Journal of Health and Nutrition Research
Vol. 5, No. 1, 2026, pg. 483-496, https://doi.org/10.56303/jhnresearch.v5i1.1355
Journal homepage: https://journalmpci.com/index.php/jhnr/index

e-ISSN: **2829-9760**

Maternal and Environmental Determinants of Linear and Cranial Growth: A 6-Year Longitudinal Study in West Sumatra

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ORIGINAL ARTICLES

Submitted: 22 February 2026

Accepted: 1 April 2026

Keywords:
First trimester, head circumference, Indonesia, maternal physical activity, protein

ABSTRACT

This study aimed to identify the integrated maternal, environmental, and biological predictors of child linear growth (Height-for-Age Z-score; HAZ) and cranial growth (Head Circumference; HC) at age six in a longitudinal Indonesian cohort. A prospective cohort study followed 120 mother-child pairs in West Sumatra from the first trimester of pregnancy (2017) through age six (2023). Data were collected on maternal nutrient intake (SQ-FFQ), Vitamin D status (serum 25(OH)D), physical activity, and environmental conditions. Integrated multiple linear regression models were constructed to determine independent predictors, adjusted for maternal education and prepregnancy BMI. In the final integrated models, child HAZ at age six was significantly predicted by maternal first-trimester energy intake ($\beta = 0.0006$, $p = 0.006$), maternal height ($p = 0.012$), and child energy intake ($p = 0.005$). Cranial growth (HC) was primarily predicted by birth weight ($\beta=0.0011$, $p=0.004$) and maternal physical activity index ($p=0.031$). Maternal Vitamin D sufficiency (≥30 ng/mL) in the first trimester showed higher mean HAZ and HC compared to deficient levels (<20 ng/mL), although these differences were not statistically significant. The findings indicate that early pregnancy may be an important period for establishing growth trajectories, shaped by maternal nutritional status and environmental conditions. These observations support the potential value of strengthening pre-conception and early pregnancy care, including nutritional optimization and access to safe water; however, further studies are required to confirm these patterns and inform targeted interventions in West Sumatra.

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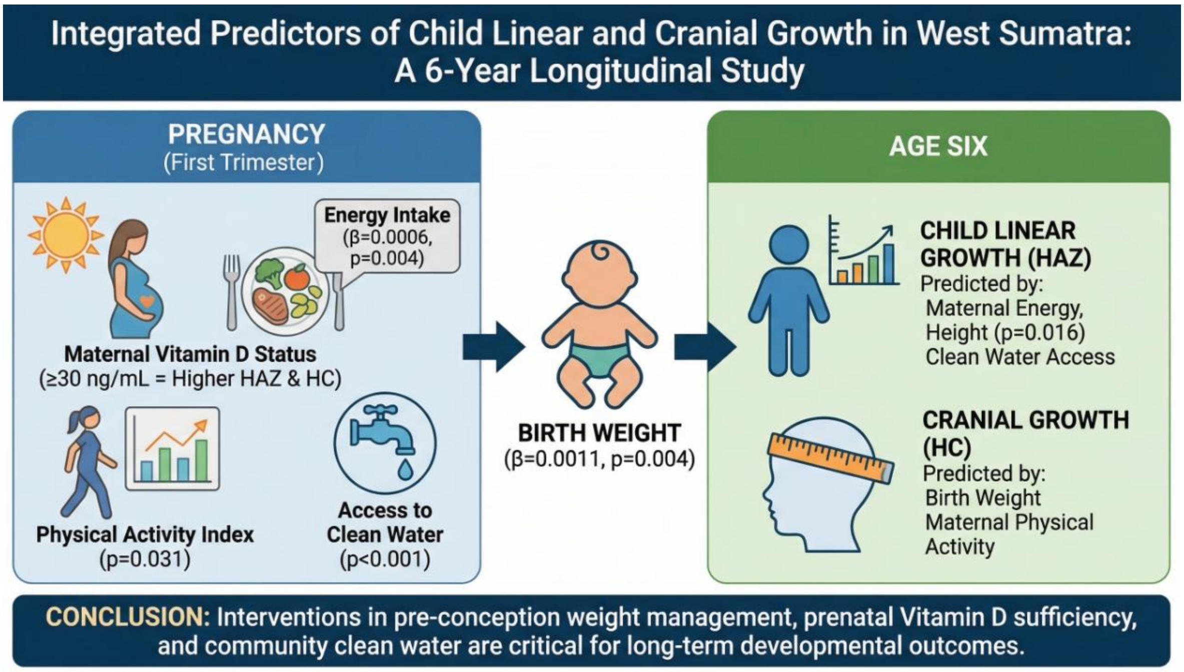
Key Messages:

- In West Sumatra, having clean water and enough calories in the first trimester are more important than family income alone to promote healthy growth.
- Birth weight and maternal physical activity are the two strongest predictors of head size at age 6.

GRAPHICAL ABSTRACT



INTRODUCTION

The first 1,000 days of life, beginning from conception, represent a critical window of biological plasticity where nutritional insults can permanently alter a child's developmental trajectory (1,2). In Indonesia, despite significant economic growth, the prevalence of stunting and suboptimal cognitive development remains a persistent public health challenge (3,4). While national programs often emphasize late-pregnancy and postnatal interventions (5), emerging evidence suggests that maternal nutritional ecology during the first trimester, specifically protein and energy density, may act as the primary 'gatekeeper' for long-term cranial growth and linear height (6–9).

Head circumference (HC) serves as a reliable anthropometric proxy for brain volume and neurodevelopmental status in early childhood (10). Unlike linear height, which post-natal environmental factors can influence, cranial growth is heavily canalized and protected, making it a sensitive indicator of early gestational programming. Canalization is a biological resilience where HC is prioritized and protected from moderate nutritional deficits to preserve neurodevelopment. Understanding how first-trimester macronutrient intake correlates with HC at age 6 allows for a more precise identification of the window where nutritional brain-sparing mechanisms are either supported or overwhelmed (11,12).

This study adopts a Nutrition Ecology framework, which views child growth not in isolation, but as a result of the complex interplay between maternal physiological status (BMI), environmental context (clean water access), and specific nutrient availability (Energy, Protein, and Vitamin D) during the embryonic stage. Although previous studies in Sumatra have explored birth outcomes (13–15), there remains a lack of longitudinal evidence examining how first-trimester energy and protein intake influence physical growth outcomes later in childhood. While the first 1,000 days framework is well established, a critical gap persists in understanding how maternal and environmental factors interact over a six-year trajectory to shape distinct growth indicators, such as head circumference (HC) and height-for-age z-scores (HAZ). To address this gap, the present study analyzes a unique longitudinal cohort to assess the predictive value of maternal first-trimester nutritional intake (energy and protein), vitamin D serum levels, environmental conditions (access to clean water), and birth characteristics (weight and length) on head circumference and linear growth (stunting) among 120 children followed up to six years of age. This investigation is particularly relevant in West Sumatra, where low dietary diversity and persistent environmental challenges, especially gaps in water, sanitation, and hygiene (WASH) infrastructure, with clean water and sanitation access falling 6.13% and 11.47% below the national average (16,17), are further

https://doi.org/10.56303/jhnresearch.v5i1.1355

compounded by recurrent hydrometeorological disasters such as flooding. These conditions may create context-specific barriers to optimal growth that are not adequately captured in cross-sectional studies.

METHODS

Study Design and Participant

This research employs a prospective longitudinal cohort design to evaluate the determinants of child physical and cranial growth. The study serves as a 6-year follow-up to a baseline investigation established in 2017. By linking maternal, prenatal, and birth data from the original cohort with a follow-up assessment conducted between December 2023 and March 2024, the study examines the long-term impact of early-life exposures on child development at age six. The study was conducted across five cities and districts in West Sumatra, Indonesia: Padang, Pariaman, Padang Pariaman, Lima Puluh Kota, and Payakumbuh. The original cohort consisted of 184 pregnant women recruited during their first trimester (gestational age <12 weeks) in 2017. For the present 6-year follow-up, 127 mother-child pairs were successfully tracked. Fifty-seven participants were excluded from the follow-up due to relocation, inability to be reached, or withdrawal from the study (Fig. 1). To ensure the validity of growth outcomes, further exclusion criteria were applied to the tracked pairs as follow: one case was excluded due to a gestational age of <37 weeks (preterm birth) and six cases were excluded due to incomplete anthropometric or nutritional data. The final analytical sample comprised 120 mother-child pairs. All children included in the final analysis were born full-term (≥37 weeks), ensuring that observed growth outcomes at age six reflect a standard gestational duration rather than complications associated with prematurity.

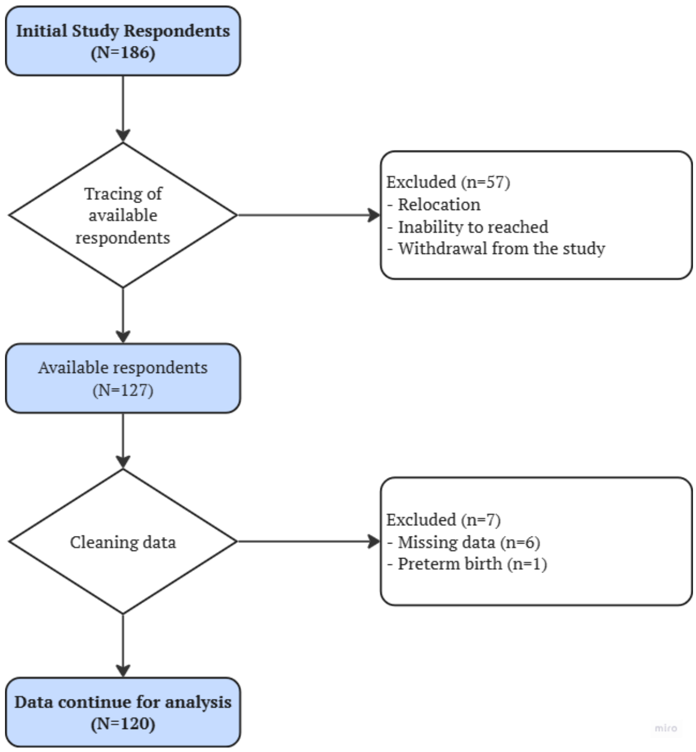


Figure 1. Flow diagram of the respondent's follow-up

Nutritional and Physical Activity Assessment

Maternal dietary intake during the first trimester was accessed using a Semi-Quantitative Food Frequency Questionnaire. Nutrient analysis, specifically for total energy (kcal) and protein intake (g), was performed using NutriSurvey with Indonesian Food Composition Tables. Maternal serum 25-hydroxyvitamin D [25(OH)D] concentrations were measured via ELISA with the intra-assay and inter-assay coefficients of variation (CV) for this analysis were maintained within acceptable ranges 5.0% and 8.10% at a concentration of 21.87 ng/mL, and 2.4% and 9.9% at 45.01 ng/mL, respectively. Detailed validation of

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these laboratory protocols has been previously documented (18). Vitamin D status was categorized as deficient (<20 ng/mL), insufficient (20–30 ng/mL), or sufficient (≥30 ng/mL) according to Endocrine Society Clinical Practice Guidelines (19). Physical Activity Index during the first trimester was calculated from type of activities.

Anthropometric Measurements

Maternal pre-pregnancy BMI was calculated from the database. At age 6, child head circumference (HC) was measured to the nearest 0.1 cm using a non-stretchable plastic tape placed over the supraorbital ridges and the most prominent part of the occiput. Linear growth was assessed via height-for-age Z-scores (HAZ) calculated using the World Health Organization (WHO) Child Growth Standards, WHO AnthroPlus application. Stunting was defined as an HAZ < -2.0 standard deviations (SD) from the median.

Statistical Analysis

Descriptive statistics were calculated for all continuous variables, expressed as mean and standard deviation (SD). Maternal nutrient intake (derived from SQ-FFQ and NutriSurvey) and child intake (2x24-hour recall) were calculated. Subjects were stratified by urban and rural status to identify geographic nutritional disparities. While the cohort was initially stratified by urban and rural status for descriptive purposes, the final integrated regression models were not stratified by location. Data management was supported by Microsoft Excel and SPSS, while all formal analyses and visualizations were performed using Python (version 3.11) with the Statsmodels, Pingouin, and Seaborn libraries. Prior to analysis, a rigorous data cleaning protocol was implemented to ensure the physiological plausibility of the longitudinal anthropometric measurements. During this process, one outlier in child head circumference (19.2 cm) was identified; however, following a cross-verification with the original paper-based research forms, the value was confirmed as a transcription error and corrected to 49.2 cm. One preterm birth (gestational age <37 weeks) (Participant 437) was excluded to ensure a homogenous full-term cohort (N=120).

The "Final Integrated Model" uses Multiple Linear Regression (Ordinary Least Squares - OLS) with the equation as below:

$$Y - \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + \epsilon$$

- Y (the outcome): Child HAZ or Head Circumference at Age 6
- X (the predictors): The maternal, social, and birth factors
- β (the coefficient): The weight of each factor

Model 1 The Height (HAZ) Path integrated variables across different levels of the child's life, namely prenatal (maternal T1 energy, maternal height), social/environment (water access, monthly income), and postnatal (child energy intake at age 6). Model 2 The Head Circumference (HC) Path integrated factors that focused on the structural growth on the brain proxy. The factors are biological foundation (birth weight, birth HC, placenta weight), maternal behavioral (physical activity (PA) index), and nutritional (maternal T1 protein, child protein at age 6). Model assumptions were rigorously verified: multicollinearity was assessed using Variance Inflation Factors (VIF < 5.0). We checked if any variables were too similar (like income and education). Since the VIF was < 5, we confirmed each variable provided unique information. Heteroscedasticity was verified using the Breusch-Pagan test. The Breusch-Pagan test was used to ensure the "errors" in our prediction were evenly distributed across the whole group, indicating the model is equally accurate for both short and tall children. Statistical significance was defined as $p < 0.05$.

Ethical Consideration

This study was conducted in accordance with the Declaration of Helsinki. The study protocol, including maternal blood collection via ELISA and child anthropometric measurements, was reviewed and approved by the Ethics Committee of the Faculty of Medicine, Universitas Andalas. Written informed consent was obtained from all participating mothers for themselves and on behalf of their children prior to enrollment at the 6-year follow-up. Data were handled with strict confidentiality, and only anonymized

https://doi.org/10.56303/jhnresearch.v5i1.1355

datasets were used for the final regression analysis to protect participant privacy.

CODE OF HEALTH ETHICS

Ethical clearance for this study was granted by the Health Research Ethics Committee of the Faculty of Medicine, Universitas Andalas (984/UN.16.12/KEP-FK/2022). All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee.

RESULTS

A total of 120 mother-child pairs from the longitudinal cohort in West Sumatra were included in the final analysis. One participant was excluded due to preterm birth (gestational age <37 weeks) to maintain the focus on long-term growth trajectories of term-born infants. All child anthropometric measurements at age 6 were verified for physiological plausibility, ensuring a robust dataset for multivariate modeling.

An attrition analysis was conducted to compare baseline maternal and neonatal characteristics between participants included in the final analysis (n=120) and those lost to follow-up or excluded (n=64). No statistically significant differences were observed between the two groups in terms of maternal age (p=0.835), maternal education years (p=0.442), pre-pregnancy BMI (p=0.658), or household income (p=0.321). Furthermore, there were no significant differences in neonatal outcomes, such as birth weight (p=0.370), suggesting that the final sample is representative of the original 2017 cohort and the risk of attrition bias is minimal.

Characteristic of Mother and Children

The maternal and child characteristics are summarized in Table 1. At the start of the study (first trimester), the mean maternal energy intake was 1,778 kcal/day, with a mean protein intake of 76.26 g/day. A significant proportion of the cohort demonstrated a height-for-age Z-score (HAZ) at age 6 that indicates a high prevalence of at-risk linear growth (Mean HAZ = -1.48 SD), with 37.5% (n=45) (HAZ <-1 SD) with a stunting risk and 29.2% (n=35) (HAZ <-2 SD) classified as stunted. The mean head circumference at age 6 was 49.81 cm, reflecting the cohort's cranial development.

Table 1. Characteristic and Nutritional Status of Mother – Child Pairs (Mean±SD)

Characteristic	Overall (N=120)	Urban (n=52)	Rural (n=68)
Maternal Factors			
Maternal Age (Years)	29.42 ± 5.72	27.94 ± 4.90	30.54 ± 6.07
Pre-pregnancy BMI (kg/m^2)	23.65 ± 4.37	23.92 ± 4.21	23.44 ± 4.51
Physical Activity Index	2.55 ± 0.36	2.56 ± 0.41	2.54 ± 0.31
T1 Energy Intake (kcal/day)	1768.38 ± 476.20	1965.23 ± 612.15	1617.85 ± 253.88
T1 Protein Intake (g/day)	76.27 ± 29.97	87.48 ± 40.03	67.69 ± 14.25
T1 Maternal Vitamin D (ng/mL)	14.50 ± 7.54	13.29 ± 7.80	15.42 ± 7.27
Birth Outcomes			
Birth Weight (g)	3217.36 ± 465.73	3150.98 ± 375.83	3302.99 ± 438.65
Birth Head Circumference (cm)	34.01 ± 2.83	34.20 ± 2.06	34.19 ± 1.79
Birth Length (cm)	48.46 ± 3.28	49.21 ± 1.13	48.31 ± 2.42
Follow-up at Age 6			
Head Circumference (cm)	49.81 ± 1.68	49.87 ± 1.71	49.77 ± 1.67
Height-for-Age (HAZ)	-1.48 ± 1.09	-1.31 ± 1.06	-1.62 ± 1.07
Weight-for-Age (WAZ)	-1.17 ± 1.25	-1.21 ± 1.16	-1.13 ± 1.33
Energy Intake (kcal/day)	1270.43 ± 420.45	1196.57 ± 331.90	1326.65 ± 471.71
Protein Intake (g/day)	44.48 ± 16.21	43.55 ± 12.28	45.20 ± 18.73

T1: Trimester 1, HAZ: height-for-age Z-score, WAZ: weight-for-age Z-score

Urban mothers had a significantly higher energy intake during the first trimester (1,965 kcal vs. 1,617 kcal in rural areas). Notably, by age 6, rural children have a higher average daily energy intake (1,326 kcal) compared to urban children (1,196 kcal). Urban mothers had a significantly higher protein intake during the first trimester (87.48 g/day vs. 67.69 g/d in rural areas). Rural mothers had higher Vitamin D

https://doi.org/10.56303/jhnresearch.v5i1.1355

levels (15.42 ng/mL) than urban mothers (13.29 ng/mL), likely due to higher sun exposure levels in rural outdoor environments.

Birth outcome shows that the rural group had a slightly higher mean birth weight (3.3 kg) than the urban group (3.1 kg), although the urban group had a higher mean birth length. Despite differences in prenatal protein intake, head circumference at age 6 is remarkably similar between the groups (49.87 vs 49.77 cm). Overall, from birth to age 6, head circumference increased from a mean of ~34.01 cm to ~49.81 cm. Rural children seem to have slightly higher protein intake (45 g/d) compared to urban children (43 g/d). However, the overall HAZ is -1.48, where the rural children show slightly more growth retardation (HAZ -1.62) than urban children (HAZ -1.31), suggesting a higher risk of stunting in the rural cohort by age 6.

Figure 2 shows that child energy intake at age 6 is the strongest predictor (*r*= 0.30) for child HAZ at age 6. Maternal height is also a strong predictor (r= 0.24), confirming the saying that taller mothers have taller children. Regarding the brain proxy at age 6, birth weight (*r*= 0.33) is the primary structural driver. A notable finding is that mothers who were more physically active (physical activity = PA index) during pregnancy had children with slightly larger head circumference (r = 0.21).

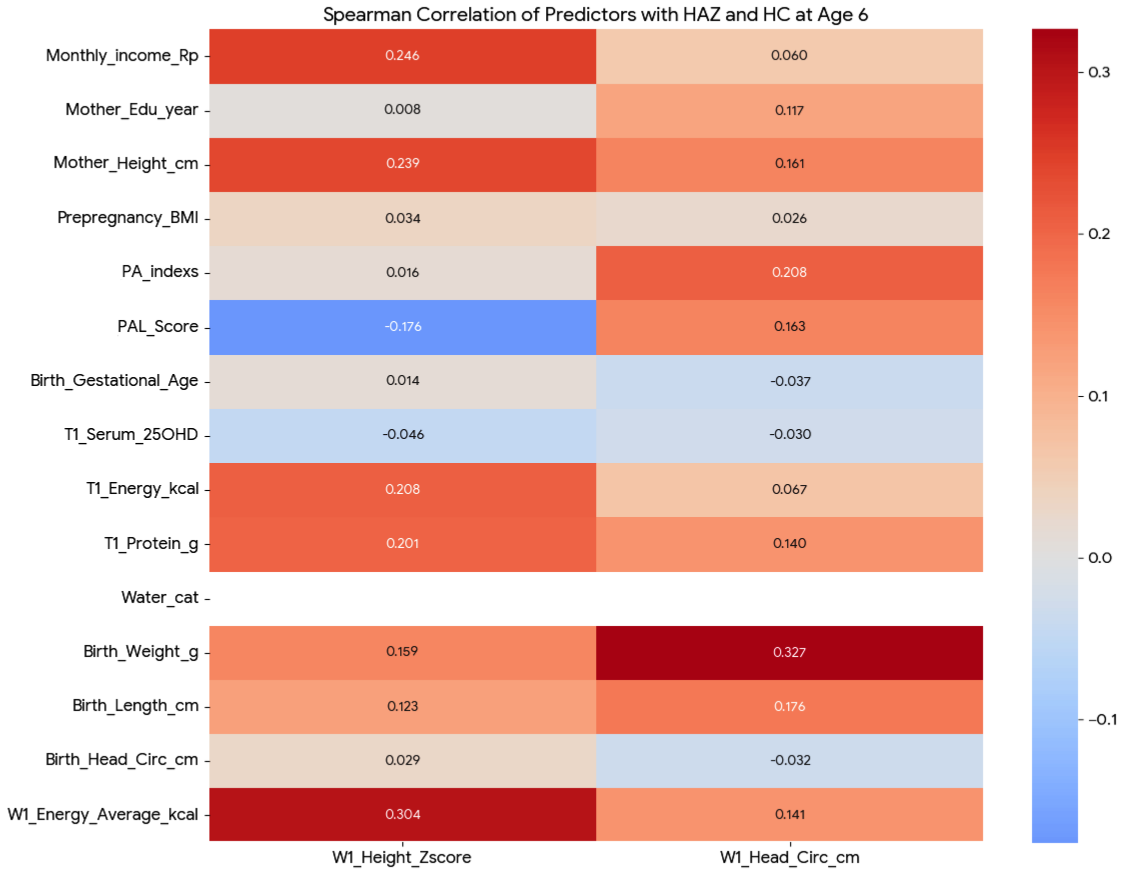

Figure 2. Correlation matrix of maternal, social environmental, and birth factors on child outcome at age 6

Maternal Vitamin D Impact on Child Growth

Table 2. Maternal Vitamin D Impact of HAZ and Head Circumference at Age 6

Maternal Vit D Status (%)	Average HAZ	Average Head Circumference (cm)
Deficient (80%)	-1.51 (Risk of stunting)	49.83
Insufficient (16.7%)	-1.54 (Risk of stunting)	49.57
Sufficient (3.3%)	-0.65 (Normal range)	50.48

Vitamin D deficiency-insufficiency is nearly universal (96.7%)(Table 2). In this study, 80% of mothers were classified as Vitamin D deficient during the first trimester, with only 3.3% reaching sufficient

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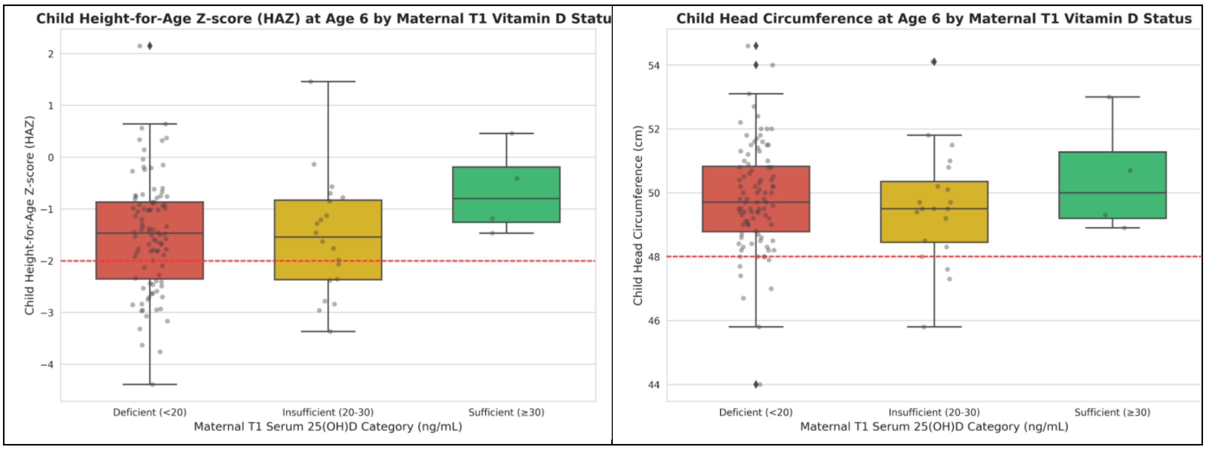
levels. The sufficient group showed the average HAZ within the normal range and the average HC was slightly larger than the deficient-insufficient group. However, the sample size (n=4) considered very small that limited the interpretation of this finding (p = 0.6).



F=1.22, p-value=0.299 *F=0.51, p-value=0.600*

Figure 3. Vitamin D growth threshold.

Fig. 3 depicts that the Deficient (< 20 ng/mL) and Insufficient (20-30 ng/mL) groups both have median HAZ hovering near or below the -2.0 SD (stunting) line. Although the p-value (p = 0.299) did not reach significance, the sufficient group showed a higher mean HAZ than the other groups. However, given the very small sample size (n=4) in the sufficient group, this trend should be interpreted with caution.

Integrated Model for Linear Growth and HAZ

Linear growth at age 6 was strongly predicted by first trimester and current nutrition (Table 3). Maternal energy intake during the first trimester was a highly significant predictor of HAZ (p = 0.006), even after adjusting for socioeconomic status. Notably, current energy intake at age 6 was also significantly predicted by height outcomes (p = 0.005), suggesting that while the growth trajectory is programmed prenatally, current nutrition remains a vital factor for height maintenance in middle childhood.

Table 3. Integrated Model for Child HAZ at Age 6

Predictor	Coefficient (β)	SE	p-value
Maternal energy T1 (kcal)	0.0006	0.0002	**0.006***
Maternal height (cm)	0.0372	0.0142	**0.012***
Monthly income (million)	0.0308	0.0317	0.408
Child energy intake (kcal)	0.0006	0.0003	**0.005***

*Model 1 (HAZ): R^2 = 0.230; Adjusted R^2 = 0.189; All VIFs < 1.3; Breusch-Pagan X^2 = 4.12 (p= 0.052). SE: standard error. HAZ: height-to-age z-score. P-value= *Significant, ***Highly significant.*

Integrated Model of Long-term Cranial Growth (Head Circumference)

This model examined the extent to which prenatal and birth factors predict head circumference at age 6, a proxy for brain volume. Multivariable linear regression analysis (Table 4) identified birth weight as a statistically significant predictor of head circumference (p < 0.05). Specifically, each 100 g increase in birth weight was associated with an estimated 0.1 cm increase in head circumference (β = 0.0011). Maternal physical activity was also positively associated with head circumference, with a 0.91 cm increase per unit rise in the PA index; however, the magnitude of this estimate should be interpreted with caution. Overall, these variables contributed to the model, although the effect sizes were modest, indicating that additional unmeasured factors are likely involved in determining cranial growth. The final integrated model prediction is presented in Table 5.

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Table 4. Integrated Model for Brain Growth at Age 6 (Head Circumference)

Predictor	Coefficient (β)	SE	p-value
Birth weight (g)	0.0011	0.0003	**0.004***
Maternal PA Index	0.9066	0.4149	**0.031***
Maternal T1 protein (g)	0.0049	0.0049	0.323
Placenta weight (g)	0.0018	0.0019	0.350
Birth HC	-0.0834	0.0821	0.312

Model 2 (HC): R^2 = 0.163; Adjusted R^2 = 0.102; All VIFs < 1.3; Breusch-Pagan X^2 =2.89 (p=0.779); PA: physical activity; T1= trimester I; HC= head circumference; SE: standard error; P-value = Significant.*

Table 5. Final Integrated Predictors of Child Growth at Age 6

Outcome	Key Significant Predictor Predictor	Coefficient (β)	p-value
Linear growth (HAZ)	Maternal T1 energy	0.0006	0.006
	Maternal height	0.0372	0.012
	Child energy (age 6)	0.0006	0.005
Cranial Growth (HC)	Birth weight	0.0011	0.004
	Maternal physical activity	0.9066	0.031

T1= trimester I, HC= head circumference.

DISCUSSION

Prenatal Programming of Linear Growth

Energy intake during the first semester is a significant positive predictor of HAZ at age 6 (Table 5). Our study provides compelling evidence that the foundation for linear growth at age 6 is establish during the earliest stages of gestation. It shows that even if a child was born with a normal weight, a lack of maternal energy in the earliest stages of pregnancy correlates with poorer linear growth six years later. The HAZ at age 6 averages -1,48. It is indicated a high risk of stunting or chronic mild malnutrition. Average maternal energy intake during first trimester are significantly lower (1,768 kcal/d) compare to the Indonesia Dietary Recommendation (AKG – angka kecukupan gizi) 2,250 + 180 g/d (20). The deficit of energy in first trimester is 662 kcal/d, which is critical for fetal growth and potential reduction in HAZ approximately 0.39 SD. A meta-analysis study support this findings where the average total energy intake in early pregnancy was below average (21). Correlation analysis indicated maternal T1 energy intake (r =0.21) and T1 protein intake (r = 0.20) are both positively correlated with the child's Age 6 HAZ. The mother's intake in T1 was a more sensitive predictor of child growth than her BMI before pregnancy. The significant association (Table 5) between maternal first trimester energy intake and child HAZ (p= 0.006) suggests a metabolic programming effect. During the first trimester, rapid cellular differentiation occurs. Specifically, an increase of 700 kcal in daily maternal prenatal energy during first trimester was associated with a 0.42-point increase (0.0006 (β)x 700 kcal) in child's HAZ. A deficit in energy availability during this window may lead to permanent adaptation in the fetal growth axis.

Child energy intake is lower than AKG around 130 kcal/day, which will resulted in additional 0.08 SD deficit in HAZ. Together, the energy deficits in utero and during childhood account for a loss of nearly half a standard deviation (0.47 SD) in HAZ. This is likely reflects the impact of repeated infection during early childhood until school-age, in particular, environmental enteric dysfunction (EED) caused by gastrointestinal infection such as giardiasis (22). This repeated infection event will prevent nutrient absorption, regardless of caloric intake (23). We observed that monthly income was not significant predictor. It seems that once biological (energy intake and maternal height) factors are accounted for, the direct impact of wealth on height disappears. Therefore, the model confirms that HAZ at age 6 is a multifactorial outcome determined by prenatal nutrition and postnatal energy. The 662 kcal deficit finding emphasize that the malnutrition intervention must begin at the start of pregnancy, not just after birth. In addition, undernutrition during first trimester might compromise immune function and increase the vulnerability of the children in later years.

Furthermore, the strong influence of maternal height (p = 0.012) confirms the intergenerational nature of growth; however, the impact of energy intake suggests that optimized prenatal nutrition can serve as a critical lever to break this cycle of stunting. Taller mother and higher birth weight provide a biological buffer that may help children navigate environmental stressor. The study from Zeevi et al. even proposes a

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method for predicting children's height target (24), which means the stature of the parent does influence child growth, in a supportive environment. This result differs with findings on 10-13 years-old children in Badung Regency. The study concludes that parental height have no relation with child height in the specific range of age (25). Even though so, our findings suggest height is plastic, as it is influenced by the first trimester; hence, it remains sensitive to current calorie intake at age 6. There is a window for intervention.

Vitamin D levels in the first trimester were predominantly low in this cohort, consistent with previous studies reporting insufficiency ranging from 20% to 82.8% (18,26). Although maternal vitamin D was not a statistically significant predictor of HAZ in the present model, a positive trend was observed. As shown in Figure 3, HAZ increased markedly, by nearly 1.0 SD once maternal levels exceeded the sufficiency threshold of 30 ng/mL (Table 2). Below this threshold, growth gains appeared limited, potentially increasing the risk of developmental delay (27,28), whereas levels above it were associated with a more favorable growth trajectory (26). These findings suggest that vitamin D may function as a threshold-dependent factor in growth; however, this interpretation should be made cautiously given the limited sample size. Evidence from prior studies indicates that supplementation to achieve sufficient levels during pregnancy may improve birth length and potentially support later growth outcomes (26,29,30).

Socio-Environment Synergy

All the respondents have an access to clean water resulting in a homogeneous exposure profile (N=120) that effectively eliminates water source as a confounding in explaining growth variability. This uniformity suggests that the "leaky bucket" effect associated with EED is more likely driven by subclinical environmental exposure, such as contact with contaminated soil or pathogens present during flood recession, rather than the primary water source itself. Given the consistency of water access, the primary drivers of growth resilience in this cohort appear to shift toward biological and nutritional factors.

Family monthly income was not found to be a significant predictor, suggesting that growth outcomes may be more strongly influenced by collective environmental capital rather than household economic status alone. Previous research has shown that higher socio-economic status can improves health outcomes by enabling families to access more favorable living enviroments (31). Although earlier study (32) identified family income as a strong predictor of stunting (OR = 3.076), our findings did not demonstrated a statistically significant correlation between monthly income and growth outcomes ($p = 0.408$). These results indicate that, within our study population, growth outcomes are driven by proximal determinants, such as maternal energy intake during the first trimester and maternal physical stature, than by distal socio-economic indicators. Notably, despite the increasing in family income throughout the six-year follow-up periods, its potential influence appears to have been overshadowed by these more immediate biological and environmental factors.

Neuro-Structural Stability and Physical Activity

Head circumference is a commonly used proxy for brain volume growth in longitudinal studies. The most statistically significant predictor of cranial growth in this study is birth weight. Every 1,000 g increase in birth weight is associated with a 1.1 cm increase in head circumference at age 6. Unlike linear growth, which showed significant sensitivity to the current environment at age six, cranial growth (measured by head circumference) remained remarkably stable and was associated with birth outcomes ($p = 0.001$). This suggests that the biological trajectory of head growth is largely set before birth. Birth weight acts as a comprehensive marker for the quality of the intrauterine environment (33). Even at age 6, the effects of neonatal size (birth weight) remain a dominant predictor of head circumference, reinforcing the importance of prenatal health for long-term neurodevelopmental markers. Birth weight is the strongest predictor of later HC, but maternal protein is the fuel that drives it.

A notable finding in this study was that the Maternal Physical Activity (PA) Index emerged as a statistically significant predictor of child head circumference at age six ($\beta = 0.91$ cm per unit increase; $p < 0.05$), although the magnitude of the association was modest ($r = 0.21$). This finding indicates that higher maternal physical activity contributes to the prediction of head circumference, but its practical significance should be interpreted cautiously, given the relatively small effect size and the multifactorial determinants

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of postnatal growth. It is suggested that a healthier maternal lifestyle provides a better physiological environment for brain and skull development. These results partially align with the previous review by Shlomo and Mor (2023), which suggested that children of physically active women during pregnancy exhibit better brain growth (34). This suggests a Neuroscience Ecology in which maternal physical health and movement may enhance placental perfusion and fetal growth factor production. However, Teo et al. suggested differently, which healthy lifestyle was not associated with placental development (35).

Maternal protein intake during the first trimester demonstrated a weak positive correlation with child height-for-age z-scores (HAZ) at six years ($r = 0.20$); however, this variable did not retain statistical significance in the multivariable predictive model. This suggests that, although protein intake may contribute to early growth trajectories, its independent predictive value is limited when considered alongside other covariates. In contrast, energy intake appeared to play a more prominent role in linear growth, consistent with the established importance of adequate caloric availability for height attainment. Notably, head circumference appeared less sensitive to variation in maternal protein intake after accounting for birth weight, suggesting that early growth constraints may be mediated by broader intrauterine factors rather than specific macronutrient effects. One possible explanation is the phenomenon of brain sparing, whereby fetal physiology prioritizes brain development over somatic growth under conditions of nutritional constraint (34). This adaptive mechanism may partially decouple cranial growth from short-term fluctuations in nutrition. Furthermore, while linear growth remains responsive to sustained postnatal nutritional inputs, cranial growth is more tightly regulated by early fetal programming and genetic influences (36,37). Nevertheless, the observed trends suggest that nutritional exposures during the first trimester may still contribute to the foundational processes underlying neurodevelopment, with effects that persist into later childhood, albeit not independently detectable within this model.

Birth weight analysis in this study reinforces the central role of the intrauterine environment in shaping long-term cranial growth. Birth weight, as an integrative marker of fetal growth conditions, emerged as a more robust predictor of head circumference at six years than head circumference measured at birth. This finding suggests that birth weight may better reflect the overall nutritional reserve and growth potential established during gestation (7,38,39). In contrast, the weaker correlation between birth head circumference and head circumference at age six indicates that early cranial size alone may not fully capture subsequent growth trajectories. The observed patterns are consistent with the concept that early fetal development establishes a biological template for later brain growth (7,8). In particular, the availability of key nutrients, including amino acids, during the first trimester, may contribute to foundational processes that influence long-term brain volume. These findings support the notion that the prenatal period (40), especially the first nine months, plays a more decisive role in determining head circumference than postnatal protein intake alone. Consequently, interventions aimed at optimizing cranial growth should prioritize improving maternal health and fetal growth, as reflected by birth weight. At the same time, the lower-than-expected correlation between birth and later head circumference suggests that postnatal factors, including energy intake during childhood, may contribute to compensatory or catch-up growth. This highlights the continued, albeit secondary, role of the postnatal environment in shaping final cranial outcomes.

Regarding micronutrient status, although the number of participants with sufficient vitamin D levels was limited, a graded (dose–response) pattern was observed, with incremental increases in maternal vitamin D associated with modest increases in child head circumference. Supporting this observation, a large-scale review involving 250,569 women reported that vitamin D supplementation was associated with increased birth weight (41). While these findings are suggestive of a potential protective role, they should be interpreted with caution due to limited statistical power in the present study. Nonetheless, they provide a rationale for larger-scale intervention studies in West Sumatra to further evaluate the role of vitamin D in supporting fetal and cranial growth.

Finally, both predictive models were statistically significant overall (F-statistic $p < 0.012$), indicating that the combination of maternal, environmental, and birth-related factors contributes meaningfully to the prediction of child growth outcomes. However, the extent to which each factor

https://doi.org/10.56303/jhnresearch.v5i1.1355

independently explains variability remains modest, underscoring the multifactorial nature of growth and the need for integrated approaches in future research.

The primary strength of this study is its prospective, longitudinal design, which enables a life-course assessment of child growth. The use of integrated models allowed simultaneous adjustment for maternal, biological, and environmental factors, providing a comprehensive analytical framework. In a context with limited longitudinal evidence, particularly in West Sumatra, this study offers novel insights into growth determinants within a high-stunting population, incorporating diverse indicators such as serum vitamin D, maternal physical activity, and environmental conditions. However, several limitations should be acknowledged. Although the overall sample size (N = 120) was adequate for regression analyses, subgroup analyses, particularly for the vitamin D sufficient group (n = 4), were underpowered. Dietary assessments relied on the SQ-FFQ and 24-hour recalls, which may introduce recall bias. Maternal physical activity was classified by activity type rather than quantified in metabolic equivalents (METs), which may limit precision in estimating energy expenditure. In addition, child serum 25-hydroxyvitamin D [25(OH)D] levels were not measured, restricting the ability to assess postnatal vitamin D status. The geographic specificity of the cohort may also limit generalizability across Indonesia, and genetic determinants of growth were not accounted for.

Future research should prioritize larger, multi-center longitudinal cohorts to enhance external validity. Subsequent work should include direct measurement of child vitamin D status to better characterize its role in postnatal growth. In addition, extending the analysis to functional outcomes, particularly cognitive development, will be critical. Building on the present findings, future studies will aim to develop predictive models of child intelligence (IQ), integrating early-life biological, nutritional, and environmental exposures to better understand long-term developmental trajectories in high-risk populations.

CONCLUSION

In conclusion, this study highlights the central role of intrauterine factors in shaping child growth outcomes up to six years of age. Birth weight emerged as a key predictor of later head circumference, reinforcing its value as an integrative marker of fetal growth conditions. Maternal factors, including energy intake and physical activity during early pregnancy, contributed to growth trajectories, although their independent effects were modest. In contrast, household income was not a significant predictor, suggesting that proximal biological and environmental exposures may be more influential than distal socio-economic factors in this setting. These findings underscore the importance of maternal health and nutrition during pregnancy, particularly in the first trimester, in establishing long-term growth potential. While postnatal influences may support catch-up growth, their role appears secondary for cranial development. Overall, the results support a life-course approach, emphasizing early, integrated maternal interventions to improve child growth and developmental outcomes in high-risk populations.

POLICY IMPLICATION

These findings highlight the importance of strengthening interventions during the pre-conception and early pregnancy periods as part of stunting reduction strategies. Maternal health programs should integrate nutritional screening, promotion of balanced diets, and appropriate physical activity before and during pregnancy. Continued improvements in water and sanitation access remain relevant to reduce adverse environmental exposures. Given the suggestive role of micronutrients such as vitamin D, further intervention studies are needed before large-scale implementation. Overall, integrated, multi-sectoral approaches are essential to support optimal child growth in high-risk populations.

FUNDING

This research was funded by the Non-Tax State Revenue (PNBP) of Faculty of Medicine, Universitas Andalas, for fiscal year 2022, under DIPA contract number 29/UN.16.02/Fd/PT.01.03/ 2022.

https://doi.org/10.56303/jhnresearch.v5i1.1355

ACKNOWLEDGMENTS

The authors would like to express their sincere gratitude to all respondents and district health center for supporting the study continuation. The authors also extend their appreciation to the supervising lecturer at Universitas Andalas for their valuable insights, support, and guidance throughout the research process.

DECLARATION OF GENERATIVE AI

During the preparation of this work, the author(s) utilized the Gemini 1.5 Flash interface to facilitate data visualization throught Python-based analytical libraries (SciPy, Statsmodels, and Seaborn). Following the computational phase, the author(s) reviewed and edited the generated outputs for mathematical accuracy and scientific relevance. The author utilized the ChatGPT to improve the readability. The author(s) take full responsibility for the integrity of the data, the interpretation of the results, and the final content of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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