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Micronutrient-Rich Dietary and Digital Nutrition Intervention in Children with Attention-Deficit Hyperactivity Symptoms: A Controlled School-Based Study

Keywords
ADHD; micronutrients; digital health; paediatric nutrition; school-based intervention; caregiver education; behaviour function

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Abstract

Objectives: To evaluate whether a five-month school-based intervention combining micronutrient-rich snacks with digital caregiver nutrition support improves nutrient intake, anthropometry, behaviour function and caregiver nutrition knowledge, attitudes and practices in children with attention-deficit/hyperactivity disorder (ADHD) symptoms in Chennai, India.

Methods: A controlled intervention included 120 children aged 4–9 years from 23 special schools. Participants were allocated to experimental and control groups within two age strata (4–6 and 7–9 years; n=30 per group). Experimental groups received one 50 g micronutrient-rich snack daily, access to an AI-integrated nutrition website and YouTube education, and monthly telephonic counselling for five months. Controls received standard telephonic counselling and generic nutrition education. Nutrient intake, anthropometry, DSM-5-based behaviour scores and caregiver knowledge, attitude and practice (KAP) scores were assessed before and after intervention.

Results: Energy intake increased from 1152 to 1328 kcal in the 4–6-year experimental group and from 1482 to 1728 kcal in the 7–9-year experimental group. Significant improvements were also observed in protein, iron, zinc, calcium, magnesium and assessed vitamins ($p<0.01$). Behaviour scores improved in both experimental groups (8.76 to 8.13, $p=0.05$; 7.00 to 6.66, $p=0.032$), whereas control-group scores did not improve. Caregiver KAP scores increased significantly, and 93.3% of caregivers rated the website Excellent.

Conclusions: A culturally adapted, multi-component dietary and digital education intervention improved nutrient intake, behaviour function and caregiver nutrition practices over five months in children with ADHD symptoms attending special schools.

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Introduction

Attention-deficit/hyperactivity disorder (ADHD) is one of the most prevalent neurodevelopmental disorders of childhood, characterised by developmentally inappropriate and pervasive levels of inattention, hyperactivity, and impulsivity that impair social, academic, and occupational functioning [1]. Meta-analytic evidence consistently estimates a global pooled prevalence of 5-7% among school-age children, with a marked male predominance and substantial variation across diagnostic criteria and sociocultural contexts [1,2]. ADHD imposes a significant disease burden not only on affected children who face heightened risks of academic underachievement, substance misuse, and poor socioeconomic outcomes in adulthood but also on families, health systems, and educational institutions worldwide.

The neurobiological underpinnings of ADHD involve disruptions in dopaminergic and noradrenergic neurotransmitter circuitry, particularly within the prefrontal cortex and striatal regions. Nutritional factors are increasingly recognised as significant modulators of these pathways [3]. Numerous studies have documented suboptimal intakes and serum levels of key micronutrients including iron, zinc, magnesium, omega-3 polyunsaturated fatty acids, and vitamins B6 and B12 in children with ADHD symptoms, with these deficiencies correlating with symptom severity and cognitive impairment [3,4]. Omega-3 fatty acids, particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), are structural components of neuronal membranes and precursors of anti-inflammatory eicosanoids, and their supplementation has demonstrated modest but consistent improvements in inattention and hyperactivity in randomised controlled trials [5].

Whole-diet approaches and dietary patterns, rather than single-nutrient supplementation, are gaining traction as sustainable strategies to address the nutritional complexity of ADHD. Prospective dietary studies have identified Western-pattern diets characterised by high intakes of refined carbohydrates, artificial additives, and ultra-processed foods, and low intakes of fruits, vegetables, and omega-3-rich sources, as associated with increased ADHD risk and severity [6]. The gut-microbiota-brain axis has further emerged as a mechanistic link between dietary quality and neurobehavioural function in children with ADHD, with micronutrient status influencing microbial composition and metabolite production that in turn affect neuroinflammation and cognition [7-9].

Alongside dietary intervention, digital health technologies offer scalable, cost-effective platforms to deliver nutrition education and behaviour change support to caregivers of children with special needs. Smartphone applications, AI-integrated websites, YouTube channels, and telephonic counselling have demonstrated promise for improving nutrition knowledge, attitudes, and feeding practices in paediatric populations with developmental disabilities [8]. In India, where smartphone penetration exceeds 750 million users, and internet connectivity is increasingly accessible even in semi-urban areas, digital platforms provide an unprecedented opportunity to extend evidence-based nutritional support beyond clinical settings.

The epidemiological picture of ADHD in India presents unique challenges. Estimates of prevalence range from 2% to 17% depending on diagnostic criteria and study population, with an overall estimated rate of approximately 11% in urban school-age children [9]. Cultural stigma, limited awareness among caregivers and educators, and constrained access to specialist paediatric care result in significant under-diagnosis and under-treatment, particularly in lower socioeconomic strata [9]. Furthermore, caregiver knowledge, attitudes, and practices regarding nutrition for children with ADHD are consistently reported to be suboptimal in Indian studies, underscoring the need for targeted educational interventions [10].

Traditional Indian food systems rich in millets, legumes, green leafy vegetables, and seeds offer a potentially underutilised nutritional resource for addressing micronutrient gaps in children with ADHD. Composite formulations using these ingredients can provide concentrated sources of iron, zinc, magnesium, and essential fatty acids in culturally acceptable forms [11]. Despite this promise, rigorous evaluation of structured multi-component dietary interventions combining locally-sourced micronutrient-rich snack formulations with digital caregiver education remains limited in the Indian special education context [12].

The present study was therefore designed to: (i) assess the baseline nutritional status, dietary patterns, and behaviour function in children with ADHD symptoms attending special schools in Chennai; (ii) formulate and characterise ten micronutrient-rich snack products suitable for children with ADHD; (iii) develop an AI-integrated digital nutrition education platform (www.nutritionadhd.com) for caregivers; and (iv) evaluate the five-month impact of this integrated dietary modification and digital health intervention on nutrient intake, anthropometry, behaviour function, and caregiver knowledge, attitude, and practice (KAP) scores [12].

Methods

Study Design and Ethical Approval

A five-month controlled school-based intervention study was conducted in phases across 23 special schools in Chennai, Tamil Nadu, India, between 2021 and 2023. Ethical clearance was obtained from the Institutional Human Ethics Committee, Avinashilingam Institute for Home Science and Higher Education for Women, Coimbatore (Reference: AUW/IHEC/FSN-2021/XPD-27). Written informed consent was obtained from all participating caregivers. Diagnosis of ADHD was confirmed by certified clinical psychologists in each school using the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5) [13], which served as the primary behavioural assessment tool throughout the study.

Participants and Allocation

Phase I involved a cross-sectional baseline assessment of 137 children (91 boys, 46 girls; aged 4-12 years) with clinically diagnosed ADHD symptoms from 23 special schools in Chennai. All children were individually assessed for nutritional status and behaviour function, and their primary caregivers were interviewed to collect sociodemographic, dietary, and clinical data. For the intervention phase, 120 children and their caregivers who fulfilled inclusion criteria and provided consent were allocated into four groups of 30: Experimental Group I (EG I, 4–6 years), Control Group I (CG I, 4-6 years), Experimental Group II (EG II, 7–9 years), and Control Group II (CG II, 7–9 years). Study flow is depicted in Figure 1.

Dietary Assessment and Nutritional Status

Dietary intake was assessed using a validated 24-hour dietary recall administered on three non-consecutive days per participant at baseline and at five months (14). Nutrient content was calculated using the Indian Food Composition Tables (IFCT 2017) and the Dietary Reference Values for Indians (ICMR 2024) [15]. Anthropometric measurements (weight, height, BMI) were recorded at baseline and post-intervention and interpreted against WHO Child Growth Standards and ICMR growth charts [16,22]. Clinical examination of hair, skin, nails, eyes, and oral mucosa was performed following WHO clinical assessment guidelines by school medical officers at each institution.

Formulation and Characterisation of Micronutrient-Rich Snacks

Ten micronutrient-rich snack products were developed in Phase II using foods rich in brain-critical nutrients protein, iron, zinc, omega-3 fatty acids, magnesium, calcium, vitamins B6 and B12: (1) Quinoa Yam Cutlet; (2) Rajkira Crackers; (3) Nut Coated Little Millet Cookie; (4) Amaransu Smoothie; (5) Scopy Urdu Muffins; (6) Checkbox Nuggets; (7) Trevally Nuggets; (8) Energy Seed Coat; (9) Round Nut Bag; and (10) Curry Stalk Pakodi. Organoleptic evaluation was performed by a trained panel of 30 using a five-point hedonic rating scale [19]. Proximate composition, mineral content, and vitamin content were determined using AOAC (2024) standard methods [17]. Fatty acid profiles were characterised by gas chromatography-mass spectrometry (GC-MS) after n-hexane extraction [18], and microbiological quality was assessed following ICMSF protocols [21].

Digital Health Intervention

Phase III involved the development and deployment of a comprehensive digital health intervention for caregivers of children in experimental groups. The AI-integrated dynamic website (www.nutritionadhd.com) was developed to provide personalised, evidence-based nutritional information specific to children with ADHD in the Indian dietary context [20]. Website content included Indian diet-specific meal plans, micronutrient reference charts, food preparation demonstrations, and interactive features (chatbot, nutritional quiz, BMI calculator). Complementary YouTube videos covering snack recipes, expert dietary guidance, and behavioural management strategies were developed and shared with caregivers. One-to-one structured telephonic counselling sessions were conducted monthly over five months by trained nutritionists, providing personalised dietary modification advice and reinforcing healthy feeding practices.

Intervention Delivery

Experimental groups (EG I and EG II) received: (a) daily provision of one serving (50 g) of the formulated micronutrient-rich snacks replacing an equivalent-volume habitual snack; (b) unrestricted access to www.nutritionadhd.com; (c) a curated YouTube video series (12 videos, one per fortnight); and (d) monthly telephonic counselling (minimum 30 minutes per session) for a period of five months. Control groups (CG I and CG II) received standard telephonic counselling and generic nutrition education materials via telephonic communication, without snack supplementation or access to the AI website.

Outcome Measures

Primary outcomes were changes in mean daily nutrient intake (energy, macronutrients, iron, zinc, calcium, magnesium, vitamins B6, B12, C, A, and D) and DSM-5-based behaviour function scores from baseline to post-intervention (13,37). Secondary outcomes included changes in anthropometric measurements and caregiver KAP scores. KAP assessments used a validated 10-point scale questionnaire administered at baseline and post-intervention.

Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics Version 26.0. Data are presented as mean ± standard deviation (SD). Within-group pre- and post-intervention comparisons were performed using paired-samples t-tests. Between-group differences were assessed using independent-samples t-tests and a one-way ANOVA with a post hoc Tukey correction. Chi-square tests were used for categorical variables, and Pearson's correlation analysis was used to examine associations between nutrient intake and behaviour scores. A p value <0.05 was considered statistically significant; $p<0.01$ is denoted ** throughout.

Results

Baseline Sociodemographic and Clinical Characteristics

Of the 137 children initially enrolled in Phase I, 120 fulfilled the inclusion criteria and consented to participate in the intervention study (Figure 1). The gender ratio was 91:46 (boys: girls), consistent with the established male predominance in ADHD prevalence [25]. A noteworthy proportion of children (20.6–33.7%) were born of consanguineous marriages, a recognised risk factor for neurodevelopmental disorders in South Asian populations [23]. Family history of hyperactivity was reported by 29–33% of boys' families, underscoring the genetic loading [24]. The socioeconomic profile was predominantly middle to upper-middle class per the Modified Kuppuswamy Scale, with fathers employed across diverse occupational categories. Maternal complications during pregnancy—including anaemia (37.5%), hypertension (33.3%), and diabetes (50%)—were prevalent, consistent with evidence linking prenatal maternal adversity to offspring ADHD risk [24].

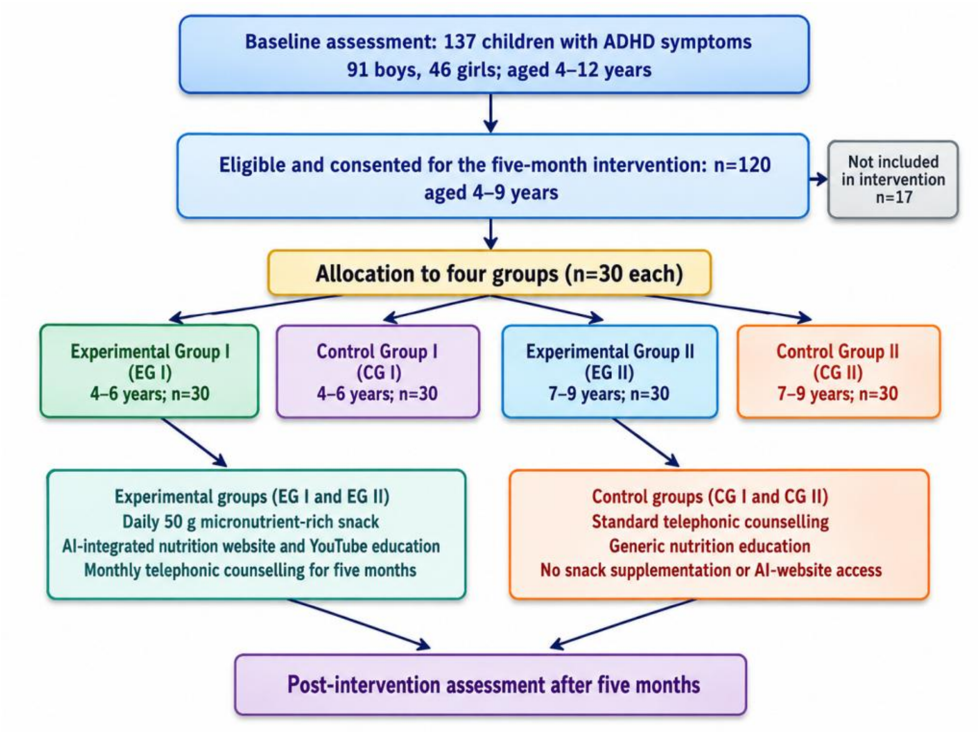

Figure 1. Study flow from baseline assessment to allocation. ADHD = attention-deficit/hyperactivity disorder; EG = Experimental Group; CG = Control Group.

Snack Formulation and Nutritional Characterisation

Ten micronutrient-rich snack formulations were developed, standardised, and subjected to sensory, proximate, mineral, vitamin, fatty acid, and microbiological analyses. Organoleptic evaluation demonstrated high acceptability (mean sensory scores 4.1–4.8/5 across all snacks). GC-MS fatty acid profiling confirmed significant proportions of alpha-linolenic acid (ALA, C18:3n-3) in quinoa cutlet (12.3%), rajkira crackers (13.48%), and nut-coated millet cookie (11.56%), reflecting the omega-3-rich ingredient matrix of chia seeds, flaxseed, amaranth, and nuts (29,30,31). Trevally nuggets provided the highest omega-3 content (820 mg per 50 g serving) attributable to the marine fish component, while checkbox nuggets and round nut bags provided the highest protein per serving (9.3 g and 9.0 g respectively) [32]. Microbiological counts were within acceptable limits confirming safety for paediatric consumption [21]. Nutrient composition of the ten formulated snacks is detailed in Table 1.

Table 1. Nutrient composition of the ten formulated micronutrient-rich snacks per 50 g serving.

Snack (per 50g serving)	Energy (kcal)	Protein (g)	Iron (mg)	Zinc (mg)	Omega-3 (mg)
Quinoa Yam Cutlet	148	7.2	3.8	1.4	215
Rajkira Crackers	162	5.9	2.1	1.2	380
Nut Coated Millet Cookie	172	6.4	2.7	1.6	290
Amaransu Smoothie	134	8.1	3.3	1.8	450
Scopy Urdu Muffins	155	5.6	2.4	1.1	180
Checkbox Nuggets	168	9.3	4.2	2.0	310
Trevally Nuggets	183	10.8	4.7	2.3	820
Energy Seed Coat	189	7.6	3.1	1.5	540
Round Nut Bag	194	9.0	3.6	2.2	470
Curry Stalk Pakodi	141	6.2	2.9	1.3	196

Values are presented per 50 g serving. Omega-3 content was characterised using gas chromatography-mass spectrometry; proximate and mineral analyses used AOAC methods.

Anthropometric Changes

Statistically significant improvements in all three anthropometric parameters were observed in both experimental groups following the five-month intervention. In EG I (4–6 years), mean weight increased from 13.7±1.28 to 17.8±1.34 kg (p=0.023), height improved from 103.2±3.43 to 116.8±1.75 cm (p<0.001), and BMI moved toward age-appropriate reference ranges (11.6 to 15.3 kg/m², p<0.001). In EG II (7–9 years), weight increased from 19.9±1.45 to 24.2±1.16 kg (p<0.001), height from 113.8±9.66 to 122.1±2.18 cm (p<0.001), and BMI from 13.5±0.30 to 15.1±0.17 kg/m² (p<0.001). In contrast, control group changes were not statistically significant for any parameter, indicating that the anthropometric improvements were attributable to the intervention [35]. Anthropometric data are presented in Table 2.

Table 2. Anthropometric measurements before and after the five-month intervention.

Measure	Group	Pre-intervention	Post-intervention	t value	p value
Weight (kg)	EG I	13.7±1.28	17.8±1.34	2.648	0.023
Weight (kg)	CG I	14.3±0.45	15.7±0.81	—	NS
Height (cm)	EG I	103.2±3.43	116.8±1.75	29.32	<0.001
Height (cm)	CG I	104.8±0.92	106.8±1.36	—	NS
BMI (kg/m²)	EG I	11.6±0.28	15.3±0.31	-68.29	<0.001
BMI (kg/m²)	CG I	12.4±0.79	13.3±0.93	—	NS
Weight (kg)	EG II	19.9±1.45	24.2±1.16	16.54	<0.001
Weight (kg)	CG II	18.8±1.08	20.5±1.47	—	NS
Height (cm)	EG II	113.8±9.66	122.1±2.18	4.28	<0.001
Height (cm)	CG II	117.1±1.20	119.8±1.03	—	NS
BMI (kg/m²)	EG II	13.5±0.30	15.1±0.17	28.50	<0.001
BMI (kg/m²)	CG II	17.2±0.82	16.3±0.95	—	NS

Data are mean ± standard deviation. BMI = body mass index; EG = Experimental Group; CG = Control Group; NS = not significant. Control-group significance is reported as stated in the source manuscript.

Nutrient Intake Changes

The five-month intervention produced clinically meaningful and statistically significant improvements in all nutrient parameters assessed in both experimental groups, while control group changes were uniformly non-significant (Table 3, Figure 2). In EG I (4–6 years), mean energy intake increased from 1152±72.5 to 1328±19.7 kcal (t=−14.94, p<0.01). Iron intake more than tripled (3.11 to 10.8 mg, t=−36.75, p<0.01), zinc increased six-fold (0.83 to 5.15 mg, t=−33.66, p<0.01), and vitamin B12 rose from near-deficient levels (0.08 µg) to within estimated average requirement (1.36 µg, t=−12.82, p<0.01) (36). In EG II (7–9 years), similar patterns of improvement were observed, with energy rising from 1482±50.8 to 1728±38.5 kcal (t=−22.89, p<0.01), iron from 5.48 to 14.1 mg (t=−23.08, p<0.01), and zinc from 1.93 to 6.52 mg (t=−54.18, p<0.01). Vitamin A intakes rose by nearly 100% in both experimental groups. These improvements can be attributed to the daily provision of snacks providing concentrated sources of these micronutrients, reinforced by caregiver dietary counselling through the digital platform [36,39].

Table 3. Mean nutrient intake in the 4–6-year cohort before and after intervention.

Nutrient (EAR)	EG I Pre	EG I Post	CG I Pre	CG I Post	t-value EG I
Energy (1360 kcal)	1152±72.5	1328±19.7*	1294±16.2	1308±13.3	−14.94 (p<0.01)
Protein (12.8 g)	10.1±1.53	14.3±0.77*	10.4±1.37	12.7±1.56	−17.21 (p<0.01)
Fats (25 g)	17.3±0.77	24.5±1.68*	19.0±0.97	21.0±1.12	−19.83 (p<0.01)
Iron (8 mg)	3.11±1.07	10.8±0.59*	4.80±0.90	6.51±1.20	−36.75 (p<0.01)
Zinc (3.7 mg)	0.83±0.35	5.15±0.49*	1.46±0.62	2.29±0.82	−33.66 (p<0.01)
Calcium (450 mg)	307.0±73.6	435.1±20.3*	326.1±12.4	361.4±16.4	−11.08 (p<0.01)
Magnesium (131 mg)	94.1±11.0	154.2±5.22*	93.0±7.24	106.7±9.58	−24.29 (p<0.01)
Vitamin B6 (1.0 mg)	0.19±0.17	1.00±0.28*	0.23±0.18	0.88±0.33	−11.31 (p<0.01)
Vitamin B12 (1 µg)	0.08±0.10	1.36±0.60*	0.90±0.45	1.71±0.47	−12.82 (p<0.01)
Vitamin C (27 mg)	16.4±1.33	30.0±1.19*	17.7±1.45	22.1±1.83	−39.14 (p<0.01)
Vitamin A (240 µg)	130.1±11.2	258.7±7.55*	134.8±12.1	145.2±11.5	−42.48 (p<0.01)
Vitamin D (400 IU)	194.9±23.6	321.9±21.8*	184.0±12.8	206.6±14.9	−17.56 (p<0.01)

Values are mean ± standard deviation. EAR = Estimated Average Requirement; EG I = Experimental Group I; CG I = Control Group I. * p<0.01 for the paired comparison in EG I.

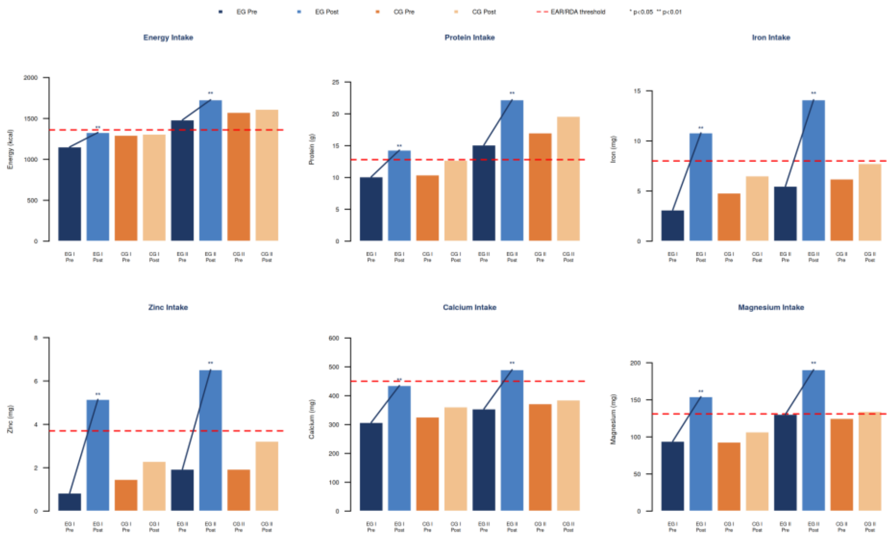

Figure 2. Mean nutrient intake before and after the five-month intervention in experimental and control groups across the 4–6-year and 7–9-year cohorts. Dashed lines indicate age-specific Estimated Average Requirements/reference thresholds. EG = Experimental Group; CG = Control Group; EAR = Estimated Average Requirement; RDA = Recommended Dietary Allowance. ** p<0.01.

Behaviour Function Scores

Both experimental groups demonstrated statistically significant improvements in DSM-5-based behaviour function scores following the intervention (Table 4, Figure 3). In EG I (4–6 years), the mean behaviour score decreased from 8.76±0.31 to 8.13±0.45 (t=2.97, p=0.05). In EG II (7–9 years), the mean score decreased from 7.00±0.75 to 6.66±0.69 (t=2.98, p=0.032). Because higher scores indicate greater symptom severity, lower post-intervention scores represent improvement in behaviour function [37]. Control-group scores increased numerically from 5.90±0.86 to 7.43±0.91 (CG I) and from 6.83±0.75 to 7.73±0.89 (CG II), but these changes were not statistically significant.

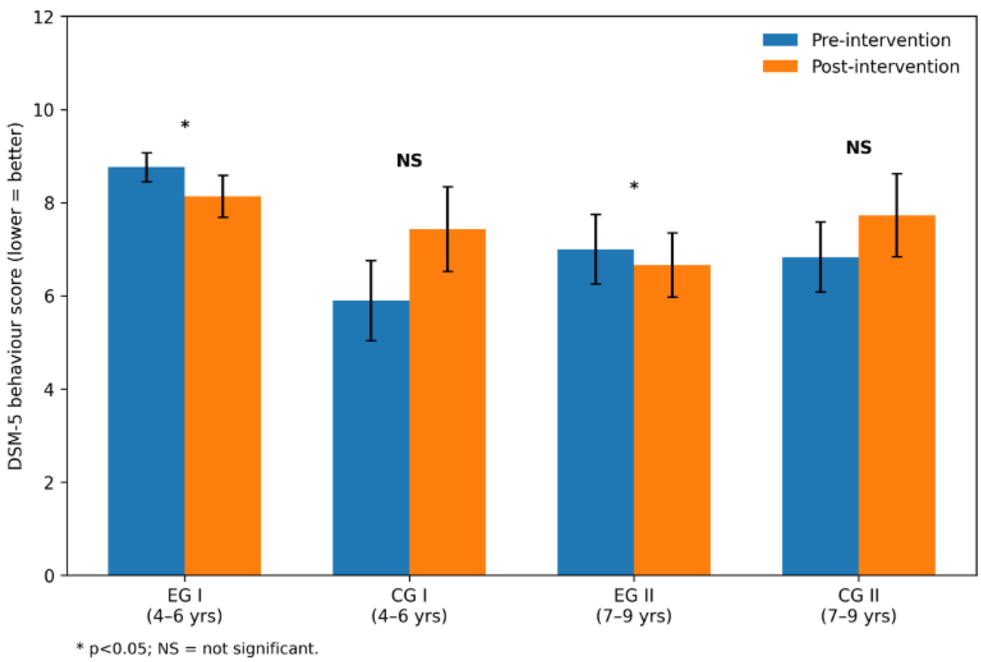

Figure 3. DSM-5-based behaviour function scores before and after the five-month intervention. Lower scores indicate better behaviour function. EG = Experimental Group; CG = Control Group; * p<0.05; NS = not significant; error bars represent ±1 standard deviation.

Caregiver Knowledge, Attitude and Practice Scores and Website Feedback

Caregiver knowledge, attitude and practice (KAP) scores improved significantly in both experimental groups following five months of digital health education (Table 4, Figure 4). Nutritional knowledge increased from 3.33±0.51 to 6.46±1.68 in EG I (t=2.95, p<0.05) and from 3.46±0.97 to 8.06±1.81 in EG II (t=7.94, p<0.001). Nutritional attitude increased from 3.13±1.07 to 6.33±1.62 in EG I (t=2.92, p<0.05) and from 2.93±1.28 to 8.43±1.19 in EG II (t=11.93, p<0.001). Nutritional practice increased from 1.73±1.38 to 7.23±1.10 in EG I (t=19.34, p<0.001) and from 2.73±0.71 to 8.93±1.20 in EG II (t=14.27, p<0.001). Control-group KAP changes were non-significant [38]. Website satisfaction was high, with 93.3% of participating caregivers rating the content as Excellent.

Table 4. Behaviour function and caregiver knowledge, attitude and practice scores before and after intervention.

Outcome	Group	Pre-intervention	Post-intervention	t value	Significance
Behaviour function (DSM-5 score), 4–6 years	EG I	8.76±0.31	8.13±0.45	2.97	p=0.05
Behaviour function (DSM-5 score), 4–6 years	CG I	5.90±0.86	7.43±0.91	—	NS
Behaviour function (DSM-5 score), 7–9 years	EG II	7.00±0.75	6.66±0.69	2.98	p=0.032
Behaviour function (DSM-5 score), 7–9 years	CG II	6.83±0.75	7.73±0.89	—	NS
Knowledge score (max 10)	EG I	3.33±0.51	6.46±1.68	2.95	p<0.05
Knowledge score (max 10)	CG I	2.86±0.94	4.93±1.82	—	NS
Knowledge score (max 10)	EG II	3.46±0.97	8.06±1.81	7.94	p<0.001
Knowledge score (max 10)	CG II	2.23±0.82	3.96±1.06	—	NS
Attitude score (max 10)	EG I	3.13±1.07	6.33±1.62	2.92	p<0.05
Attitude score (max 10)	CG I	3.56±0.72	5.03±1.27	—	NS
Attitude score (max 10)	EG II	2.93±1.28	8.43±1.19	11.93	p<0.001
Attitude score (max 10)	CG II	3.23±0.72	4.13±1.56	—	NS
Practice score (max 10)	EG I	1.73±1.38	7.23±1.10	19.34	p<0.001
Practice score (max 10)	CG I	2.66±0.94	3.80±1.88	—	NS
Practice score (max 10)	EG II	2.73±0.71	8.93±1.20	14.27	p<0.001
Practice score (max 10)	CG II	3.16±0.94	5.56±1.62	—	NS
Website satisfaction: Excellent (%)	Experimental caregivers	—	93.3	—	Descriptive

Lower DSM-5 behaviour scores indicate fewer/less severe symptoms. KAP = knowledge, attitude and practice; EG = Experimental Group; CG = Control Group; NS = not significant. Scores are reported as mean ± standard deviation unless otherwise stated

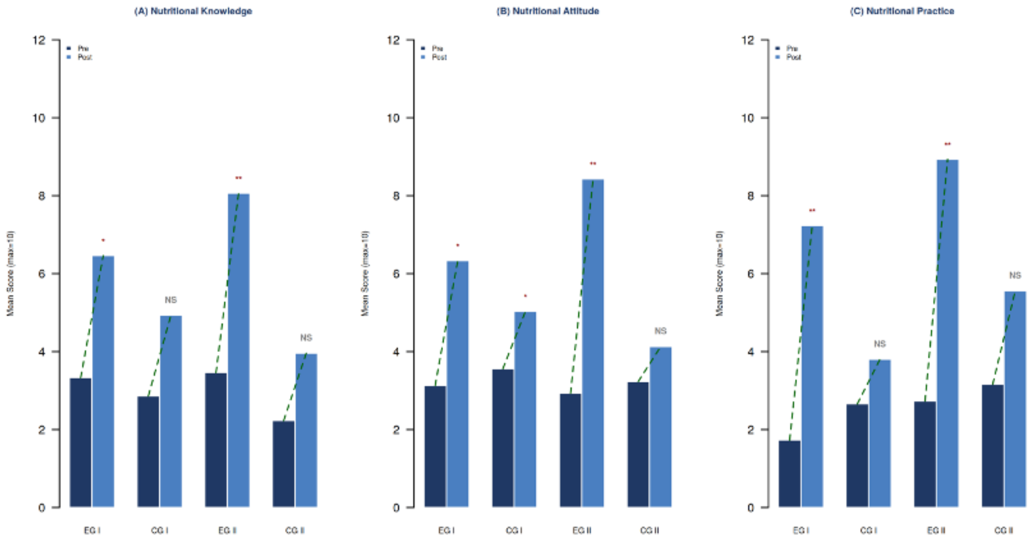

Figure 4. Caregiver knowledge, attitude and practice (KAP) scores before and after the five-month digital health and dietary intervention. EG = Experimental Group; CG = Control Group; KAP = knowledge, attitude and practice; * $p<0.05$; ** $p<0.001$; NS = not significant.

Discussion

A five-month controlled school-based intervention study conducted in the Indian special education setting provided compelling evidence that a multi-component approach combining micronutrient-rich dietary modification with AI-integrated digital caregiver education significantly improved nutrient intake, behavioural functioning, and caregiver nutrition literacy among children with ADHD symptoms. These findings contributed to the growing body of evidence supporting holistic, nutritionally informed approaches to ADHD management that extended beyond pharmacological treatment alone.

The dramatic improvements in iron and zinc intake in experimental groups are particularly noteworthy given the central roles of these micronutrients in dopaminergic neurotransmission and ADHD pathophysiology. Iron serves as a cofactor for tyrosine hydroxylase, the rate-limiting enzyme in dopamine synthesis, and serum ferritin levels are inversely associated with ADHD severity [42]. Zinc modulates dopamine transporter function and is required for the enzymatic synthesis of several neurotransmitters, with randomised trials demonstrating symptom improvements with zinc supplementation [41]. The tripling of iron intake (3.11 to 10.8 mg/day) and six-fold increase in zinc intake (0.83 to 5.15 mg/day) observed in EG I represent clinically meaningful corrections of micronutrient deficiency through food-based rather than pharmaceutical supplementation, thereby avoiding the tolerability concerns associated with high-dose mineral supplements.

The omega-3 fatty acid content of our formulated snacks—confirmed by GC-MS profiling—is consistent with the growing evidence for the neuromodulatory role of EPA and DHA in ADHD. A recent meta-analysis of 16 randomised controlled trials demonstrated that omega-3 supplementation, particularly EPA-predominant formulations, produced statistically significant reductions in inattention and hyperactivity scores [40]. Our GC-MS data confirmed high proportions of alpha-linolenic acid (ALA) in several snack formulations, particularly trevally nuggets, which also provided the highest absolute omega-3 content (820 mg per serving). While ALA conversion to EPA and DHA in children is inefficient, regular consumption of multiple ALA-rich snacks alongside fish-based nuggets is expected to contribute meaningfully to EPA and DHA status over five months.

The magnesium and vitamin B complex improvements observed in experimental groups are consistent with the established roles of these nutrients in ADHD. Magnesium is required for over 300 enzymatic reactions including those involved in adenosine triphosphate synthesis and nervous system function, and magnesium deficiency is documented in 72–80% of children with ADHD in some series [43]. A recent randomised trial demonstrated that combined vitamin D and magnesium supplementation over 8 weeks significantly reduced ADHD total scores and improved emotional and social functioning in affected children [43]. Vitamins B6 and B12 are cofactors in the synthesis of serotonin, dopamine, and norepinephrine, and their deficiency is associated with impaired neurotransmission and worsened inattentive symptoms [44]. The near-doubling of vitamin B12 intake in EG I (0.08 to 1.36 µg/day) from near-depleted baseline levels is clinically significant and may contribute to improved neurotransmitter synthesis.

The improvement in behaviour function scores, assessed using DSM-5 criteria, is consistent with evidence that multi-micronutrient interventions may support behavioural outcomes in children with ADHD [39]. Although control-group scores increased numerically, those changes were not statistically significant; therefore, the present data support an intervention-associated improvement in the experimental groups without establishing deterioration in the controls.

The caregiver KAP findings are among the most striking outcomes of this intervention. The improvement in practice scores—from means of 1.73 and 2.73 (EG I and EG II) at baseline to 7.23 and 8.93 post-intervention—indicates a transformative shift in caregivers' feeding behaviours that appears to have directly translated into improved dietary diversity and micronutrient intake for their children. This magnitude of change in nutrition practice following a structured digital intervention is consistent with findings from web-based nutrition education programmes for caregivers of children with developmental disabilities [46]. The strong website satisfaction ratings (93.3% Excellent) further validate the cultural acceptability and practical utility of the India-specific digital platform developed in this study, supporting its potential for wider deployment within the national special education infrastructure.

Telephonic counselling provided an important complementary channel to the digital platform, enabling individual tailoring of dietary advice to household food budgets, local food availability, and cultural preferences. This multi-channel approach—website, YouTube, and telephonic counselling—mirrors successful digital health models demonstrating that multi-modal delivery maximises reach, engagement, and behaviour change [45,47]. The AI integration of the website enabled dynamic content personalisation based on child age, dietary intake, and symptom profile, representing a scalable prototype for precision nutrition support in neurodevelopmental conditions.

From a broader dietary perspective, our findings align with the growing recognition that whole-diet approaches rather than single-nutrient supplementation offer the most sustainable pathway to nutritional support in ADHD [48]. The incorporation of quinoa, amaranth, millets, legumes, nuts, seeds, and marine fish into culturally familiar snack formats—tested and accepted organoleptically—demonstrates that nutrient-dense traditional Indian ingredients can be mobilised effectively within a structured dietary intervention programme for special schools [53,54]. School-based delivery ensures consistent access to the intervention while leveraging the institutional infrastructure of special schools to reach a high-risk population that may have limited access to community health services.

Several limitations of this study deserve acknowledgement. First, the absence of biochemical investigations (serum micronutrient levels, fatty acid profiles) due to COVID-19 pandemic-related constraints limits mechanistic interpretation of the observed outcomes. Future studies should incorporate biomarkers to corroborate dietary data and elucidate the nutrient-cognition pathways modulated by intervention. Second, the intervention was confined to children aged 4–9 years enrolled in special schools, limiting generalisability to older children, those in mainstream educational settings, and children in rural or resource-constrained environments. Third, the study lacked a randomised allocation mechanism due to the pragmatic school-based design, representing a potential source of selection bias. Future research should employ cluster-randomised controlled trial designs with biomarker endpoints and extended follow-up periods to assess the durability of improvements [55].

Conclusions

This study demonstrates that a five-month integrated intervention combining ten formulated micronutrient-rich snacks—providing iron, zinc, omega-3 fatty acids, magnesium, calcium, and vitamins B6, B12, A, C, and D—with AI-integrated digital caregiver education delivered via website, YouTube, and telephonic counselling significantly improves macro- and micronutrient intake, behavioural function, and caregiver nutrition knowledge, attitudes, and practices in children with ADHD symptoms attending special schools in Chennai, India. These findings underscore the importance of addressing the dietary dimension of ADHD management through culturally appropriate, multi-component, digitally-enabled strategies. The significant and sustained improvements in caregiver KAP scores suggest that digital platforms offering India-specific dietary guidance may be particularly powerful levers for sustainable nutritional behaviour change. Special schools represent a vital implementation setting for such interventions, offering structured access to a high-risk paediatric population while enabling continuity of dietary monitoring. Replication in larger, randomised multi-site trials with biomarker-based outcome validation is warranted to confirm these findings and facilitate policy translation.

Declarations

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Ethical approval: The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Human Ethics Committee, Avinashilingam Institute for Home Science and Higher Education for Women, Coimbatore (Approval No. AUW/IHEC/FSN-2021/XPD-27).

Informed consent: Written informed consent was obtained from all participating caregivers prior to data collection. Assent was obtained from children aged 7 years and above.

Conflicts of interest: The authors declare no conflict of interest.

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