Review Article:

The Impact of Early Life Nutrition on Cognitive Development and Academic Achievement in Preschool Children A Systematic Review and Meta Analysis

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Abstract:

The initial years of life are a critical period for brain development, characterized by rapid growth and structural differentiation. Nutritional deficiencies during this phase may hinder cognitive advancement, contributing to long-term academic challenges and learning disabilities. This systematic review aims to evaluate and synthesize the evidence on various nutritional strategies (including breastfeeding, formula feeding, dietary supplements, and fortified foods) and their effects on cognitive performance and school readiness in preschool-aged children. The review was conducted following PRISMA guidelines and included studies published in English from PubMed, ScienceDirect, and Web of Science databases. Studies involving children aged 3–6 years were selected, focusing on randomized controlled trials, cohort studies, case-control studies, and cross-sectional designs. Outcomes of interest included changes in cognitive development and academic performance linked to early-life nutrition. Twelve studies met the inclusion criteria. Findings indicated a significant association between breastfeeding and improved cognitive outcomes (odds ratio: 2.35, 95% CI: 1.91–2.90; P<0.00001). No statistically significant correlation was found between formula feeding and cognitive outcomes (P=0.10). Furthermore, a strong relationship was observed between early nutritional interventions and improvements in overall cognitive development and school readiness (P=0.008). However, associations between early nutrition and cognitive literacy/numeracy were not statistically significant (P>0.05). Early-life nutrition positively influences cognitive development in preschool-aged children. Although improvements in general cognitive abilities were clear, no strong evidence was found linking early nutrition to literacy and numeracy outcomes. Continued research is essential to further clarify these relationships.

Keywords:
Nutrition Disorders, Cognitive Development, Preschool Child, Breast Feeding, Child Development, Neurodevelopmental Disorders

Introduction:

Early childhood, particularly from birth to five years, represents a critical window for cognitive development due to the rapid expansion and differentiation of the brain during this period[1]. Proper nutrition is fundamental during these years, as it provides essential proteins, vitamins, minerals, and fatty acids required for the development of language, memory, problem-solving, and motor coordination skills. Omega-3 fatty acids, for example, play a key role in brain function and overall neurodevelopment. In contrast, inadequate nutrition negatively affects cognitive abilities, increases the risk of learning difficulties and reduced academic performance, and has been associated with lower IQ scores later in life[1].

Malnutrition occurs when nutrient intake does not meet physiological needs and may manifest as undernutrition or overnutrition[2]. Undernutrition is a significant global public health concern, particularly among young children, as it impairs the intake of vital macronutrients and micronutrients necessary for proper growth and neurological development[3]. Early childhood malnutrition commonly results in stunting, wasting, weight loss, and cognitive impairments[4]. An estimated 148 million children under the age of five worldwide experience stunted growth, and approximately 45 million are underweight due to chronic malnutrition[3,4,5.] Such nutritional deficits increase the risk of psychiatric disorders and lead to delayed developmental milestones and reduced functional capabilities[5]. Cognitive impairments are closely linked to inadequate weight gain, low height-for-age ratios, and insufficient nutritional intake[6].

Optimal brain development requires a balanced intake of proteins, carbohydrates, vitamins, and essential minerals[7]. Specific nutrients such as iron, vitamin B12, and long-chain polyunsaturated fatty acids (LC-PUFAs) are crucial for brain growth and function[8]. Iron supports brain network formation and cognitive processing; its deficiency, particularly during the first two years of life, may lead to developmental delays and cognitive impairment[7,9,10]. Zinc plays a comparable role in neurodevelopment, memory, attention, and motor skills, and chronic deficiency has been associated with stunting and impaired neural transmission[7,11-14]. Choline supports

cell membrane integrity and cognitive function[15].

Iodine, required for thyroid hormone synthesis, is essential for brain development and metabolism[7]. Iodine deficiency is a leading global cause of preventable intellectual disability and has profound effects on cognitive outcomes[7,16]. Folate supports DNA and RNA synthesis and nervous system development[17], and maternal folate deficiency is linked to neural tube defects such as spina bifida and anencephaly[18]. Vitamin B12 is essential for neurotransmission and neuronal health; deficiency may cause neurological deficits and brain atrophy[19]. Vitamin A contributes to visual and neural development, while LC-PUFAs such as DHA and EPA are important for memory, visual processing, and cognitive performance[7,20].

The first 1,000 days of life are regarded as the most critical for brain development, and deficiencies in key nutrients during this period can lead to long-term cognitive and developmental impairments[21]. Adequate iron and zinc intake during infancy has been shown to support healthy weight-for-age and height-for-age outcomes[22,23]. Choline supplementation for mothers or children may also support healthy brain development[24]. Although cognitive development continues beyond infancy, the second 1,000 days of life also represent a crucial phase marked by rapid acquisition of cognitive skills such as memory and attention control, yet this period receives less policy attention[25].

Cognitive development in preschool children strongly predicts later academic achievement[26]. However, evidence on the long-term effects of early nutritional interventions remains limited. Childhood malnutrition and lack of proper stimulation increase the risk of poor academic performance, reduced cognitive function, and lower school attendance, ultimately leading to poorer socio-economic outcomes in adulthood[27,28].

This systematic review aims to evaluate the effects of nutritional interventions—including breastfeeding, formula feeding, micronutrient supplementation, dietary modifications, and fortified foods—on cognitive development and physical growth among preschool-aged children. Additionally, it will examine the relationship between early nutritional status and early academic abilities such as literacy, numeracy,

and school readiness. The findings will help inform parents, caregivers, educators, policymakers, and healthcare professionals about the importance of adequate nutrition during early childhood to support optimal cognitive development and academic preparedness.

Methods:

Literature Search Strategy:

A systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. A comprehensive electronic search was performed using PubMed, ScienceDirect, and Web of Science, and only English-language publications were included.

The search strategy incorporated a combination of relevant keywords and Medical Subject Headings (MeSH) aligned with the study objectives. Search terms included: nutrition, infant nutrition, toddler nutrition, preschool nutrition, breastfeeding, formula feeding, dietary supplements, fortified foods, micronutrient intake, cognitive development, IQ, intelligence, attention, memory, language skills, problem-solving, executive function, academic performance, academic achievement, school readiness, literacy, numeracy, early literacy, early numeracy, and school performance, along with terms related to the target population such as preschool-aged children, preschoolers, early childhood, and young children aged three to six years. The search identified a total of 151 articles—38 from PubMed, 83 from ScienceDirect, and 30 from Web of Science. Following initial screening, 12 distinct articles remained for full-text assessment.

Inclusion and Exclusion Criteria:

Studies were eligible if they examined the effects of early-life nutritional interventions on cognitive development or academic performance in preschool-aged children (3–6 years). Eligible designs included randomized controlled trials, cohort studies, case-control studies, and cross-sectional research. Only studies published in English were included.

Studies were excluded if they were published in languages other than English, did not focus on nutrition as an intervention, or failed to report outcomes related to cognitive development or academic performance.

Selection of Articles and Data Extraction:

Article screening and selection were

performed in multiple stages by four independent reviewers (N.S.J., S.K.A., Y.A.A., M.A.A.). Titles and abstracts were initially screened to determine relevance, followed by full-text review to assess eligibility based on predefined inclusion and exclusion criteria. Data extraction was conducted independently using a standardized data-collection form.

Extracted data included study identification details (title, authors, publication year, journal), study characteristics (design, sample size, duration), participant information (age range, mean age, socioeconomic status, gender distribution, health status), nutritional exposure details (type and timing), and outcome measures (cognitive outcomes such as IQ, memory, language, attention; academic outcomes such as standardized testing, teacher-reported performance). Information on confounders (parental education, socioeconomic status, home environment), risk of bias, study conclusions, limitations, and recommendations for future research was also recorded.

Disagreements during screening or data extraction were resolved through discussion and consensus. Duplicate records were removed using Mendeley. This rigorous process ensured a comprehensive and unbiased synthesis of available evidence regarding the impact of early-life nutrition on cognitive and academic development in preschool-aged children.

Statistical Analysis:

Data analysis was conducted using Resource Manager (Version 5.4.1). Heterogeneity was assessed using the I^2 statistic and was considered statistically significant at $p < 0.05$. A fixed-effect model was applied when heterogeneity was low, whereas a random-effects model was used where substantial heterogeneity was observed ($I^2 > 50\%$).

Results:

After searching through the electronic databases, 143 papers were obtained. The study titles and abstracts were screened whereby 116 papers were excluded, and 27 publications that remained were assessed for full text eligibility. Fifteen of those studies were excluded. Finally, the meta-analysis and systematic review involved 12 studies (Figure 1).

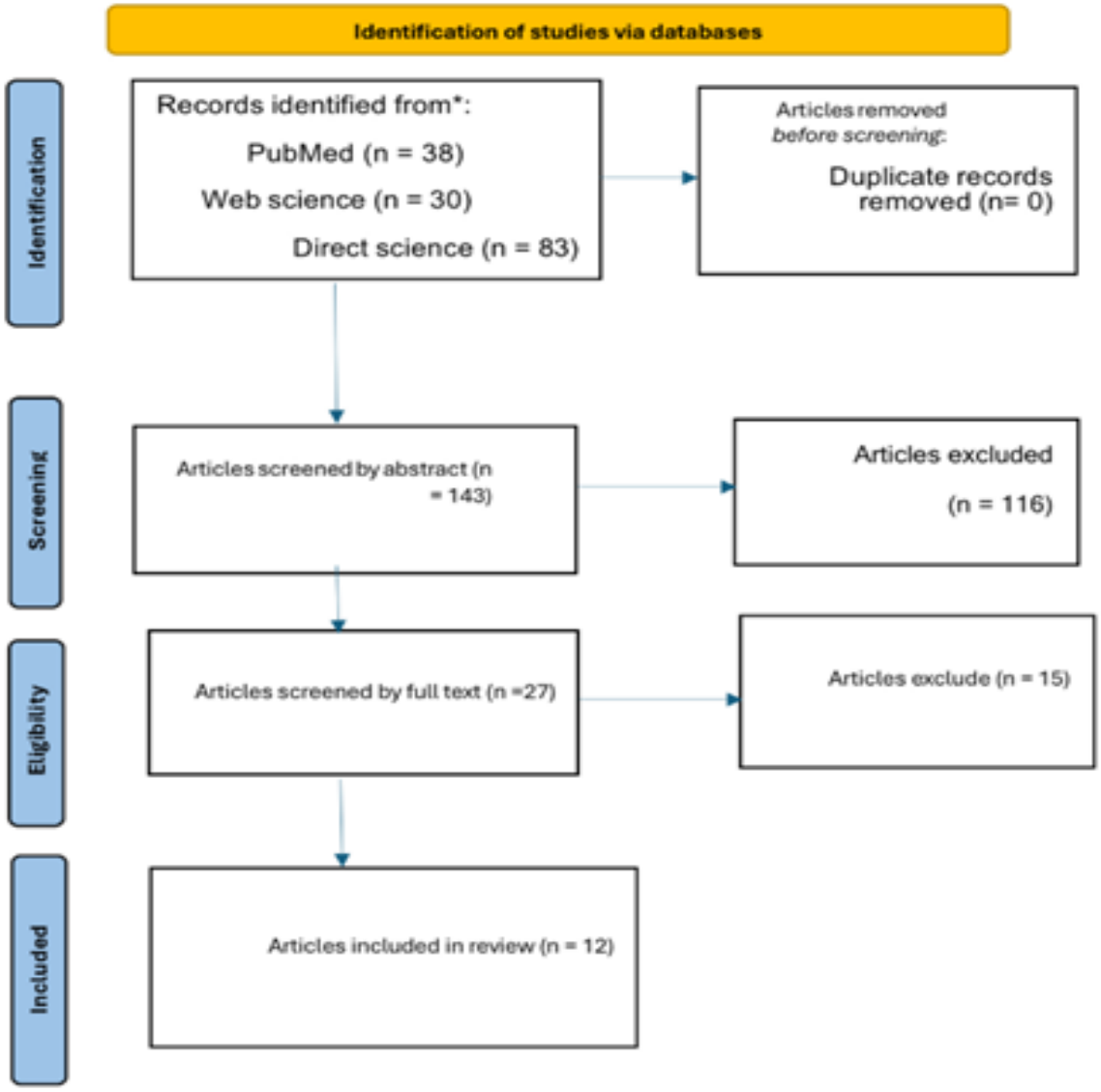


Figure 1: PRISMA Flow Diagram.

Qualitative Synthesis:

Table 1 lists the publications included in the review; each article looked at the impact of early life nutrition on preschool-aged children's cognitive development and academic performance. The studies were all conducted in various parts of the world and published in English. Three of the included studies were conducted in the United States, two in China, two in India, and one each in Nigeria, Nepal, Ecuador, Poland, and Austria. A total of 24754 participants were included in the included research; the study with the lowest sample size had 230 participants, while the one with the biggest sample size had 13500 participants.

Table 1: Characteristics of the Studies.

Authors	Region	Study Design	Sample	Intervention	Inclusion	Results/Conclusion
Roberts et al., 2020 [29]	USA	Randomized controlled trial	1059 children	NEWSUP, a new food supplement, is high in plant polyphenols, omega-3 fatty acids, micronutrients, and protein content.	The impact of early-life dietary interventions on cognitive development and academic achievement in preschool-aged children will be investigated utilizing RCTs, cohort studies, case-control studies, and cross-sectional studies published in English.	Undernutrition during childhood has a major effect on academic performance and long-term cognitive function. Remarkably, a 23-week dietary supplementation program improved the nutritional status, brain health, and executive function of vulnerable young children in low-income countries
Schneider et al., 2023 [30]	USA	Observational longitudinal cohort study	293	Dietary nutrient intake data analysis for 88 nutrient	Studies involving preschool-aged children (3-6 years). The impact of early-life dietary interventions on cognitive development and academic achievement in preschool-aged children will be investigated utilizing RCTs, cohort studies, case-control studies, and cross-sectional studies published in English.	The study investigates how a kid's diet affects their cognitive development in a typically developing youngster and shows how dietary treatments can be specifically designed to help this crucial stage
Thilakaratne et al., 2024 [31]	USA	Prospective cohorts study	349	Essential metals include zinc (Zn).	The impact of early-life dietary interventions on cognitive development and academic achievement in preschool-aged children will be investigated utilizing RCTs, cohort studies, case-control studies, and cross-sectional studies published in English.	Lower cognitive test scores are associated with early lead exposure, whereas magnesium has a good effect on cognition and may have positive benefits on cognitive capacities

Maszz-talerz-Kozubek et al., 2024 [32]	Poland	Cross-sectional study	467	Breastfeeding, complementary foods	Published in English, RCTs, cohort studies, case-control studies, and cross-sectional studies.	Early adoption of good eating practices can be achieved by consistent family meals, continued breastfeeding, creating a welcoming environment at mealtimes, and reducing screen usage
Thanhaeuser et al., 2023 [33]	Austria	Secondary outcome analysis of a randomized controlled trial conducted retrospectively.	230	Soybean oil-based lipid emulsion vs. mixed lipid emulsion (fish oil).	The impact of early-life dietary interventions on cognitive development and academic achievement in preschool-aged children will be investigated utilizing Published in English, RCTs, cohort studies, case-control studies, and cross-sectional studies.	The trial was not designed to detect a difference in preschool-age cognitive outcomes because this was a secondary analysis.
Weigel et al., 2023 [34]	Ecuador	Cross-sectional study	7005	Household food insecurity (HFI)	The impact of early-life dietary interventions on cognitive development and academic achievement in preschool-aged children will be investigated utilizing RCTs, cohort studies, case-control studies, and cross-sectional studies published in English.	HFI is linked to a higher risk of developmental delays
Ansuya et al., 2023 [35]	India	Cluster-randomized controlled trial	253	Home-based nutrition-focused intervention	The impact of early-life dietary interventions on cognitive development and academic achievement in preschool-aged children will be investigated utilizing RCTs, cohort studies, case-control studies, and cross-sectional studies published in English.	Improvement in the intervention group's cognitive development positively

Senbanjo et al., 2022 [36]	Nigeria	randomized controlled trial	630	Three parallel treatment groups receiving different daily amounts (200 mL, 400 mL, or 600 mL) of a fortified multi-nutrient dairy-based supplement	The impact of early-life dietary interventions on cognitive development and academic achievement in preschool-aged children will be investigated utilizing RCTs, cohort studies, case-control studies, and cross-sectional studies published in English.	Although there was no difference in the groups' cognitive scores, a longer study period may be required.
Chen et al., 2021 [37]	China	Cross-sectional observational study with a quasi-experimental component.	1334	Just questionnaire there is no intervention	The impact of early-life dietary interventions on cognitive development and academic achievement in preschool-aged children will be investigated utilizing RCTs, cohort studies, case-control studies, and cross-sectional studies published in English.	Anemia affects weight control, stunting impacts visual and motor development, and wasting has no observable effect on any developmental outcome. Nutritional conditions, such as anemia, stunting, and wasting, are linked to children's cognitive development."
Sharma et al., 2023 [38]	Nepal	Cross-sectional study	401	General nutritional supplements	The impact of early-life dietary interventions on cognitive development and academic achievement in preschool-aged children will be investigated utilizing RCTs, cohort studies, case-control studies, and cross-sectional studies published in English.	Preschoolers' cognitive development is heavily influenced by their nutritional status, since undernourished children exhibit slower rates of cognitive development.
Colombo et al., 2023 [39]	China	Randomized Controlled Trial	292	Bovine milk fat globule membrane and bovine lactoferrin in infant formula	The impact of early-life dietary interventions on cognitive development and academic achievement in preschool-aged children will be investigated utilizing Published in English, the studies include RCTs, cohort studies, case-control studies, and cross-sectional studies.	The study found that infant formula containing lactoferrin and bovine milk fat globule membrane during the first year of life enhances neurodevelopmental outcomes at age 5.5, including improved executive function and IQ.

Upadhyay et al., 2024 [40]	India	Randomized Controlled Trial	13500	Comprehensive strategy including general health, nutrition supplements, water, sanitation, and hygiene measures.	The impact of early-life dietary interventions on cognitive development and academic achievement in preschool-aged children will be investigated utilizing RCTsPublished in English, cohort studies, case-control studies, cross-sectional studies, and RCTs.	Compared to controls, prenatal and early childhood interventions improved children's cognitive, linguistic, motor, and socioemotional scores.

HAZ-Height for age Z-scores, MD-Means difference, CI-Confidence interval, VCI- verbal comprehension index, WMI-Working Memory Index, NEWSUP-New food supplements, HFI-Household food insecurity.

Quantitative Synthesis:

The results in the figure 2 indicate a statistically significant association (P<0.00001) between breastfeeding and cognitive development among the treated group, with odds ratio of 2.35 at 95% confidence interval (1.91-2.90). The test of heterogeneity of this factor was very low (Tau2=0.00, I2=0%).

In regards to formula feeding, the results shows that the association between formula feeding and cognitive development was not statistically significant (P=0.10) with odds ratio of 2.57 at 95% CI (0.84-7.90). There was also a low heterogeneity of the studies analyzed (I2=0%).

Dietary supplements also shown to have a statistically significant association with cognitive development (P<0.00001) with odds ratio of 2.85 at 95% CI (2.20-3.68). There was also a high heterogeneity of the included studies (I2=86%).

Moreover, there was a moderate statistically significant association of the fortified foods and cognitive development (P=0.5) with odds ratio of 2.07 at 95% CI (0.99-4.30). The heterogeneity of the studies analyzed was also very high (I2=86%).

Furthermore, a statistically significant correlation was observed between early nutrition and readiness and reading (P=0.008). However, the association

between early nutrition and cognitive literacy and cognitive numeracy was not statistically significant (P>0.05) though the overall effect was in favor of the treated group.

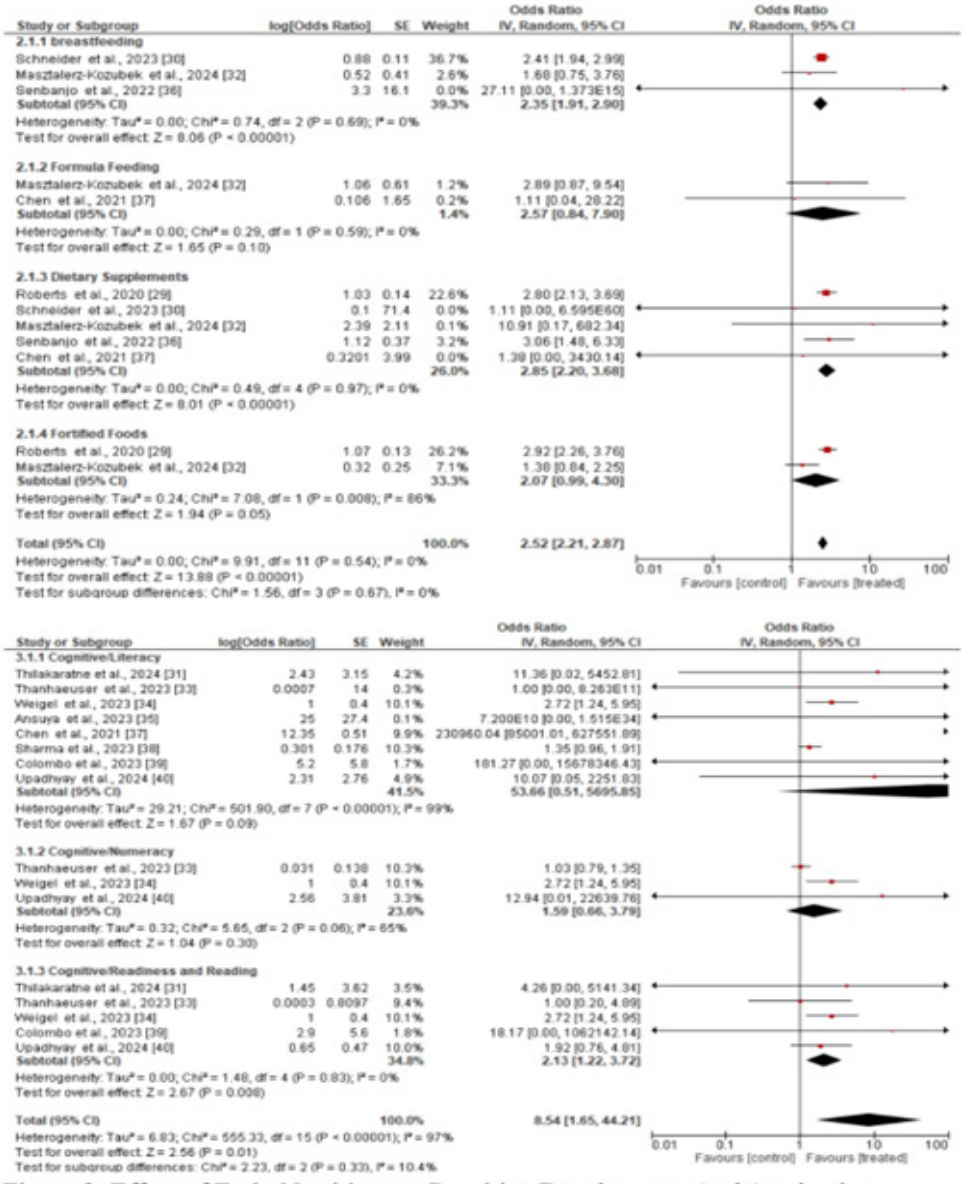


Figure 2:Effect of Early Nutrition on Cognitive Development and Academic Performance.

Risk of Bias based on Quality Assessment of Cross-Sectional studies- Newcastle Ottawa Quality Assessment Scale (NOS)

The Newcastle Ottawa Quality Assessment Scale (NOS) was used to evaluate the quality of cohort, cross-sectional, retrospective and prospective studies, as indicated in Table 2. Of the seven studies that were assessed, five were found to be of good quality [31, 32, 33, 34, and 37]. However, two of the seven studies [30, 38] were of moderate quality.

Table 2: Risk of Bias based on Quality Assessment of Cohort, Case Control and Retrospective/Prospective studies-NOS.

Authors	Selection				Comparability	Outcome	
	The exposed cohort's representativeness	The non-exposed cohort's selection	Determining the exposure	Non-participants	Comparability of cohorts based on the analysis or design	Evaluation of the result	Test of statistics
Schneider et al., 2023 [30]	*	*	*	؟.	**	The food security measurement was limited to the previous 12-month period, potentially not reflecting households' food situations over a longer period.	*
Thilakaratne et al., 2024 [31]	*	*	*	؟.	**	*	*
Masztalerz-Kozubek et al., 2024 [32]	*	*	*	؟.	**	*	*
Thanhaeuser et al., 2023 [33]	*	*	*	؟.	*	*	*
Weigel et al., 2023 [34]	*	*	*	؟.	**	*	*
Chen et al., 2021 [37]	*	*	*	؟.	**	*	*
Sharma et al., 2023 [38]	*	*	*	؟.	*	*	The study employed a stepwise regression analysis to identify predictors, with a statistical significance level of less than 0.05.

Selection:
Q1. Is the exposure cohort representative? *
Q2. How was the non-exposure cohort chosen? *
Q3. Determination of the exposure? *
Q4. Proof that the desired outcome did not exist at the outset of the research? **
Comparability
Q5. Is the cohort comparable based on the analysis or design? **
Outcome:
Q6: Evaluation of the result? *
Q7: Test Statistics? *
*indicate satisfactory for selection and outcome **indicate satisfactory for Comparability

Risk of Bias based on Quality Assessment of Randomized Control Trial-Cochrane Risk of Bias Tool:

Based on the findings presented in Figure 3, most of the items (5/7) in the included randomized control trials showed minimal risk of bias. Nonetheless, random sequencing and allocation concealment generated a substantial risk of bias for two out of seven items.

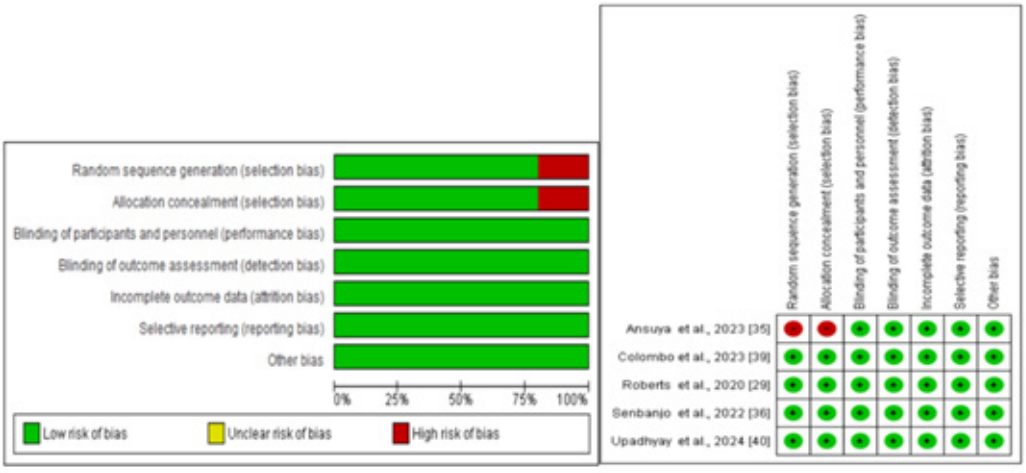


Figure 3: Summary of risk of bias for the included RCTs.

Figure 4 depicts an asymmetrical funnel, with most of the studies centered in the center. However, more studies were on the left side of the funnel than on the right side. This demonstrates that there is a probability of risk of publication bias in favor of the treated group.

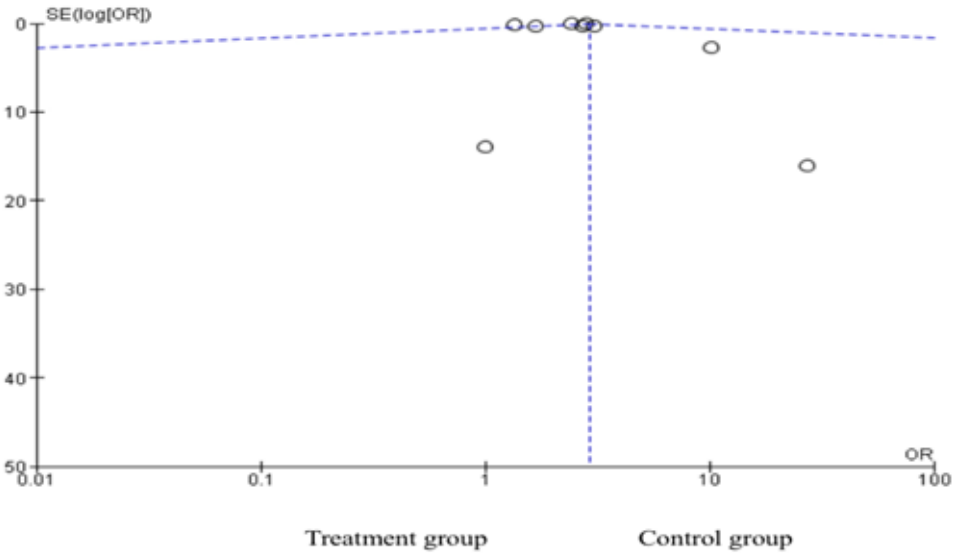


Figure 4: Assessment of the publication bias.

SE-standard Error, OR-Odds Ratio

Figure 4: Assessment of the publication bias.

Discussion:

This systematic review highlights the crucial role of early-life nutrition in shaping cognitive development and school readiness among preschool-aged children. Across the included studies, breastfeeding consistently emerged as a strong predictor of improved cognitive performance. These findings align with previous research suggesting that breast milk provides essential nutrients and bioactive components that support brain maturation, neural connectivity, and executive function development.[1] Breastfeeding also strengthens immunity and reduces infection-related interruptions to growth and learning, further supporting cognitive outcomes.[29]

In contrast, formula feeding demonstrated mixed results. While some studies reported cognitive improvements among infants receiving enriched formulas, the overall evidence did not support a strong independent association between standard formula feeding and later cognitive ability. This variability may reflect differences in formula composition, timing of introduction, and maternal/infant health factors.[30,31] Nevertheless, advancements in formula fortification — particularly with compounds such as lactoferrin and milk fat globule membrane — show emerging potential, as demonstrated by Colombo et al.[39]

Micronutrient-based interventions and dietary supplements showed notable benefits for cognitive development. Studies reported improvements in memory, attention, and overall neurodevelopment following targeted nutritional programs, especially in malnourished or food-insecure populations.[34,35] These effects are likely mediated by nutrients such as iron, zinc, and essential fatty acids, which are well-established as critical for neuronal growth, synapse formation, and neurotransmitter activity.[7,9,11–15] Children exposed to nutrition-focused interventions also demonstrated better socio-emotional outcomes, suggesting that diet influences multiple dimensions of development, beyond cognition alone.[40]

Fortified foods also supported cognitive gains, though effects varied depending on study duration and nutrient composition. Some studies emphasized the importance of sustained supplementation to observe meaningful changes, as short-term interventions may not sufficiently address chronic nutritional deficiencies.[36] Consistent with this, Chen et al. found that children suffering from anemia or stunting exhibited impaired cognitive function, underscoring the detrimental effects of persistent undernutrition.[37]

Early nutrition also contributed to improved school readiness and reading development, reinforcing evidence that foundational cognitive skills develop alongside adequate dietary intake.[38] However, associations with early literacy and numeracy were less consistent. These

skills may be influenced more strongly by home learning environments, stimulation, and early education access — factors that interact with, but are not solely determined by, nutrition.[26,27]

Collectively, these findings reaffirm that early nutrition is essential for optimal neurodevelopment. Nutritional deprivation in early childhood — especially in critical growth windows such as the first 1,000 days — can disrupt brain development and have lasting academic and cognitive consequences.[3,5,21] While nutrition alone cannot address all developmental disparities, it forms a critical foundation upon which early learning and socio-emotional growth depend.

Limitations of the included studies must be acknowledged. Variability in assessment tools, intervention types, and follow-up durations may have introduced heterogeneity. Some studies relied on self-reported dietary intake, and the review included only English-language publications. Additionally, environmental and socio-economic factors may moderate nutritional effects, warranting further investigation.

Conclusion:

In the treated group specifically, a statistically significant relationship was observed between breastfeeding and cognitive development. Fortified diets and dietary supplements also demonstrated a strong correlation with cognitive growth. Furthermore, a statistically significant correlation between reading readiness and early nutrition was found. The link between early nutrition. and cognitive literacy and cognitive numeracy was not statistically significant, even though the treated group demonstrated overall improvements in reading and numeracy ability. Accordingly, this study highlights the need of ensuring that children receive adequate nutrients during their early infancy and the necessity for a healthy diet to raise awareness in order to support cognitive development in preschool-aged children.

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