
Kangalgil et al. 2021 [50]	Turkey	Asia	142	Cross-sectional study	Iron	All 3 trimesters	29.1	NR	Serum ferritin < 0.034 nmol/L (15 µg/L)
Mamme et al. 2023 [51]	Ethiopia	Africa	446	Longitudinal study	Iron, folate	All 3 trimesters	25.7	Serum ferritin and folate levels were measured using the electrochemiluminescence method on a fully automated Cobas e411 (Cobas 4000 analyser series; Germany and Japan) immunoassay analyser	Serum ferritin < 0.034 nmol/L (15 ng/mL) Serum folate < 9.1 nmol/L (4 ng/ mL)
Mei et al. 2021 [52]	United State	America	1171	Cross-sectional study	Iron	All 3 trimesters	27.5	Serum ferritin was measured using a single-incubation 2-site immunoradiometric assay (BioRad Lab oratories, Hercules,CA) and RocheTina-quant ferritin immunoturbidimetric assay on the Hitachi 912 clinical analyzer (RocheDiagnostics)	Serum ferritin < 0.027 nmol/L (12 µg/L)
Mgamb et al. 2017 [61]	Kenya	Africa	247	Cross-sectional study	Folate	All 3 trimesters	29	Serum folate was measured using electrochemiluminescence immunoassay	Serum folate < 10 nmol/L (4 ng/mL)
Ndem et al. 2021 [62]	Nigeria	Africa	180	Cross-sectional study	Folate, vitamin B_{12}	All 3 trimesters	30.0	Serum levels of folate and vitamin B_{12} were assayed by ELISA method using AccuDiag™ ELISA Kit (Diagnostic Automation/Cortez Diagnostics, Inc. USA)	Serum folate < 6.8 nmol/L (3 ng/mL) Serum vitamin B_{12} < 148 pmol/L (200 pg/mL)

(*Continued*)

Table 1. Continued.

Study	Country	Geographic region	No. of participants (n)	Study design	Erythropoiesis deficiencies	Gestational age (trimester)	Maternal mean or median* age (years)	Laboratory assays	Threshold values
Pathak et al. 2007 [4]	India	Asia	283	NR	Iron, folate, vitamin B_{12}	All 3 trimesters	22.9	Serum ferritin levels were assessed by the standard enzyme-linked immunosorbent assay (ELISA) method with the use of a Micro-well Enzyme Immunoassay Human Ferritin Quantitative EIA Kit (Bioplus) Serum folate was assessed by estimating the serum folate levels by the standard radioimmunoassay method with the use of the Simul TRAC-SNB Radioassay Kit Serum vitamin B_{12} was estimated by the microbiologic method	Serum ferritin < 0.027 nmol/L (12 ng/mL) Serum folate < 6.8 nmol/L (3 ng/mL) Serum vitamin B_{12} < 148 pmol/L (200 pg/mL)
Pobee et al. 2021 [76]	Ghana	Africa	109	Cross-sectional study	Iron	All 3 trimesters	27.1	Serum ferritin was determined *via* ELISA (Ramco Laboratories TX, USA)	Serum ferritin < 0.034 nmol/L (15 µg/L)
Ramírez-Vélez et al. 2016 [69]	Colombia	America	1781	Cross-sectional study	Vitamin B_{12}	NR	24.4	Serum vitamin B_{12} was measured using the method of direct chemiluminescence (ADVIA Centaur equipment, Siemens)	Serum vitamin B_{12} < 148 pmol/L (200 pg/mL)
Rayis et al. 2023 [63]	Sudan	Africa	300	Cross-sectional study	Folate, vitamin B_{12}	NR	26*	Serum folate and vitamin B_{12} were performed by immunofluorescent assay following the manufacturer's instructions (Immulite kits, Siemens Healthcare, Los Ange- les, CA, USA)	Serum folate < 9.1 nmol/L (4 ng/mL) Serum vitamin B_{12} < 110.7 pmol/L (150 pg/mL)
Rezgale et al. 2022 [77]	United Kingdom	Europe	933	Cross-sectional study	Iron	All 3 trimesters	29.9	NR	Serum ferritin < 0.067 nmol/L (30 µg/L)
Rizwan et al. 2021 [70]	Parkistan	Asia	190	Cross-sectional study	Vitamin B_{12}	All 3 trimesters	32.5	Serum vitamin B_{12} was measured using ELISA assay	Serum vitamin B_{12} < 221.4 pmol/L (300 pg/mL)
Samuel et al. 2013 [71]	India	Asia	352	Cross-sectional study	Vitamin B_{12}	First trimester	22.6	Serum vitamin B_{12} was measured using electrochemiluminescence method (Elecsys 2010, Roche Diagnostics Mannheim, USA)	Serum vitamin B_{12} < 150 pmol/L (203 pg/mL)
Saravanan et al. 2021 [64]	United Kingdom	Europe	4746	Cross-sectional study	Folate, vitamin B_{12}	First trimester	30.5	Serum folate and vitamin B_{12} were measured by electro-chemiluminescent immunoassay (Roche Cobas analyser, Roche Diagnostics, Burgess Hill, UK)	Serum folate < 10 nmol/L (4.4 ng/mL) Serum vitamin B_{12} deficiency was defined using two different cut-offs: < 150 pmol/L (203 pg/mL) and < 220 pmol/L (298 pg/mL)
Siridamrongvattana et al. 2013 [53]	Vietnam	Asia	399	Prospective cohort study	Iron	First trimester	28.4	Serum ferritin was measured using a chemiluminescent immunoassay (Beckman Coulter, USA)	Serum ferritin < 0.034 nmol/L (15 ng/mL)

(*Continued*)

Table 1. Continued.

Study	Country	Geographic region	No. of participants (n)	Study design	Erythropoiesis deficiencies	Gestational age (trimester)	Maternal mean or median* age (years)	Laboratory assays	Threshold values
Sobowale et al. 2022 [72]	Bangladesh	Asia	404	Cross-sectional study	Vitamin B_{12}	First and second trimesters	23.6	Serum vitamin B12 was measured using electrochemiluminescence immunoassay (ECLIA) on a Roche automated immunoassay analyzer Cobas e601 using a commercial kit, Elecsys Vitamin B12II (Roche Diagnostics, GmbH,68305 Mannheim, Germany)	Serum vitamin B_{12} < 150 pmol/L (203 pg/mL)
Srour et al. 2018 [54]	Palestine	Asia	300	Cross-sectional study	Iron	All 3 trimesters	26.3	Serum ferritin was measured using ferritin reagent kits and the automated chemistry analyzer machine (Abbott, USA) per the instructions of the manufacturer	Serum ferritin < 0.034 nmol/L (15 ng/mL)
Teichman et al. 2021 [55]	Canada	America	25880	Retrospective cohort study	Iron	All 3 trimesters	31*	NR	Serum ferritin < 0.067 nmol/L (30 µg/L)
Visentin et al. 2016 [73]	Canada	America	219	Cross-sectional study	Vitamin B_{12}	First and second trimester	32	Serum vitamin B12 was measured using the Access competitive-binding immunoenzymatic assay (Beckman Coulter)	Serum vitamin B_{12} < 148 pmol/L (200 pg/mL)
Weyers et al. 2016 [56]	South Africa	Africa	103	NR	Iron	All 3 trimesters	24*	Serum ferritin was measured using the Advia Centaur XP immunoassay system (Siemens Healthcare Diagnostics Inc., Tarrytown, NY, USA)	Serum ferritin < 0.067 nmol/L (30 µg/L)
Yila et al. 2016 [65]	Japan	Asia	15266	Prospective cohort study	Folate	First trimester	27.5	Serum folate was measured using direct chemiluminescent acridinium ester technology	Serum folate < 6.8 nmol/L (3 ng/mL)
Yuan et al. 2019 [57]	China	Asia	11569	Retrospective cohort study	Iron	All 3 trimesters	28*	Serum ferritin was analyzed by means of chemiluminescent immunoassay, immune turbidimetry and particle enhanced immunonephelometry using automated analyzer UniCel DxI 800 Access, Beckman Coulter Inc., USA	Serum ferritin < 0.027 nmol/L (12 µg/L)

Abbreviation: NR, not reported.

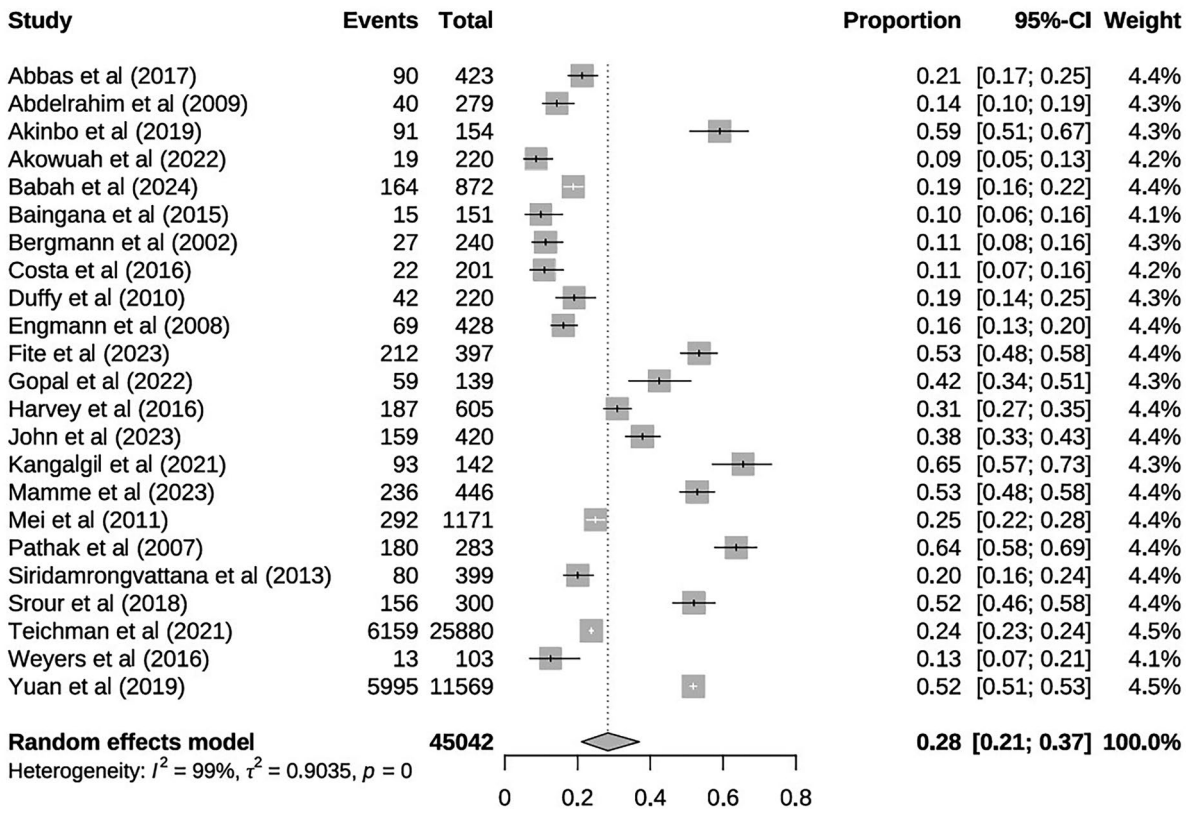

Figure 2. Forest plot of the prevalence of single iron deficiency among pregnant women. Horizontal bar at each study represents the 95% confidence interval. CI, confidence interval.

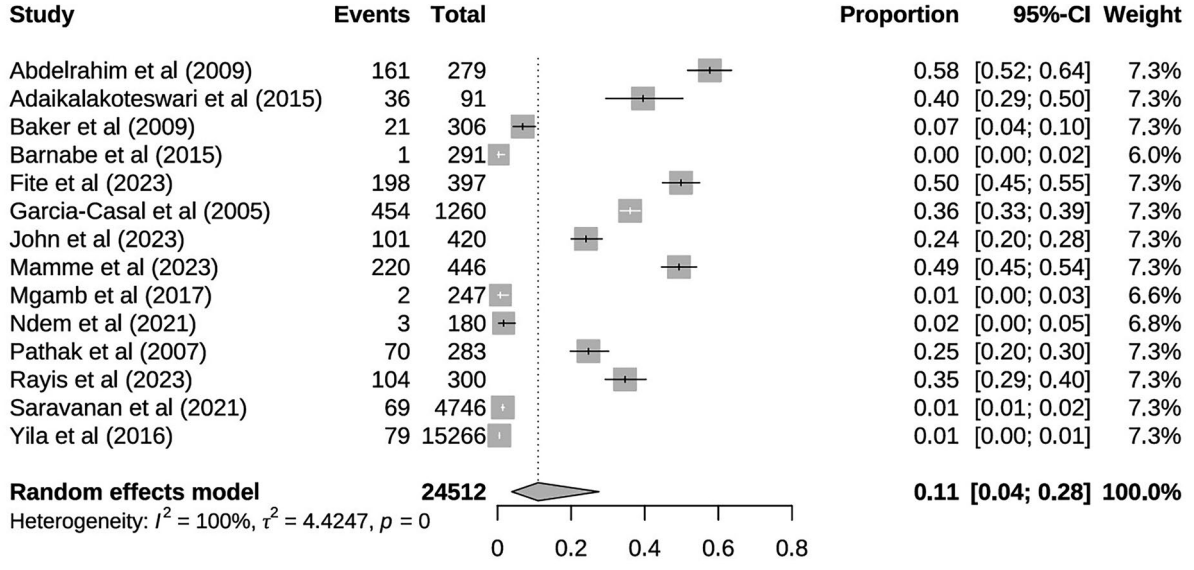

Figure 3. Forest plot of the prevalence of single folate deficiency among pregnant women. Horizontal bar at each study represents the 95% confidence interval. CI, confidence interval.

with significant heterogeneity present (all $p < 0.001$). Countries with the highest prevalence of single iron deficiency were India (67.7%) and Turkey (65.5%) (Figure 5). Sudan (57.7%) and Ethiopia (49.9%) showed the highest prevalence of single folate deficiency (Figure 6). India (74.1%) and Venezuela (61.4%) were observed to have the highest prevalence of single vitamin B_{12} deficiency (Figure 7).

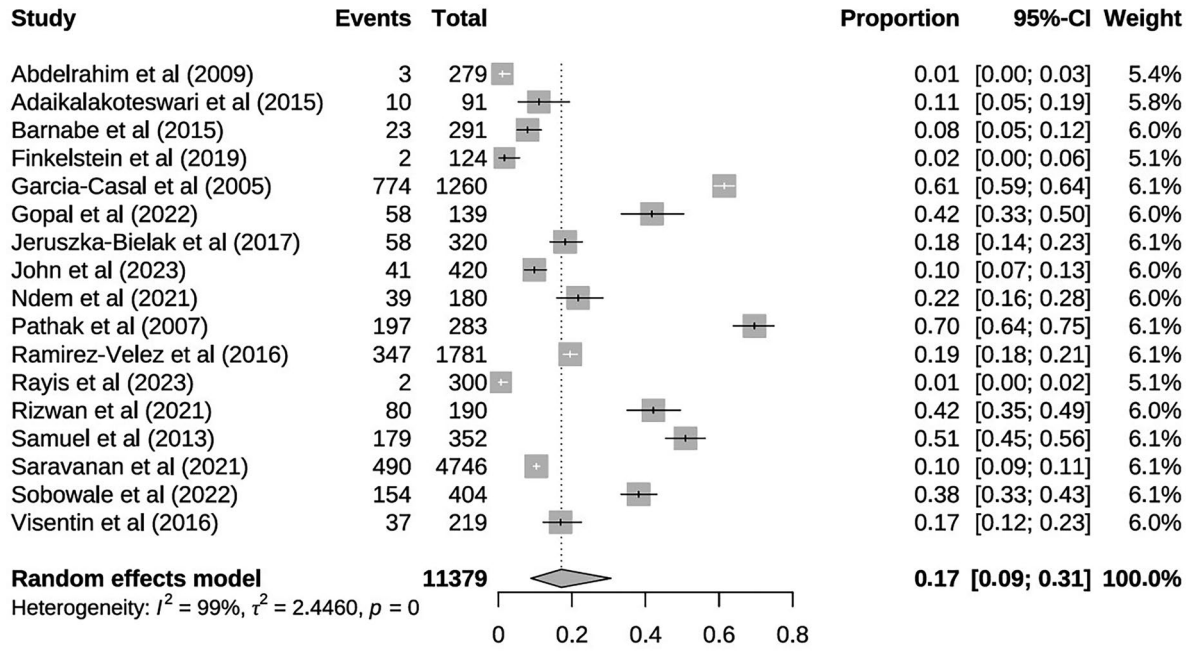

Figure 4. Forest plot of the prevalence of single vitamin B_{12} deficiency among pregnant women. Horizontal bar at each study represents the 95% confidence interval. CI, confidence interval.

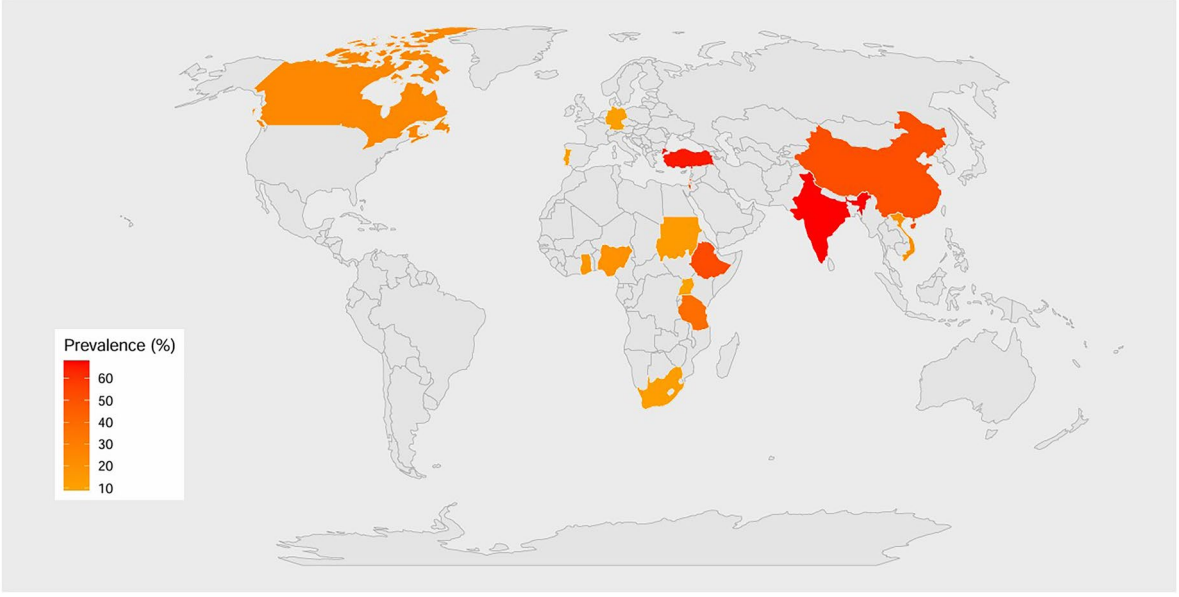

Figure 5. Prevalence of single micronutrient deficiency across countries. Color gradient depicts different prevalence of iron deficiency in each country; the darker the color, the higher the prevalence of iron deficiency. The highest prevalence was in India (67.7%) and Turkey (65.5%).

3.4.2. Subgroup analysis and heterogeneity

Due to the high heterogeneity, a subgroup meta-analysis was performed and revealed that age, region, and diagnosis criteria were significant factors influencing prevalences of single erythropoiesis-associated micronutrient deficiencies. A subgroup analysis by income level demonstrated no significant association in the prevalence of erythropoiesis-related micronutrient deficiencies. Classification according to geographic region showed that Asian region had the highest prevalence of iron deficiency at 48.6% (95% CI, 34.4–63%) (Table 2), while Afican region recorded the highest prevalence of folate deficiency at 19.8%

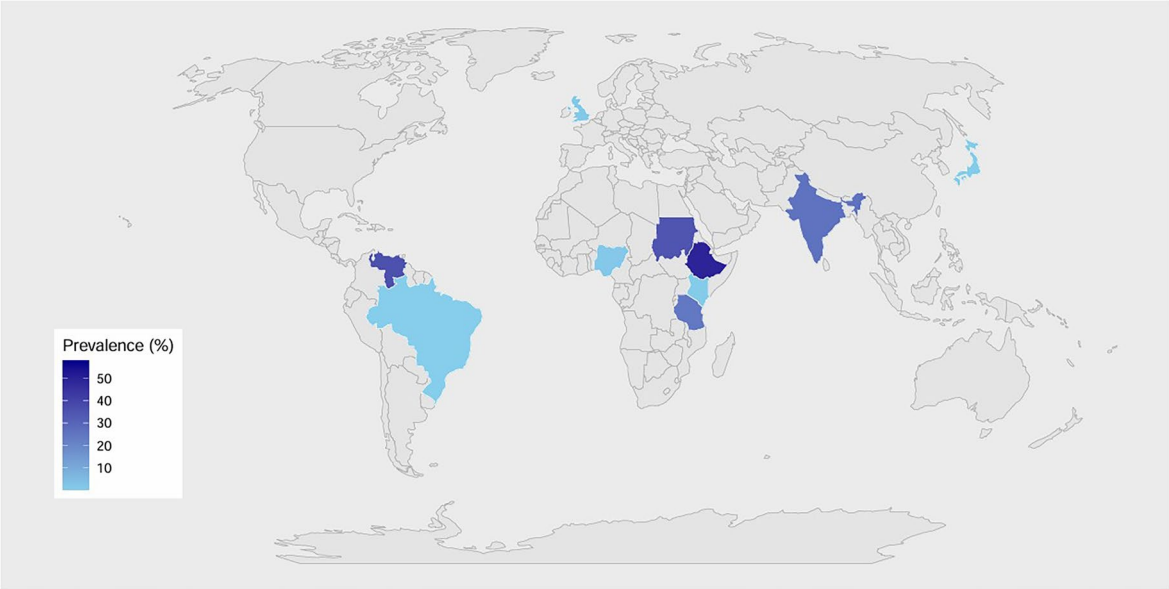

Figure 6. Prevalence of single micronutrient deficiency across countries. Color gradient depicts different prevalence of folate deficiency in each country; the darker the color, the higher the prevalence of folate deficiency. The highest prevalence was in Sudan (57.7%) and Ethiopia (49.9%).

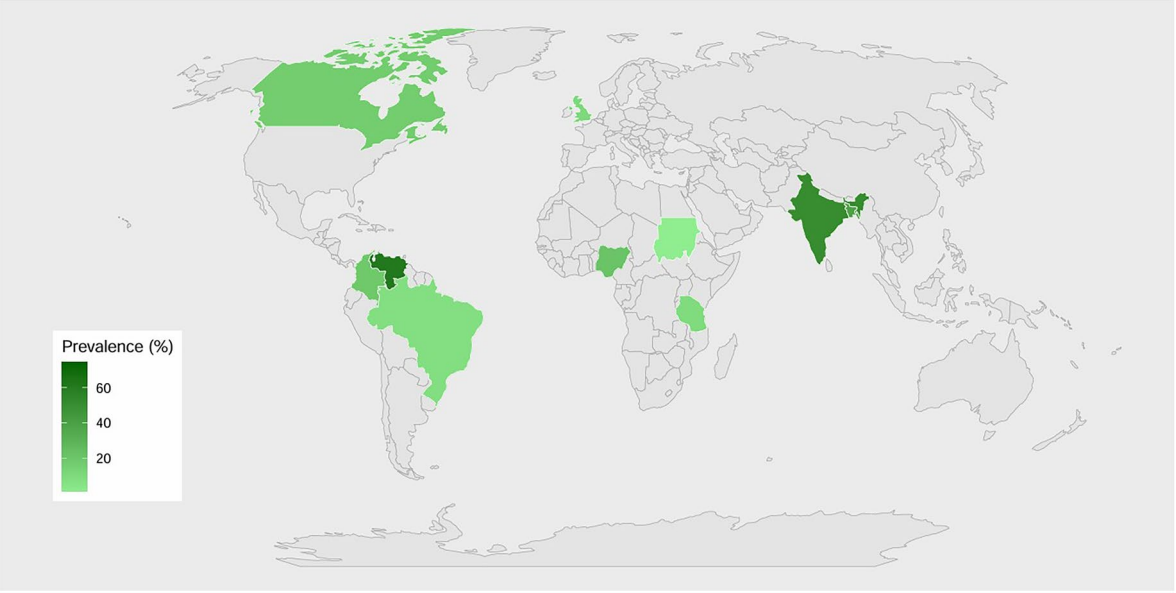

Figure 7. Prevalence of single micronutrient deficiency across countries. Color gradient depicts different prevalence of vitamin B_{12} deficiency in each country; the darker the color, the higher the prevalence of vitamin B_{12} deficiency. The highest prevalence was in India (74.1%) and Venezuela (61.4%).

(95% CI, 5.3–52%) (Table 3). Additionally, the Asian region also had the highest prevalence of vitamin B_{12} deficiency at 48.7% (95% CI, 37.3–60.2%) (Table 4).

In terms of diagnostic criteria, among 12 studies utilizing the WHO standard, the pooled prevalence of an iron deficiency, defined as serum ferritin of < 15 µg/L [34], was 31.5% (95% CI, 22.9–41.5%). Nine studies that applied individual country classifications demonstrated that 19.8% (95% CI, 10.9–33.1%) suffered from an iron deficiency. The prevalence of iron deficiency in two studies that did not report the standard of serum ferritin levels was 55.4% (95% CI, 50–60.6%) (Table 2). As to folate deficiencies, among six studies employing the WHO standard, the pooled prevalence of folate deficiency, identified as serum folate of < 4 ng/mL [17], was 6.6% (95% CI, 1–32.3%). Seven studies that applied individual country

Table 2. Subgroup analysis of prevalence differences of single iron deficiency outcomes.

Characteristic	No. of studies	n	Iron deficiency prevalence % (95% CI)	I^2	*P* value[a]
Age					0.76
≤25 years	7 [4, 41–43, 47, 48, 56]	2185	26.4% (13.3%–45.7%)	98.3%*	
>25 years	16 [24, 37–40, 44–46, 49–55, 57]	42857	29.5% (20.6%–40.3%)	99.6%*	
Geographic region					< 0.01
Africa	12 [24, 37–42, 45–47, 51, 56]	4113	24% (15.5%–35.1%)	97.7%*	
Europe	3 [43, 44, 49]	1046	16.3% (7.7%–31.4%)	96.2%*	
Asia	6 [4, 48, 50, 53, 54, 57]	12832	48.6% (34.4%–63%)	97%*	
Americas	2 [52, 55]	27051	23.8% (23.3%–24.3%)	0%	
Diagnosis criteria					< 0.01
WHO	12 [24, 37, 38, 41, 45, 48–51, 53–55]	30125	31.5% (22.9%–41.5%)	97.8%*	
Self-country classification**	9 [4, 40, 42–44, 46, 52, 56, 57]	14366	19.1% (9.7%–34.2%)	98.8%*	
NR	2 [39, 47]	551	55.4% (50%–60.6%)	31%	
Income level					0.72
Low middle income	13 [4, 24, 37–42, 46-48, 51, 53]	4611	29% (19.1%–41.3%)	98%*	
Upper middle income	4 [45, 50, 56, 57]	12034	34.3% (13.7%–63.1%)	97.6%*	
High income	6 [43, 44, 49, 52, 54, 55]	28397	23.2% (12%–40.2%)	97.7%*	

Iron deficiency is defined as serum ferritin of < 15 µg/L according to WHO.
[a]analyzed by chi-squared test.
*p value < 0.05.
**Diagnosis criteria were defined by each country's guidelines.
Abbreviations: CI, confidence interval; n, number of participants; NR, not reported; WHO, World Health Organization.

Table 3. Subgroup analysis of prevalence differences of single folate deficiency outcomes.

Characteristic	No. of studies	*n*	Folate deficiency prevalence % (95% CI)	I^2	*p* value[a]
Age					0.12
≤25 years	4 [4, 47, 59, 66]	2246	25.7% (10.5%–50.5%)	97.7%*	
>25 years	10 [24, 38, 51, 58, 60–65]	22266	7.4% (1.8%–26%)	99.6%*	
Geographic region					0.74
Africa	7 [24, 38, 47, 51, 61–63]	2269	19.8% (5.3%–52%)	96.8%*	
Europe	3 [58, 59, 64]	5143	8.2% (1%–43.4%)	99.2%*	
Asia	2 [4, 65]	15549	4% (0.1%–70.6%)	99.8%*	
American	2 [60, 66]	1551	5% (0%–87.7%)	96.1%*	
Diagnostic criteria					< 0.01
WHO	6 [24, 51, 60, 61, 63, 64]	6450	6.6% (1%–32.3%)	99.4%*	
Self-country classification**	7 [4, 38, 58, 59, 62, 65, 66]	17665	12.5% (3%–40.1%)	99.6%*	
NR	1 [47]	397	49.9% (45%–54.8%)	–	
Income level					0.06
Low middle income	7 [4, 24, 38, 47, 51, 62, 63]	2305	29.2% (13.2%–52.8%)	96.6%*	
Upper middle income	3 [60, 61, 66]	1798	2.7% (0.1%–39.8%)	96.7%*	
High income	4 [58, 59, 64, 65]	20409	4.2% (0.6%–25.6%)	99.3%*	

Folate deficiency is defined as serum folate of < 4 ng/mL according to WHO.
[a]analyzed by chi-squared test.
*p value < 0.05.
**Diagnosis criteria were defined by each country's guidelines.
Abbreviations: CI, confidence interval; n, number of participants; NR, not reported; WHO, World Health Organization.

classifications revealed a folate deficiency prevalence of 12.5% (95% CI, 3–40.1%). One study that did not reveal the cutoff level for a serum folate deficiency reported the highest prevalence at 49.9% (95% CI, 45–54.8%) (Table 3). For vitamin B_{12} deficiencies, there was no significant difference as shown in 17 studies regarding diagnosis criteria using the WHO [17], CDC [35], and individual country classifications (Table 4). In age-based classification, pregnant women aged ≤ 25 years had a significantly highest vitamin B_{12} deficiency prevalence at 34.9% (95% CI, 15.2–61.6%).

3.4.3. Pooled prevalence of multiple erythropoiesis-associated micronutrient deficiencies

The pooled prevalences of a double deficiency of iron or folate were 53.1% (95% CI, 49.8–56.5%) and 49.6% (95% CI, 46.2–53%), respectively (Table S4). The pooled prevalences of a double deficiency of

Table 4. Subgroup analysis of prevalence differences of single vitamin B_{12} deficiency outcomes.

Characteristic	No. of studies	*n*	Vitamin B_{12} deficiency prevalence % (95% CI)	I^2	*p* value[a]
Age					0.02
≤25 years	7 [4, 48, 66, 67, 69, 71, 72]	4343	34.9% (15.2%–61.6%)	99.1%*	
>25 years	10 [24, 38, 58, 60, 62-64, 68, 70, 73]	7036	9.8% (4.7%–19.6%)	95.8%*	
Geographic region					<0.01
Africa	4 [24, 38, 62, 63]	1179	4.1% (0.7%–19.5%)	94.5%*	
Europe	2 [58, 64]	4837	10.3% (9.5%–11.2%)	0%	
Asia	5 [4, 48, 70-72]	1368	48.7% (37.3%–60.2%)	94.4%*	
America	6 [60, 66-69, 73]	3995	15.7% (5.7%–36.3%)	99.3%*	
Diagnosis criteria					0.26
WHO	7 [24, 38, 48, 63, 64, 71, 72]	6640	111.7% (3%–36.1%)	99%*	
Self-country classification**	6 [4, 58, 60, 66, 69, 70]	3896	30.7% (13%–56.7%)	99.3%*	
CDC	4 [62, 67, 68, 73]	843	12.3% (4.6%–29.1%)	80.1%*	
Income level					0.43
Low middle income	9 [4, 24, 38, 48, 62, 63, 70-72]	2547	19.7% (6.4%–46.8%)	97.7%*	
Upper middle income	3 [60, 66, 69]	3332	24.5% (5.7%-63.3%)	99.7%*	
High income	5 [58, 64, 67, 68, 73]	5500	11.1% (6.3%–18.8%)	88.2%*	

Vitamin B_{12} deficiency is defined as plasma vitamin B_{12} < 150 pmol/L (203 pg/mL) according to WHO, or plasma vitamin B_{12} < 148 pmol/L according to CDC.
[a]analyzed by chi-squared test.
*p value < 0.05.
**Diagnosis criteria were defined by each country's guidelines.
Abbreviations: CI, confidence interval; n, number of participants; NR, not reported; WHO, World Health Organization.

folate or vitamin B_{12} were 6.2% (95% CI, 1.2–25.8%) and 11.8% (95% CI, 3.3–34.1%), respectively (Table S5). Pooled prevalences of a triple deficiency of iron or folate or vitamin B_{12} were 36.1% (95% CI, 13.1–68%), 34.3% (95% CI, 16.9–57.3%), and 12.6% (95% CI, 0.7–74.8%), respectively (Table S6).

3.5. Secondary outcome of meta-analysis

3.5.1. Pooled prevalence of erythropoiesis-associated micronutrient deficiencies by trimester

The pooled prevalences of iron and vitamin B_{12} deficiencies were estimated to increase with gestational age (iron deficiency at 11.3, 35.3, and 45.1% and vitamin B_{12} deficiency at 10.3, 31.5, and 69.7% in the first, second, and third trimesters, respectively). A folate deficiency was prevalent in 10.4, 6.2, and 19.2% during the first, second, and third trimesters, respectively (Table S7).

3.6. Sensitivity analysis

After excluding studies that did not report the diagnostic criteria of micronutrient deficiencies, a sensitivity analysis incorporating 21 studies with a single iron deficiency [24,37,39–57], and 13 studies with a single folate deficiency [4,38,50,53,58–66] revealed the pooled prevalences of single iron and folate deficiencies were 26.1% (95% CI 19.2–34.5%) and 9.5% (95% CI 3.2–25.2%), respectively (Figure S1). In a further sensitivity analysis using the outlier removal method, no outliers were identified. Next, we applied the trim-and-fill method and concluded that no significant difference was observed between the new prevalence and the original prevalence (all p values > 0.05) (Table S8).

3.7. Publication bias

Egger's tests revealed no publication bias in the prevalence of single iron, folate, and vitamin B_{12} deficiencies ($p = 0.83$, $p = 0.32$, and $p = 0.82$, respectively) (Table S9).

4. Discussion

In the current systematic review and meta-analysis, we compiled the most comprehensive and up-to-date data on prevalences of erythropoiesis-related micronutrient deficiencies from 43 studies involving pregnant women across 28 countries and five global regions. Single iron, folate, and vitamin B_{12} deficiencies were respectively observed in 28.4, 11.1, and 17.1% of the pregnant population.

Our study estimated that a single iron deficiency was prevalent in pregnant women, especially in Asia, results that align with a previous study [78]. A previous systematic review and meta-analysis conducted in an Asian country estimated comparable prevalences of 31.6–34.6% of pregnant women with an iron deficiency [78], while another study by Zhou et al. [79] revealed that nearly half of Chinese pregnant women experienced an iron deficiency, which is higher than our finding. Serum ferritin was reported to be a reliable marker of iron storage levels. Routine screening for serum ferritin in pregnant women is recommended to initiate interventions and prevent iron deficiency anemia during pregnancy [80,81]. WHO recommended daily iron supplementation (30–60 mg elemental iron, often combined with folic acid) throughout pregnancy in low- and middle-income countries to prevent maternal anemia, puerperal sepsis, low birth weight, and preterm birth [82]. Additionally, previous findings suggested that an iron deficiency is the most common nutritional problem worldwide, especially in various developing countries [12]. Furthermore, it remains the most common nutritional deficiency in the developed world, with up to 50% of cases stemming from insufficient iron intake [12]. This underscores the significance of iron supplementation throughout the gestational period to prevent an iron deficiency [83].

A folate deficiency was estimated to have the lowest prevalence among all single erythropoiesis micronutrients at 11.1%. This suggests that the recommendation for folate supplementation is effective in mitigating the deficiency prevalence during pregnancy [84,85]. A previous systematic review and meta-analysis highlighted the benefits of folic acid intake both before and immediately after conception [86]. The significance of an adequate periconceptional folate supply and the association of the mother's folate status with fetal neural tube defects and other congenital malformations are widely acknowledged [86]. A prior systematic review and meta-analysis indicated that the overall prevalence of a folate deficiency among pregnant women was estimated to be 20.01% [80], which was twice as high as our finding. This indicates that a folate deficiency is a substantial public health issue among pregnant women [87]. In terms of a single vitamin B_{12} deficiency, we estimated that 17.1% of individuals suffered from this micronutrient deficiency during pregnancy, which was lower than the range of 40–70% of Indian pregnant women reported by Behere et al. in a recent systematic review and meta-analysis [20]. Finkelstein et al. found that 26–51% of pregnant women had a vitamin B_{12} deficiency [88], which was greater than our finding. Some factors may account for the differences between our study and previous systematic reviews on the prevalence of folate and vitamin B_{12} deficiencies. Our systematic review and meta-analysis included more recent studies, which could reflect improvements in maternal nutrition, supplementation practices, and national fortification programs across the countries [89]. Additionally, differences in geographical location and population in the included studies could have influenced the pooled estimates, since the nutritional status of pregnant women could vary substantially across the regions and socioeconomic contexts [89]. Furthermore, our study incorporated broader global data, potentially yielding different prevalence estimates.

To prevent neural tube defects, folic acid supplementation during pregnancy has been implemented in many countries [90]. WHO guidelines recommended daily oral iron and folic acid supplementation (400 µg) to all pregnant women, starting as early as possible during pregnancy [82]. Sununtnasuk et al. [91] conducted a study across 20 countries and reported that 83% of pregnant women had at least one antenatal care visit, of whom 81% received iron-folic acid tablets. Another study indicated that the compliance rate of iron and folic acid supplement was 66.6% in Ethiopia [92]. A maternal imbalance characterized by high levels of folate and low levels of vitamin B_{12} (referred to as a "folate-vitamin B_{12} imbalance") may contribute to metabolic disorders [93]. Previous studies observed that high blood folate/vitamin B_{12} ratio could increase the risk of gestational diabetes mellitus [64,94,95]. Methionine cycle-related metabolites, including S-adenosylmethionine, S-adenosylhomocysteine, and homocysteine, may mediate the effects of folate and vitamin B_{12} on the development of gestational diabetes mellitus [93].

Our data demonstrated that deficiency prevalences of iron and vitamin B_{12} were predicted to increase with gestational age, in line with previous studies. An iron deficiency was shown to be higher in pregnant women in their second and third trimesters [81,96]. Iron requirements could be changed throughout the pregnancy, initially driven by the expansion of maternal red cell mass and later by the increasing demands of the placenta and fetus, which could further lead to a progressive decline in ferritin levels [97,98]. This highlights the challenge of applying uniform thresholds for the deficiency across all trimesters and supports the need for trimester-specific reference ranges or cutoffs [97,98]. In addition, Behere

et al. reported that the prevalence of a vitamin B_{12} deficiency increased by 10–20% between early to later pregnancy. Meanwhile, another study showed that pooled estimates of a vitamin B_{12} deficiency in the first, second, and third trimesters were 21, 19, and 29%, respectively [19]. Our findings showed that iron and vitamin B_{12} deficiencies were significantly more common in the Asian region. This can be attributed to the predominantly plant-based diets in Asia, especially in South Asia, which might lead to deficiencies. Non-heme iron from plant-based foods is less efficiently absorbed by the body compared to animal-derived heme iron. Additionally, diets low in animal products can lead to vitamin B_{12} deficiencies [99]. Geographic variations were reported to contribute to differences in prevalences of vitamin B_{12} deficits during pregnancy [20]. As to the income status, authors proposed that income level was a factor contributing to observed variations in prevalences of micronutrient deficiencies. High deficiency prevalences of iron, folate, and vitamin B_{12} during pregnancy were reported in countries with low socioeconomic conditions [100,101] and developing countries [102]. This is inconsistent with our results, which did not indicate a significant relationship between income level and erythropoiesis-related micronutrient deficiencies. One possible reason for this inconsistency is that the countries with lower socioeconomic conditions have implemented nationwide fortification programs and antenatal supplementation initiatives, which could mitigate the expected disparities in micronutrient deficiencies [89]. In addition, the difference could be due to heterogeneity in study populations. Our analysis incorporated a wider range of recent studies from diverse regions, dietary patterns, and health systems, which could have captured more variability in contextual factors compared with earlier reviews. Our findings observed the variance in prevalence rates of the three micronutrients (iron, folate, and vitamin B_{12}) between the regions and significant variances between the countries of the same region. This could be attributed to the variations in national fortification programs, access to healthcare, and overall population nutritional status [89].

However, this meta-analysis has some limitations. First, incorporating multiple diagnostic standards for erythropoiesis-related micronutrient deficiencies contributed to the high heterogeneity. We performed subgroup meta-analyses to indicate sources of this heterogeneity and strengthen our findings. Second, given the limited data available for risk factors associated with these micronutrient deficiencies in pregnant women, additional studies are needed to investigate these associations. Third, the inclusion of only English-language studies may lead to the omission of some relevant research. Nevertheless, previous evidences indicated that the exclusion of non-English studies generally exerts only a minor effect on pooled estimates in systematic reviews [103–105]. Considering the large number and wide geographical distribution of studies included, it is unlikely that any missed studies would have significantly impacted our overall findings. Four, the variations in assays and threshold values used to determine serum ferritin, folate, and vitamin B_{12} deficiencies could influence the prevalence estimates. The previous research observed that commonly used methods for measuring ferritin concentrations generally demonstrated comparable accuracy and performance [106]. The reference values for serum folate and vitamin B_{12} were consistent when the data were assessed by the same method, and the results across different techniques showed a strong correlation [107]. Nonetheless, the assay variability remains an important methodological factor. For instance, one recent study reported that Beckman Coulter assays tended to underestimate total vitamin B_{12} concentrations, whereas Abbott assays overestimated them compared with Roche assays traceable to the WHO international standard [21]. Further research is needed to clarify the influence of assay variability on the prevalence estimates of iron, folate, and vitamin B_{12} deficiencies. Future meta-analyses should account for the assay method as a source of heterogeneity to enhance the validity. Five, the search strategy was conducted by the research team without the involvement of an information specialist. Additionally, our analysis focused solely on iron deficiency, and further research should comprehensively examine both iron deficiency and iron deficiency anemia. Our study presents the most recent findings on prevalences of erythropoiesis-related micronutrient deficiencies in pregnant women around the world, accompanied by a thorough analysis to resolve heterogeneity among the studies. Despite certain limitations, our findings offered valuable insights for early detection and prevention of micronutrient deficiencies during pregnancy, and could inform policymakers, stakeholders, and clinicians in designing targeted interventions, clinical recommendations, and public health policies, as well as serve as a foundation for further research and meta-analyses.

5. Conclusions

In summary, this meta-analysis displayed high prevalences of erythropoiesis-related micronutrient deficiencies in pregnant women worldwide. We highlighted that age, geographic region, and diagnostic criteria significantly impacted prevalences of single micronutrient deficiencies in pregnant women. Asia had the greatest iron and vitamin B_{12} deficiency prevalences. Pregnant women aged ≤ 25 years exhibited the highest prevalence of a vitamin B_{12} deficiency. The iron and vitamin B_{12} deficiency prevalences were estimated to increase with gestational age. While these findings offer important insights, the study also identified country- and region-level differences in the prevalence of erythropoiesis-related micronutrient deficiencies, along with substantial variability in the underlying data, assay methods, and threshold values used to determine deficiency status and derive pooled estimates. These factors may contribute to uncertainty regarding the precise magnitude of the reported prevalences. Nonetheless, the results underscore the need for improved data quality and greater methodological consistency. Further epidemiological and nutritional research as well as additional meta-analyses are needed to elucidate the risk factors and identify appropriate remedies for mitigating high prevalences of erythropoiesis-associated micronutrient deficiencies in pregnant women.

Acknowledgments

This manuscript was edited by Wallace Academic Editing.

Authors contributions

CRediT: **Nhi Thi Hong Nguyen**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing; **Yang-Ching Chen**: Conceptualization, Methodology, Software; **Nguyen Thanh Nhu**: Investigation, Methodology, Visualization; **Hoang Bui Bao**: Conceptualization, Investigation; **Chien-Yeh Hsu**: Conceptualization, Formal analysis; **Arpita Das**: Investigation, Visualization; **Jane C.-J. Chao**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Supervision, Visualization, Writing – original draft, Writing – review & editing.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The authors have not declared a specific grant from any funding agency in the public, commercial, or not-for-profit-sectors.

ORCID

Nhi Thi Hong Nguyen http://orcid.org/0000-0001-7195-6171
Yang-Ching Chen http://orcid.org/0000-0002-0682-3716
Nguyen Thanh Nhu http://orcid.org/0000-0002-1636-6061
Hoang Bui Bao http://orcid.org/0000-0003-4066-7312
Chien-Yeh Hsu http://orcid.org/0000-0001-8233-6461
Arpita Das http://orcid.org/0000-0001-7043-3328
Jane C.-J. Chao http://orcid.org/0000-0002-3610-9580

Data availability statement

All data relevant to this study are included in the article or uploaded as supplementary materials. The data that support the findings of this study are available from the corresponding author upon the request.

References

[1] Baker BC, Hayes DJL, Jones RL. Effects of micronutrients on placental function: evidence from clinical studies to animal models. Reproduction. 2018;156(3):R69–R82. doi: 10.1530/REP-18-0130.

[2] Gernand AD, Schulze KJ, Stewart CP, et al. Micronutrient deficiencies in pregnancy worldwide: health effects and prevention. Nat Rev Endocrinol. 2016;12(5):274–289. doi: 10.1038/nrendo.2016.37.

[3] Koury MJ, Ponka P. New insights into erythropoiesis: the roles of folate, vitamin B_{12}, and iron. Annu Rev Nutr. 2004;24(1):105–131. doi: 10.1146/annurev.nutr.24.012003.132306.

[4] Pathak P, Kapil U, Yajnik CS, et al. Iron, folate, and vitamin B_{12} stores among pregnant women in a rural area of Haryana State, India. Food Nutr Bull. 2007;28(4):435–438. doi: 10.1177/156482650702800409.

[5] Cavill I. Iron and erythropoiesis in normal subjects and in pregnancy. J Perinat Med. 1995;23(1-2):47–50. doi: 10.1515/jpme.1995.23.1-2.47.

[6] Ashworth CJ, Antipatis C. Micronutrient programming of development throughout gestation. Reproduction. 2001;122(4):527–535. doi: 10.1530/rep.0.1220527.

[7] Mayasari NR, Bai CH, Chao JC, et al. Relationships between dietary patterns and erythropoiesis-associated micronutrient deficiencies (iron, folate, and vitamin B_{12}) among pregnant women in Taiwan. Nutrients. 2023;15(10):2311. doi: 10.3390/nu15102311.

[8] Mishra J, Tomar A, Puri M, et al. Trends of folate, vitamin B_{12}, and homocysteine levels in different trimesters of pregnancy and pregnancy outcomes. Am J Hum Biol. 2020;32(5):e23388. doi: 10.1002/ajhb.23388.

[9] Furness D, Fenech M, Dekker G, et al. Folate, vitamin B_{12}, vitamin B_6 and homocysteine: impact on pregnancy outcome. Matern Child Nutr. 2013;9(2):155–166. doi: 10.1111/j.1740-8709.2011.00364.x.

[10] Alwan NA, Hamamy H. Maternal iron status in pregnancy and long-term health outcomes in the offspring. J Pediatr Genet. 2015;4(2):111–123. doi: 10.1055/s-0035-1556742.

[11] Hernández-Martínez C, Canals J, Aranda N, et al. Effects of iron deficiency on neonatal behavior at different stages of pregnancy. Early Hum Dev. 2011;87(3):165–169. doi: 10.1016/j.earlhumdev.2010.12.006.

[12] Abu-Ouf NM, Jan MM. The impact of maternal iron deficiency and iron deficiency anemia on child's health. Saudi Med J. 2015;36(2):146–149. doi: 10.15537/smj.2015.2.10289.

[13] Georgieff MK. Iron deficiency in pregnancy. Am J Obstet Gynecol. 2020;223(4):516–524. doi: 10.1016/j.ajog.2020.03.006.

[14] Zou R, El Marroun H, Cecil C, et al. Maternal folate levels during pregnancy and offspring brain development in late childhood. Clin Nutr. 2021;40(5):3391–3400. doi: 10.1016/j.clnu.2020.11.025.

[15] Scholl TO, Johnson WG. Folic acid: influence on the outcome of pregnancy. Am J Clin Nutr. 2000;71(5 Suppl):1295S–1303S. doi: 10.1093/ajcn/71.5.1295s.

[16] Ami N, Bernstein M, Boucher F, et al. Folate and neural tube defects: the role of supplements and food fortification. Paediatr Child Health. 2016;21(3):145–154. doi: 10.1093/pch/21.3.145.

[17] de Benoist B. Conclusions of a WHO technical consultation on folate and vitamin B_{12} deficiencies. Food Nutr Bull. 2008;29(2 Suppl):S238–S244. doi: 10.1177/15648265080292S129.

[18] Molloy AM, Kirke PN, Brody LC, et al. Effects of folate and vitamin B_{12} deficiencies during pregnancy on fetal, infant, and child development. Food Nutr Bull. 2008;29(2 Suppl):S101–S111. doi: 10.1177/15648265080292s114.

[19] Sukumar N, Venkataraman H, Wilson S, et al. Vitamin B_{12} status among pregnant women in the UK and its association with obesity and gestational diabetes. Nutrients. 2016;8(12):768. doi: 10.3390/nu8120768.

[20] Behere RV, Deshmukh AS, Otiv S, et al. Maternal vitamin B_{12} status during pregnancy and its association with outcomes of pregnancy and health of the offspring: a systematic review and implications for policy in India. Front Endocrinol (Lausanne). 2021;12:619176. doi: 10.3389/fendo.2021.619176.

[21] Cesana BM, da Molin S, Jassam N, et al. Assessing the harmonization of current total vitamin B_{12} measurement methods: relevance and implications. Clin Chem Lab Med. 2025;63[Online ahead of print](12):2433–2441. doi: 10.1515/cclm-2025-0939.

[22] Black MM. Effects of vitamin B_{12} and folate deficiency on brain development in children. Food Nutr Bull. 2008;29(2 Suppl):S126–S131. doi: 10.1177/15648265080292s117.

[23] Rogne T, Tielemans MJ, Chong MF, et al. Associations of maternal vitamin B_{12} concentration in pregnancy with the risks of preterm birth and low birth weight: a systematic review and meta-analysis of individual participant data. Am J Epidemiol. 2017;185(3):212–223. doi: 10.1093/aje/kww212.

[24] John SE, Azizi K, Hancy A, et al. The prevalence and risk factors associated with iron, vitamin B_{12} and folate deficiencies in pregnant women: a cross-sectional study in Mbeya, Tanzania. PLOS Glob Public Health. 2023;3(4):e0001828. doi: 10.1371/journal.pgph.0001828.

[25] WHO. Strategies to prevent anaemia: recommendations from an expert group consultation. New Delhi: India; 2016.

[26] Lassale C, Gaye B. Addressing global micronutrient inadequacies: enhancing global data representation. Lancet Glob Health. 2024;12(10):e1561–e1562. doi: 10.1016/S2214-109X(24)00338-3.

[27] Sukumar N, Rafnsson SB, Kandala NB, et al. Prevalence of vitamin B-12 insufficiency during pregnancy and its effect on offspring birth weight: a systematic review and meta-analysis. Am J Clin Nutr. 2016;103(5):1232–1251. doi: 10.3945/ajcn.115.123083.

[28] Lindström E, Hossain MB, Lönnerdal B, et al. Prevalence of anemia and micronutrient deficiencies in early pregnancy in rural Bangladesh, the MINIMat trial. Acta Obstet Gynecol Scand. 2011;90(1):47–56. doi: 10.1111/j.1600-0412.2010.01014.x.

[29] Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ. 2021;372:n71. doi: 10.1136/bmj.n71.

[30] Munn Z, Moola S, Lisy K, et al. Methodological guidance for systematic reviews of observational epidemiological studies reporting prevalence and cumulative incidence data. Int J Evid Based Healthc. 2015;13(3):147–153. doi: 10.1097/XEB.0000000000000054.
[31] Higgins JP, Thompson SG, Deeks JJ, et al. Measuring inconsistency in meta-analyses. BMJ. 2003;327(7414):557–560. doi: 10.1136/bmj.327.7414.557.
[32] Our World in Data. World regions according to the World Health Organization. [Accessed on August 26, 2024]. Available from: https://ourworldindata.org/grapher/who-regions.
[33] Fantom N, Serajuddin U. The World Bank's classification of countries by income. Washington, DC: World Bank Group; 2016.
[34] WHO. Serum ferritin concentrations for the assessment of iron status and iron deficiency in populations. Geneva: World Health Organization; 2011.
[35] Qi YP, Do AN, Hamner HC, et al. The prevalence of low serum vitamin B_{12} status in the absence of anemia or macrocytosis did not increase among older U.S. adults after mandatory folic acid fortification. J Nutr. 2014;144(2):170–176. doi: 10.3945/jn.113.183095.
[36] Sterne JA, Gavaghan D, Egger M. Publication and related bias in meta-analysis: power of statistical tests and prevalence in the literature. J Clin Epidemiol. 2000;53(11):1119–1129. doi: 10.1016/s0895-4356(00)00242-0.
[37] Abbas W, Adam I, Rayis DA, et al. A higher rate of iron deficiency in obese pregnant sudanese women. Open Access Maced J Med Sci. 2017;5(3):285–289. doi: 10.3889/oamjms.2017.059.
[38] Abdelrahim II, Adam GK, Mohmmed AA, et al. Anaemia, folate and vitamin B_{12} deficiency among pregnant women in an area of unstable malaria transmission in eastern Sudan. Trans R Soc Trop Med Hyg. 2009;103(5):493–496. AA. doi: 10.1016/j.trstmh.2008.10.007.
[39] Akinbo FO, Alabi LO, Aiyeyemi JA. Micronutrient deficiencies among pregnant women with Plasmodium falciparum infection in Owo, Ondo State, Nigeria. Af J Clin Exp Micro. 2019;20(2):127–136. doi: 10.4314/ajcem.v20i2.6.
[40] Akowuah JA, Owusu-Addo E, Opuni AA. Predictors of anaemia prevalence among Ghanaian pregnant women: a cross-sectional study. Inquiry. 2022;59:469580221086919. doi: 10.1177/00469580221086919.
[41] Babah OA, Akinajo OR, Beňová L, et al. Prevalence of and risk factors for iron deficiency among pregnant women with moderate or severe anaemia in Nigeria: a cross-sectional study. BMC Pregnancy Childbirth. 2024;24(1):39. doi: 10.1186/s12884-023-06169-1.
[42] Baingana RK, Enyaru JK, Tjalsma H, et al. The aetiology of anaemia during pregnancy: a study to evaluate the contribution of iron deficiency and common infections in pregnant Ugandan women. Public Health Nutr. 2015;18(8):1423–1435. doi: 10.1017/S1368980014001888.
[43] Bergmann RL, Gravens-Müller L, Hertwig K, et al. Iron deficiency is prevalent in a sample of pregnant women at delivery in Germany. Eur J Obstet Gynecol Reprod Biol. 2002;102(2):155–160. doi: 10.1016/s0301-2115(01)00609-1.
[44] da Costa AG, Vargas S, Clode N, et al. Prevalence and risk factors for iron deficiency anemia and iron depletion during pregnancy: a prospective study. Acta Med Port. 2016;29:514–518. doi: 10.20344/amp.6808.
[45] Duffy EM, Bonham MP, Wallace JM, et al. Iron status in pregnant women in the Republic of Seychelles. Public Health Nutr. 2010;13(3):331–337. doi: 10.1017/S1368980009991054.
[46] Engmann C, Adanu R, Lu TS, et al. Anemia and iron deficiency in pregnant Ghanaian women from urban areas. Int J Gynaecol Obstet. 2008;101(1):62–66. doi: 10.1016/j.ijgo.2007.09.032.
[47] Fite MB, Tura AK, Yadeta TA, et al. Co-occurrence of iron, folate, and vitamin A deficiency among pregnant women in eastern Ethiopia: a community-based study. BMC Nutr. 2023;9(1):72. doi: 10.1186/s40795-023-00724-x.
[48] Gopal M, Sunitha K, Arockiasamy J, et al. Micronutrient deficiency in pregnancy: time to think beyond iron and folic acid supplementation. Indian J Community Med. 2022;47(3):425–428. doi: 10.4103/ijcm.ijcm_743_21.
[49] Harvey T, Zkik A, Auges M, et al. Assessment of iron deficiency and anemia in pregnant women: an observational French study. Womens Health (Lond). 2016;12(1):95–102. doi: 10.2217/whe.15.91.
[50] Kangalgil M, Sahinler A, Kırkbir IB, et al. Associations of maternal characteristics and dietary factors with anemia and iron-deficiency in pregnancy. J Gynecol Obstet Hum Reprod. 2021;50(8):102137. doi: 10.1016/j.jogoh.2021.102137.
[51] Mamme NY, Roba HS, Fite MB, et al. Serum folate deficiency and associated factors among pregnant women in Haramaya District, Eastern Ethiopia: a community-based study. BMJ Open. 2023;13(5):e068076. doi: 10.1136/bmjopen-2022-068076.
[52] Mei Z, Cogswell ME, Looker AC, et al. Assessment of iron status in US pregnant women from the National Health and Nutrition Examination Survey (NHANES), 1999-2006. Am J Clin Nutr. 2011;93(6):1312–1320. doi: 10.3945/ajcn.110.007195.
[53] Siridamrongvattana S, Van Hoa N, Sanchaisuriya K, et al. Burden of anemia in relation to thalassemia and iron deficiency among Vietnamese pregnant women. Acta Haematol. 2013;130(4):281–287. doi: 10.1159/000351168.
[54] Srour MA, Aqel SS, Srour KM, et al. Prevalence of anemia and iron deficiency among Palestinian pregnant women and its association with pregnancy outcome. Anemia. 2018;2018:9135625–9135627. doi: 10.1155/2018/9135625.
[55] Teichman J, Nisenbaum R, Lausman A, et al. Suboptimal iron deficiency screening in pregnancy and the impact of socioeconomic status in a high-resource setting. Blood Adv. 2021;5(22):4666–4673. doi: 10.1182/bloodadvances.2021004352.

[56] Weyers R, Coetzee MJ, Nel M. Iron status determination in pregnancy using the Thomas plot. Int J Lab Hematol. 2016;38(2):119–124. doi: 10.1111/ijlh.12448.
[57] Yuan X, Hu H, Zhang M, et al. Iron deficiency in late pregnancy and its associations with birth outcomes in Chinese pregnant women: a retrospective cohort study. Nutr Metab (Lond). 2019;16(1):30. doi: 10.1186/s12986-019-0360-9.
[58] Adaikalakoteswari A, Vatish M, Lawson A, et al. Low maternal vitamin B_{12} status is associated with lower cord blood HDL cholesterol in white Caucasians living in the UK. Nutrients. 2015;7(4):2401–2414. doi: 10.3390/nu7042401.
[59] Baker PN, Wheeler SJ, Sanders TA, et al. A prospective study of micronutrient status in adolescent pregnancy. Am J Clin Nutr. 2009;89(4):1114–1124. doi: 10.3945/ajcn.2008.27097.
[60] Barnabé A, Aléssio AC, Bittar LF, et al. Folate, vitamin B_{12} and homocysteine status in the post-folic acid fortification era in different subgroups of the Brazilian population attended to at a public health care center. Nutr J. 2015;14(1):19. doi: 10.1186/s12937-015-0006-3.
[61] Mgamb E, Gura Z, Wanzala P, et al. Folate deficiency and utilization of folic acid fortified flour among pregnant women attending antenatal clinic at Pumwani Maternity Hospital, Kenya, 2015. Pan Afr Med J. 2017;28(Suppl 1):8. doi: 10.11604/pamj.supp.2017.28.1.9296.
[62] Ndem BN, Akwiwu EC, Akpan PA, et al. Timely accessing of antenatal care and prevalence of vitamin B12 and folate deficiencies among pregnant women ina nigerian population. NZJ Med Lab Sci. 2021;75:12–15.
[63] Rayis DA, Karar A, Alshareef SA, et al. Early pregnancy serum levels of folate and vitamin B_{12} in overweight and obese women in Khartoum, Sudan. Trans R Soc Trop Med Hyg. 2023;117(2):128–131. doi: 10.1093/trstmh/trac096.
[64] Saravanan P, Sukumar N, Adaikalakoteswari A, et al. Association of maternal vitamin B_{12} and folate levels in early pregnancy with gestational diabetes: a prospective UK cohort study (PRiDE study). Diabetologia. 2021;64(10):2170–2182. doi: 10.1007/s00125-021-05510-7.
[65] Yila TA, Araki A, Sasaki S, et al. Predictors of folate status among pregnant Japanese women: the Hokkaido Study on Environment and Children's Health, 2002–2012. Br J Nutr. 2016;115(12):2227–2235. doi: 10.1017/S0007114516001628.
[66] García-Casal MN, Osorio C, Landaeta M, et al. High prevalence of folic acid and vitamin B_{12} deficiencies in infants, children, adolescents and pregnant women in Venezuela. Eur J Clin Nutr. 2005;59(9):1064–1070. doi: 10.1038/sj.ejcn.1602212.
[67] Finkelstein JL, Guillet R, Pressman EK, et al. Vitamin B_{12} status in pregnant adolescents and their infants. Nutrients. 2019;11(2):397. doi: 10.3390/nu11020397.
[68] Jeruszka-Bielak M, Isman C, Schroder TH, et al. South Asian ethnicity is related to the highest risk of vitamin B_{12} deficiency in pregnant Canadian women. Nutrients. 2017;9(4):317. doi: 10.3390/nu9040317.
[69] Ramírez-Vélez R, Correa-Bautista JE, Martínez-Torres J, et al. Vitamin B_{12} concentrations in pregnant Colombian women: analysis of nationwide data 2010. BMC Pregnancy Childbirth. 2016;16(1):26. doi: 10.1186/s12884-016-0820-4.
[70] Rizwan AS, Robeen K, Ahmad A, et al. Frequency of hypovitaminosis B_{12} in pregnant women with gestational diabetes mellitus. PJMHS. 2021;15(7):2296–2298. doi: 10.53350/pjmhs2115102753.
[71] Samuel TM, Duggan C, Thomas T, et al. Vitamin B_{12} intake and status in early pregnancy among urban South Indian women. Ann Nutr Metab. 2013;62(2):113–122. doi: 10.1159/000345589.
[72] Sobowale OI, Khan MR, Roy AK, et al. Prevalence and risk factors of vitamin B_{12} deficiency among pregnant women in rural Bangladesh. Nutrients. 2022;14(10):1993. doi: 10.3390/nu14101993.
[73] Visentin CE, Masih SP, Plumptre L, et al. Low serum vitamin B_{12} concentrations are prevalent in a cohort of pregnant Canadian women. J Nutr. 2016;146(5):1035–1042. doi: 10.3945/jn.115.226845.
[74] Arija V, Ribot B, Aranda N. Prevalence of iron deficiency states and risk of haemoconcentration during pregnancy according to initial iron stores and iron supplementation. Public Health Nutr. 2013;16(8):1371–1378. doi: 10.1017/S1368980013000608.
[75] Calje E, Skinner J. The challenge of defining and treating anemia and iron deficiency in pregnancy: a study of New Zealand midwives' management of iron status in pregnancy and the postpartum period. Birth. 2017;44(2):181–190. doi: 10.1111/birt.12282.
[76] Pobee RA, Setorglo J, Klevor M, et al. The prevalence of anemia and iron deficiency among pregnant Ghanaian women, a longitudinal study. PLoS One. 2021;16(3):e0248754. doi: 10.1371/journal.pone.0248754.
[77] Rezgale R, Pudule I, Cauce V, et al. Iron status in pregnant women in Latvia: an epidemiological, cross-sectional, multicenter study according to WHO and UK criteria. Medicina (Kaunas). 2022;58(7):955. doi: 10.3390/medicina58070955.
[78] Abd Rahman R, Idris IB, Isa ZM, et al. The prevalence and risk factors of iron deficiency anemia among pregnant women in Malaysia: a systematic review. Front Nutr. 2022;9:847693. doi: 10.3389/fnut.2022.847693.
[79] Zhou Y, Lyu Y, Ye W, et al. The prevalence of anemia among pregnant women in China: a systematic review and meta-analysis. Nutrients. 2024;16(12):1854. doi: 10.3390/nu16121854.
[80] Bencaiova G, Burkhardt T, Breymann C. Anemia-prevalence and risk factors in pregnancy. Eur J Intern Med. 2012;23(6):529–533. doi: 10.1016/j.ejim.2012.04.008.

[81] Loy SL, Lim LM, Chan SY, et al. Iron status and risk factors of iron deficiency among pregnant women in Singapore: a cross-sectional study. BMC Public Health. 2019;19(1):397. doi: 10.1186/s12889-019-6736-y.
[82] WHO. Guideline: daily iron and folic acid supplementation in pregnant women. Geneva: World Health Organization; 2012.
[83] Peña-Rosas JP, De-Regil LM, Garcia-Casal MN, et al. Daily oral iron supplementation during pregnancy. Cochrane Database Syst Rev. 2015;2015(7):CD004736. doi: 10.1002/14651858.CD004736.pub5.
[84] Greenberg JA, Bell SJ, Guan Y, et al. Folic acid supplementation and pregnancy: more than just neural tube defect prevention. Rev Obstet Gynecol. 2011;4(2):52–59.
[85] Nelson DB, Spong CY. Reaffirming recommendations for folic acid supplementation: everything old is new again. JAMA. 2023;330(5):419–420. doi: 10.1001/jama.2023.12972.
[86] Fekete K, Berti C, Trovato M, et al. Effect of folate intake on health outcomes in pregnancy: a systematic review and meta-analysis on birth weight, placental weight and length of gestation. Nutr J. 2012;11(1):75. doi: 10.1186/1475-2891-11-75.
[87] Gebremichael B, Roba HS, Getachew A, et al. Folate deficiency among women of reproductive age in Ethiopia: a systematic review and meta-analysis. PLoS One. 2023;18(5):e0285281. doi: 10.1371/journal.pone.0285281.
[88] Finkelstein JL, Fothergill A, Venkatramanan S, et al. Vitamin B_{12} supplementation during pregnancy for maternal and child health outcomes. Cochrane Database Syst Rev. 2024;1(1):CD013823. doi: 10.1002/14651858.CD013823.pub2.
[89] Keats EC, Haider BA, Tam E, et al. Multiple-micronutrient supplementation for women during pregnancy. Cochrane Database Syst Rev. 2019;3(3):Cd004905. doi: 10.1002/14651858.CD004905.pub6.
[90] Maruvada P, Stover PJ, Mason JB, et al. Knowledge gaps in understanding the metabolic and clinical effects of excess folates/folic acid: a summary, and perspectives, from an NIH workshop. Am J Clin Nutr. 2020;112(5):1390–1403. doi: 10.1093/ajcn/nqaa259.
[91] Sununtnasuk C, D'Agostino A, Fiedler JL. Iron + folic acid distribution and consumption through antenatal care: identifying barriers across countries. Public Health Nutr. 2016;19(4):732–742. doi: 10.1017/s1368980015001652.
[92] Ejara D, Ferede A, Shifa JE, et al. Compliance level and associated factors of iron folic acid supplementation among pregnant women in North Shoa Zone, Ethiopia. Sci Rep. 2024;14(1):13407. doi: 10.1038/s41598-024-63111-x.
[93] Liu X, Zeng X, Wang J, et al. Associations of maternal serum folate, vitamin B_{12} and their imbalance with gestational diabetes mellitus: the mediation effects of the methionine cycle related metabolites. Clin Nutr. 2025;48:50–59. doi: 10.1016/j.clnu.2025.03.009.
[94] Li S, Hou Y, Yan X, et al. Joint effects of folate and vitamin B_{12} imbalance with maternal characteristics on gestational diabetes mellitus. J Diabetes. 2019;11(9):744–751. doi: 10.1111/1753-0407.12899.
[95] Lai JS, Pang WW, Cai S, et al. High folate and low vitamin B_{12} status during pregnancy is associated with gestational diabetes mellitus. Clin Nutr. 2018;37(3):940–947. doi: 10.1016/j.clnu.2017.03.022.
[96] Cogswell ME, Parvanta I, Ickes L, et al. Iron supplementation during pregnancy, anemia, and birth weight: a randomized controlled trial. Am J Clin Nutr. 2003;78(4):773–781. doi: 10.1093/ajcn/78.4.773.
[97] Darnton-Hill I, Mkparu UC. Micronutrients in pregnancy in low- and middle-income countries. Nutrients. 2015;7(3):1744–1768. doi: 10.3390/nu7031744.
[98] Pavord S, Daru J, Prasannan N, et al. UK guidelines on the management of iron deficiency in pregnancy. Br J Haematol. 2020;188(6):819–830. doi: 10.1111/bjh.16221.
[99] Obeid R, Heil SG, Verhoeven MMA, et al. Vitamin B_{12} intake from animal foods, biomarkers, and health aspects. Front Nutr. 2019;6:93. 28;6:93. doi: 10.3389/fnut.2019.00093.
[100] Shi H, Chen L, Wang Y, et al. Severity of anemia during pregnancy and adverse maternal and fetal outcomes. JAMA Netw Open. 2022;5(2):e2147046. doi: 10.1001/jamanetworkopen.2021.47046.
[101] Santana G, Reise R, Koenig M, et al. Evaluating test utilization for anemia during pregnancy. Int J Lab Hematol. 2022;44(3):673–678. doi: 10.1111/ijlh.13797.
[102] Sifakis S, Pharmakides G. Anemia in pregnancy. Ann N Y Acad Sci. 2000;900(1):125–136. doi: 10.1111/j.1749-6632.2000.tb06223.x.
[103] Moher D, Pham B, Klassen TP, et al. What contributions do languages other than English make on the results of meta-analyses? J Clin Epidemiol. 2000;53(9):964–972. doi: 10.1016/s0895-4356(00)00188-8.
[104] Jüni P, Holenstein F, Sterne J, et al. Direction and impact of language bias in meta-analyses of controlled trials: empirical study. Int J Epidemiol. 2002;31(1):115–123. doi: 10.1093/ije/31.1.115.
[105] Morrison A, Polisena J, Husereau D, et al. The effect of English-language restriction on systematic review-based meta-analyses: a systematic review of empirical studies. Int J Technol Assess Health Care. 2012;28(2):138–144. doi: 10.1017/s0266462312000086.
[106] Garcia-Casal MN, Peña-Rosas JP, Urrechaga E, et al. Performance and comparability of laboratory methods for measuring ferritin concentrations in human serum or plasma: a systematic review and meta-analysis. PLoS One. 2018;13(5):e0196576. doi: 10.1371/journal.pone.0196576.
[107] Ajuria-Morentin I, Mar Medina C, Urbieta E, et al. Determination of reference values for serum folate and vitamin B_{12} using three different immunoassays: is it worth making an effort to produce them in our laboratory? Clin Lab. 2014;60(7):1135–1143. doi: 10.7754/Clin.Lab.2013.130729.