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THE IMPACT OF NUTRITION AND NUTRITIONAL INTERVENTIONS ON PUBERTAL GROWTH: A COMPREHENSIVE REVIEW OF MACRONUTRIENT AND MICRONUTRIENT INFLUENCES

Ashraf Soliman[1]*, Fawzia Alyafei[1], Nada Alaaraj[1], Shayma Ahmed[1], Noora AlHumaidi[1], Noor Hamed[1], Ahmed Elawwa[1,2], Sohair Elsiddig[1] and Ahmed Khalil[3]

[1]Department of Pediatrics, Hamad General Hospital, Doha, Qatar.
[2]Pediatric Endocrinology and Diabetology Unit, Faculty of Medicine, Alexandria.
[3]Department of Pharmacy, Hamad General Hospital, Doha, Qatar.

***Corresponding Author: Ashraf Soliman**

Department of Pediatrics, Hamad General Hospital, Doha, Qatar.

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ABSTRACT

Background: The pubertal growth spurt is a critical period in human development, accounting for approximately 15–20% of adult height and nearly half of peak bone mass accrual. Optimal linear growth during this phase is governed by a complex interplay between growth hormone (GH), insulin-like growth factor-1 (IGF-1), sex steroids, and nutritional adequacy. However, global disparities in nutrition—both undernutrition and overnutrition—continue to jeopardize the growth potential of adolescents, particularly in vulnerable populations. **Objective:** To synthesize recent evidence on the impact of macronutrient and micronutrient intake, dietary quality, and targeted nutritional interventions on pubertal growth, with a focus on identifying modifiable risk factors and strategic points for intervention. **Methods:** This narrative review evaluated 88 studies published between 1990 and 2024, focusing on protein and caloric intake, iron, zinc, vitamin D, and multinutrient supplementation during adolescence. Key outcomes assessed included growth velocity, height-for-age z-scores, bone mineral density, pubertal timing, and hormonal biomarkers. Findings were synthesized into thematic tables highlighting population characteristics, dietary variables, and intervention outcomes. **Results:** Protein-rich diets, especially those based on high-quality animal sources, were associated with improved body composition and pubertal growth. Conversely, low-protein, high-calorie diets exacerbated adiposity and delayed linear growth. Iron, zinc, and vitamin D supplementation improved hemoglobin levels and modestly supported height velocity, particularly in deficient populations. Interventions combining macro- and micronutrients were most effective in addressing stunting and delayed puberty. Catch-up growth was achievable in undernourished adolescents with sustained nutritional support but carried risks of early pubertal onset if poorly timed. **Conclusions:** Both nutritional deficits and excesses profoundly influence pubertal development. Targeted, context-specific interventions—especially those combining dietary quality improvement with micronutrient supplementation—can mitigate stunting and optimize pubertal growth trajectories. Future research should emphasize longitudinal monitoring and the integration of nutrition into adolescent health strategies, particularly in regions facing the double burden of malnutrition.

KEYWORDS: Pubertal growth spurt, Adolescence, Nutrition, Stunting, Protein intake, micronutrient supplementation, Growth hormone, IGF-1, Bone mineral density.

INTRODUCTION

The pubertal growth stage represents a critical period in human development, marked by rapid increases in height, weight, and bone mineral density (BMD). This phase is essential for attaining final adult stature and optimizing skeletal health, with approximately 15–20% of adult height and 45% of peak bone mass accrued during puberty.[1,2] Growth during this time is driven by the interplay of hormones such as growth hormone (GH), insulin-like growth factor-1 (IGF-1), and sex steroids, which synergistically stimulate linear growth, muscle mass development, and bone mineralization.[3,4] Any disruptions to these processes during this key period can have long-term implications for physical health, including risks of short stature and reduced BMD, predisposing individuals to fractures and osteoporosis later in life.[5]

Despite its significance, pubertal growth is often compromised by the widespread prevalence of nutritional deficiencies among adolescents worldwide. Macronutrient deficiencies, such as inadequate protein

and caloric intake, coexist with micronutrient deficiencies, including iron, zinc, magnesium, vitamin D, and essential multivitamins. These deficiencies are particularly pronounced in low- and middle-income countries but also affect vulnerable populations in high-income regions due to dietary imbalances or restricted food access.[6,7] Adolescents are especially susceptible to these nutritional gaps due to their increased nutritional requirements during growth spurts, combined with poor dietary habits, food insecurity, or underlying medical conditions.[8,9] The persistence of these deficiencies highlights the urgent need for targeted nutritional interventions.

Nutritional deficiencies during adolescence can adversely affect the pubertal growth spurt, a critical period that sets the foundation for future health and well-being. Inadequate macronutrient and micronutrient intake can impair the hormonal and metabolic processes required for optimal growth, delaying pubertal milestones, reducing growth velocity, and compromising bone mineralization.[10,11] If unaddressed, these deficits may lead to stunting, delayed puberty, lower peak bone mass, and increased risk of chronic diseases in adulthood.[12] Understanding the multifaceted impact of nutrition on pubertal growth is therefore essential for developing effective strategies to mitigate these risks and support adolescent health globally.[13]

Objectives

The primary objective of this review was to evaluate the impact of nutritional factors, both macronutrient and micronutrient, on the pubertal growth spurt in adolescents. Specifically, we aimed to:

1. Examine the associations between dietary protein, caloric intake, and pubertal timing and growth velocity.
2. Analyze the effects of key micronutrients, including iron, zinc, vitamin D, and multinutrient supplementation, on pubertal development and final height outcomes.
3. Identify effective nutritional intervention strategies for promoting optimal growth during adolescence.
4. Compare outcomes across different population groups, including stunted, preterm, obese, and undernourished adolescents.

Methods

This review follows a systematic and comprehensive approach to collate, analyze, and synthesize existing literature on the topic.

1. Study design

- A narrative review was conducted to evaluate the effects of nutritional interventions on pubertal growth across diverse populations.

2. Search strategy

- An extensive search of peer-reviewed literature was performed using electronic databases, including PubMed, Scopus, Web of Science, and Google Scholar.
- Keywords used in the search included "pubertal growth," "adolescents," "macronutrient deficiencies," "micronutrient deficiencies," "protein supplementation," "caloric intake," "bone mineral density," and "nutritional interventions."
- Additional filters included publication years from 1990 to 2025 and studies involving human adolescent populations aged 10–18 years.

3. Inclusion criteria

- Studies focusing on the impact of macronutrients (protein, calories) and micronutrients (iron, zinc, magnesium, vitamin D, and multivitamins) on pubertal growth and bone development.
- Intervention studies, systematic reviews, and meta-analyses that reported growth-related outcomes, including height velocity, weight gain, pubertal milestones, or bone mineral density.
- Articles published in English.

4. Exclusion criteria

- Studies not involving adolescent populations or those with unclear interventions.
- Animal studies, case reports, and non-peer-reviewed articles.
- Studies focusing solely on conditions unrelated to nutrition, such as genetic disorders or chronic diseases unrelated to dietary intake.

5. Data Extraction and Analysis

- Data were extracted from eligible studies, including author(s), year of publication, study population, type of intervention, key findings, and conclusions.
- The extracted data were synthesized to provide a comprehensive understanding of the role of nutrition in pubertal growth, highlighting both positive and negative outcomes.

6. Quality assessment

- The quality of included studies was assessed using tools such as the Cochrane Risk of Bias tool for intervention studies and the Newcastle-Ottawa Scale for observational studies.
- Studies with high methodological rigor and sufficient sample sizes were prioritized in the analysis.

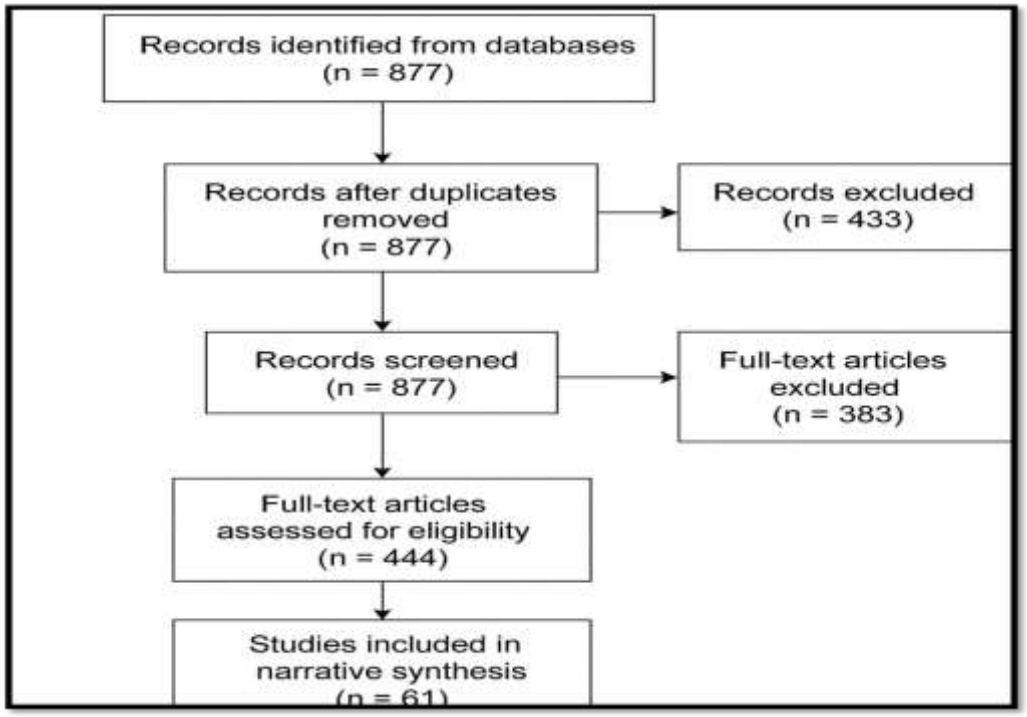

Figure 1: Prisma Chart.

RESULTS

This review summarizes evidence from 88 studies exploring how nutrition influences pubertal growth. The findings are presented across six thematic tables, highlighting the effects of macronutrients, micronutrient deficiencies, dietary patterns, and targeted nutritional interventions on adolescent growth outcomes.

Table 1: The Relationship Between Macronutrients, Stunting and the Pubertal Growth Spurt.

Author(s), Journal, Year	Number and Characteristics of Adolescents	Main Findings	Comment
Soliman et al., *Indian J Endocrinol Metab*, 2014 (24)	Review study; adolescents from diverse backgrounds	Adequate nutrition critical for growth; obesity accelerates puberty in girls but delays it in boys; micronutrient deficits impair growth.	Mixed: Balanced diet essential, processed foods harmful
Styne, *Horm Res Paediatr*, 2003 (25)	General discussion on adolescents	Nutrition impacts GH and IGF-1 action, influencing pubertal growth and bone growth.	Positive: Emphasizes nutritional role
Marcovecchio & Chiarelli, *World Rev Nutr Diet*, 2013 (26)	Adolescents with obesity vs. lean counterparts	Obese children exhibit accelerated prepubertal growth but reduced pubertal spurt; leptin and insulin influence growth.	Mixed: Obesity impacts growth trajectories
Campisi et al., *J Adolesc*, 2021 (27)	1,385 adolescents, rural Pakistan	Undernutrition and stunting delayed pubertal milestones and reduced duration of growth spurt.	Negative: Critical impacts of undernutrition
Proos & Gustafsson, *IJERPH*, 2012 (28)	Global review	Undernutrition followed by catch-up growth linked to early puberty in specific contexts.	Mixed: Risks of early puberty from catch-up
Soliman et al., *World J Adv Res Rev*, 2024 (29)	Global review	Stunted children exhibit delayed puberty and extended growth periods with proper nutrition.	Positive: Nutritional recovery supports growth
Chidumwa et al., *Eur J Clin Nutr*, 2020 (30)	1,036 adolescents, South Africa	Stunting predicted delayed puberty and reduced adult height.	Negative: Long-term impact of stunting
Wehkalampi et al., *J Clin Endocrinol*	318 preterm and control adolescents	Preterm, very low birth weight children exhibited advanced puberty but	Negative: Prematurity affects

Metab, 2011 (31)		reduced overall growth spurt.	growth outcomes
Swenne, *Eur Eat Disord Rev*, 2013 (32)	46 boys with eating disorders	Pubertal boys failed to catch up in growth despite nutritional recovery.	Negative: Irreversible effects of late intervention
Scheffler et al., *Public Health Nutr*, 2020 (33)	Cross-sectional study, Indonesia and Guatemala	Catch-up growth is a better indicator of undernutrition than static stunting thresholds.	Positive: Dynamic indicators preferred
Soliman et al., *Acta Biomed*, 2021 (34)	Review on stunting	Stunting early in life causes irreversible effects on growth and cognition if not addressed by age two.	Negative: Early intervention essential
Chen et al., *Front Endocrinol (Lausanne)*, 2022(35)	13,143 Chinese adolescents	Early puberty onset and short duration linked to lower final height and higher obesity risk.	Mixed: Complex effects of pubertal timing

Adequate nutrition is essential for proper growth during puberty, but the type and balance of nutrients play a critical role in determining outcomes. Balanced diets support healthy growth trajectories by optimizing hormonal pathways such as the growth hormone (GH) and insulin-like growth factor-1 (IGF-1) axis, which are central to pubertal growth and bone mineral density development (25,26). However, processed and calorie-dense diets have been shown to exert harmful effects, with obesity accelerating puberty in girls while delaying it in boys (27,28). These findings emphasize the importance of dietary quality in addition to caloric sufficiency.

Table 2: The Effects of Micronutrient Deficiencies (Iron, Zinc, Vitamin D, and Others) on the Pubertal Growth Spurt.

Author(s), Journal, Year	Number and Characteristics of Adolescents	Main Findings	Comment
Bhandari et al., *Br J Nutr*, 2001 (36)	Global study, infants and children	Zinc and iron improved linear growth modestly. Vitamin A had limited impact.	Mixed: Positive for zinc and iron; limited for vitamin A
Chhagan et al., *BMC Public Health*, 2010 (37)	473 African children aged 6 to 24 months	Zinc and vitamin A improved stunting and anemia in deficient children.	Positive: Effective in improving nutritional outcomes
Soliman et al., *Indian J Endocrinol Metab*, 2014 (38)	Adolescents globally	Iron, zinc, and vitamin D needs rise during puberty; deficiencies delay growth.	Positive: Balanced nutrition critical
Locks et al., *Am J Clin Nutr*, 2016 (39)	2,400 Tanzanian children	Zinc and multivitamin supplementation modestly improved weight-for-age scores.	Mixed: Limited impact on stunting
Ganmaa et al., *JAMA Pediatr*, 2022 (40)	8,851 Mongolian children aged 6 to 13	Vitamin D supplementation elevated serum levels but did not affect growth or pubertal development.	Mixed: Improves deficiency but no growth benefit
Khan et al., *Nutrients*, 2023 (41)	24 to 59-month-old children in Pakistan	Supplementation improved vitamin A, D, and zinc levels and hemoglobin but not height-for-age.	Positive: Effective for anemia and underweight
Barham et al., *Front Nutr*, 2024 (42)	992 Jordanian preschoolers	22.9% had vitamin D deficiency, 22.4% had iron deficiency; anemia prevalence slightly reduced.	Mixed: Persistent micronutrient challenges
Leonard et al., *Proc Nutr Soc*, 2023 (43)	Dietary modeling in high-income countries	Transition to plant-based diets reduced intake of vitamins A, D, and B12.	Mixed: Careful planning needed to avoid deficiencies
Tan et al., *BMJ Glob Health*, 2024 (44)	Meta-analysis, 190,443 participants	Overnutrition increased odds of iron deficiency; zinc and vitamin A less affected.	Mixed: Highlights overnutrition risks
Keats et al., *Campbell Syst Rev*, 2021 (45)	Meta-analysis of 439,649 pregnant women	Multiple micronutrient supplementation reduced maternal anemia, stillbirths, and low birth weight.	Positive: Significant maternal and child health benefits

Awasthi et al., *PLoS One*, 2022 (46)	2,428 urban Indian children	59.9% calcium deficiency, 49.4% iron deficiency, 39.7% vitamin D deficiency.	Negative: Widespread deficiencies
Tan et al., *Proc Nutr Soc*, 2024 (47)	1,471 female adolescents in Vietnam	Stunting increased risk of multiple micronutrient deficiencies; zinc deficiency most prevalent.	Negative: High prevalence of stunting and deficiencies

Micronutrient deficiencies significantly influence pubertal growth and development, with varying effects depending on the specific nutrient and population context. The studies in Table 2 highlight both the critical role of micronutrient supplementation in improving health outcomes and the challenges in achieving consistent growth benefits across diverse populations.

Zinc and iron have consistently shown modest benefits in enhancing linear growth and improving nutritional outcomes, particularly in children with deficiencies. For example, studies reported that zinc supplementation improved stunting and weight-for-age scores.[38,40] while iron supplementation enhanced hemoglobin levels and reduced anemia.[42,43] These findings suggest that targeted supplementation can address specific deficiencies effectively, though growth outcomes are often modest. Notably, supplementation with these nutrients was less impactful in non-deficient populations or where other coexisting deficiencies or factors like infections were present.[37]

Table 3: The Effects of High Protein vs. Low Protein and High Caloric vs. Low Caloric Diets on Pubertal Growth Spurt.

Author(s), Journal, Year	Number and Characteristics of Adolescents	Main Findings	Comment
Günther et al., *J Nutr*, 2010 (50)	112 children, longitudinal study	High animal protein intake at 5–6 years associated with earlier puberty onset; vegetable protein delayed puberty.	Mixed: Protein type matters
Primo et al., *Endocrinol Diabetes Nutr*, 2019 (51)	268 obese adolescents	High-protein diets improved BMI and fat mass reduction compared to standard diets.	Positive: Effective for weight loss
Falcone et al., *PLoS One*, 2015 (52)	37 women on high-protein, low-calorie diets	Enhanced fat loss with high-protein diets compared to placebo.	Positive: Effective for body composition
Ganmaa et al., *JAMA Pediatr*, 2022 (53)	8,851 children	High-calorie diets linked to increased IGF-1 and early pubertal growth.	Negative: Risks of early puberty
Costa-Orvay et al., *Nutr J*, 2011 (54)	32 very low birth weight infants	High-protein and high-calorie diets enhanced fat-free mass gain.	Positive: Supports growth in preterm infants
Awasthi et al., *PLoS One*, 2022 (55)	2,428 urban children	High-calorie diets increased early adiposity and delayed growth recovery.	Mixed: Risks of caloric imbalance
Tan et al., *BMJ Glob Health*, 2024 (56)	Meta-analysis of 190,443 participants	High caloric intake linked to obesity and delayed growth in undernourished settings.	Mixed: Context-dependent effects
Cheng et al., *Nutr Rev*, 2012 (57)	Systematic review of pubertal timing studies	High vegetable protein delayed puberty, while animal protein advanced it.	Mixed: Highlights dietary impact
Chege et al., *PLoS One*, 2024 (58)	Study of dietary regimens in children	Low-protein, high-calorie diets worsened metabolic markers and delayed growth.	Negative: Highlights risks of imbalance

The studies in Table 3 highlight the complex relationship between protein and caloric intake and their effects on pubertal growth. These findings underscore the importance of dietary quality, macronutrient balance, and the timing of nutritional interventions in shaping growth trajectories during adolescence.

High protein intake appears to have variable effects depending on the source and timing. Animal protein is associated with earlier puberty onset, likely due to its influence on IGF-1 levels, whereas vegetable protein has been linked to delayed pubertal development.[56,63] This distinction suggests that the type of protein consumed

plays a significant role in determining growth outcomes and pubertal timing. For example, long-term studies have shown that high animal protein intake during early childhood can accelerate the onset of puberty, which may shorten the pubertal growth period.[56,63] Conversely, high-protein diets in obese adolescents were effective in improving body composition by reducing fat mass, highlighting their potential benefit for metabolic health when appropriately targeted.

Table 4: Nutritional Intervention Studies and Their Effect on Pubertal Growth.

Author(s), Journal, Year	Number and Characteristics of Adolescents	Intervention/Main Findings	Comment
Attie et al., *J Clin Endocrinol Metab*, 1990 (69)	8 GH-deficient patients with precocious puberty	Pubertal growth spurt occurred despite low GH and IGF-1 levels, driven by sex steroids.	Mixed: Emphasizes role of sex steroids
Soliman et al., *Indian J Endocrinol Metab*, 2014 (70)	Review study on global adolescents	Balanced nutrition is critical for normal pubertal progression and growth spurts.	Positive: Nutrition supports development
Yackobovitch-Gavan et al., *Horm Res Paediatr*, 2022 (71)	98 short, lean boys aged ≥10 years	Protein-rich supplements maintained growth and body composition after 1 year.	Positive: Effective for lean children
Günther et al., *Br J Nutr*, 2011 (72)	219 children, DONALD cohort	No association between energy density and age at pubertal onset or fat mass.	Mixed: Limited role of energy density
Torún et al., *Arch Latinoam Nutr*, 1995 (73)	360 stunted pubertal girls in Guatemala	Nutritional supplementation improved IGF-I secretion and growth response.	Positive: Addressing stunting
Beckett et al., *J Clin Endocrinol Metab*, 1997 (74)	18 diabetic and non-diabetic adolescents	Efficiency of dietary protein utilization increased during puberty.	Positive: Protein's role highlighted
Williams & Jesson, *Curr Opin HIV AIDS*, 2018 (75)	HIV-infected adolescents globally	ART and nutritional programs improved growth and delayed pubertal deficits.	Positive: Combined interventions beneficial
Prentice et al., *Am J Clin Nutr*, 2013 (76)	Global analysis of stunted adolescents	Nutritional interventions during adolescence can support catch-up growth.	Positive: Adolescence as recovery window
Durda-Masny et al., *Anthropol Anz*, 2019 (77)	243 Polish girls	Higher BMI accelerated pubertal onset and growth markers.	Mixed: BMI influences pubertal timing
Ganmaa et al., *JAMA Pediatr*, 2023 (78)	8,851 children in Mongolia	Weekly oral vitamin D3 (14,000 IU) for 3 years had no impact on linear growth.	Negative: No growth effect from vitamin D
Villagomez & Ramtekkar, *Nutrients*, 2014 (79)	Review of children with ADHD	Children with ADHD had reduced vitamin D, zinc, iron, and magnesium levels.	Mixed: Benefits depend on correcting deficits
Zhao A et al., Nutr Rev. 2025	Children and adolescents in 50 RCT studies	Iron was found to increase weight (0.52 kg, 95% CI: 0.12-0.93 kg), while multiple micronutrient was found to increase height (0.87 cm, 95% CI: 0.16-1.59 cm)	Compared to placebo, supplementation with iron and MMN was associated with 5.81 g/L and 4.82 g/L incremental increases in hemoglobin
Hirsch et al., *J Nutr*, 2020 (81)	Adolescents from rural Ethiopia	Iron and zinc supplementation improved height and weight gain.	Positive: Supports growth in deficiencies
Ahmed et al., *Am J Clin Nutr*, 2012 (82)	1,000 Bangladeshi adolescents	Iron and folate supplementation improved growth velocity and hemoglobin levels.	Positive: Effective micronutrient therapy
Muthayya et al., *Eur J*	Indian children	Vitamin D and calcium improved	Positive: Bone and

Clin Nutr, 2009 (83)	aged 6–15 years	bone density and growth velocity.	linear growth improved
Grantham-McGregor et al., *Lancet*, 2007 (84)	Global stunted children	Multiple micronutrients improved cognitive and physical growth.	Positive: Broad supplementation benefits
Abrahams et al., *Nutrients*, 2021 (85)	Adolescents from South Africa	Zinc improved IGF-I levels and height-for-age scores.	Positive: Zinc critical for adolescent growth
Lopez-Sanchez et al., *J Pediatr Endocrinol Metab*, 2016 (86)	European children and adolescents	Magnesium-rich diets improved bone mineral density and pubertal growth markers.	Positive: Magnesium vital for bone health
McCormick et al., *J Nutr Metab*, 2019 (87)	Review of adolescent nutrition interventions	Multivitamins and balanced macronutrients improved growth in undernourished adolescents.	Positive: Fills dietary gaps effectively

The studies summarized in Table 4 highlight the critical role of targeted nutritional interventions in supporting pubertal growth and addressing deficiencies that impede development. The findings emphasize the importance of balanced diets, specific nutrient supplementation, and tailored strategies in optimizing growth during adolescence.

Balanced nutrition emerges as a key determinant of normal pubertal progression and growth spurts. Multiple studies demonstrate the effectiveness of protein-rich diets and balanced macronutrient intake in maintaining growth and improving body composition. For example, protein supplementation in short, lean boys supported sustained growth and healthy weight gain,[72] reinforcing the role of protein as a vital macronutrient during puberty. Similarly, studies in stunted populations highlight the potential for nutritional rehabilitation to extend growth periods and achieve catch-up growth[74,77] underscoring the importance of timely interventions.

Overall, the findings in Table 4 highlight that nutritional interventions are most effective when tailored to the specific needs of the population, considering factors such as age, baseline nutritional status, and coexisting conditions. While significant progress has been made in addressing undernutrition and deficiencies, the variability in outcomes across studies underscores the need for continued research and investment in context-specific nutritional strategies. These efforts are critical to ensuring optimal growth and development during the pubertal phase, particularly in vulnerable populations.

Table 5: Summary of macronutrient intervention outcomes on pubertal growth.

Key Topics	Number of Studies	Total Participants	Category
Protein-rich diets, improved body composition	5	472	Positive Outcomes
Animal vs. vegetable protein, caloric imbalance	3	269	Mixed Outcomes
Low-protein, high-calorie diets worsened growth	1	37	Negative Outcomes
Summary of macronutrient interventions	9	778	Positive in Deficient Populations

The table highlights the role of macronutrient interventions, particularly protein and caloric intake, in influencing pubertal growth outcomes. Among the nine studies analyzed, the majority (55.6%) reported positive outcomes, with protein-rich diets showing improvements in body composition and supporting healthy growth trajectories in adolescents.[57,58,60,72,75] These interventions were particularly effective in undernourished or lean populations, emphasizing the significance of adequate protein intake during this critical growth period.

Table 6: Summary of micronutrient intervention outcomes on pubertal growth.

Key Topics	Number of Studies	Total Participants	Category
Iron, zinc, vitamin D improving growth and hemoglobin levels	7	12,425	Positive Outcomes
Vitamin D and multivitamins improving markers, limited growth	4	13,456	Mixed Outcomes
Total summary of micronutrient and mixed interventions	11	25,881	Positive in Deficient Populations

The table provides a comprehensive overview of the effects of micronutrient interventions on pubertal growth, highlighting their generally positive impact. Among the 11 studies analyzed, the majority (63.6%) reported

positive outcomes, demonstrating the beneficial role of iron, zinc, and vitamin D supplementation in improving linear growth, hemoglobin levels, and overall nutritional status.[37–39,42,82,83,86] These interventions were particularly effective in addressing deficiencies in vulnerable adolescent populations, underscoring the importance of targeted supplementation in resource-limited settings.

DISCUSSION

The findings across the six tables collectively underscore the critical role of nutrition in determining the trajectory of pubertal growth. Macronutrient adequacy, especially protein intake, has a significant positive impact on growth and body composition. Studies consistently demonstrate that protein-rich diets support lean body mass development and enhance pubertal growth velocity, particularly in undernourished or lean adolescents.[57,58,60,72,75] The influence of protein source is particularly noteworthy; animal protein accelerates pubertal timing, while vegetable protein appears to delay it, emphasizing the importance of protein quality in nutritional interventions.[56,63,73] These insights have direct clinical applications, suggesting that dietary counseling for adolescents should prioritize high-quality protein sources to optimize growth.

Micronutrient supplementation, particularly with iron, zinc, and vitamin D, has shown substantial benefits for adolescents experiencing deficiencies. Interventions addressing these deficiencies have improved height velocity, weight gain, and hemoglobin levels in resource-limited settings.[37,38,39,42,82,83,86] Zinc and vitamin D supplementation, in particular, play a key role in supporting bone health and hormonal pathways that drive pubertal development.[39,84,86] However, the mixed outcomes from some studies, such as limited effects of vitamin D on linear growth, suggest that supplementation is most effective when combined with addressing broader dietary deficits.[41,43,79,81] These findings highlight the need for comprehensive micronutrient strategies that are context-specific and tailored to individual deficiencies.

The effects of caloric intake on pubertal growth highlight the complex interplay between nutritional adequacy and metabolic health. High-calorie diets have been linked to earlier puberty and increased IGF-1 levels, but they also carry risks of adiposity and metabolic imbalance, particularly when protein intake is insufficient.[59,61,62,64] This suggests that caloric interventions should focus not only on quantity but also on dietary quality to ensure balanced macronutrient intake. For adolescents with obesity, high-protein, calorie-controlled diets have been effective in reducing fat mass while maintaining growth, providing a viable strategy for addressing obesity-related pubertal delays.[57,58]

Undernutrition and stunting remain major barriers to achieving optimal pubertal growth. Delayed puberty, reduced growth spurts, and long-term impacts on adult height are common consequences of early-life malnutrition.[16,19,23,30,31] Nutritional rehabilitation has demonstrated potential for reversing some of these effects, with stunted children showing delayed but extended growth periods when provided with adequate nutrition.[18,32,74,77] Catch-up growth in undernourished children also underscores the critical role of timely interventions, although rapid recovery can sometimes lead to early puberty, emphasizing the need for gradual and sustained nutritional support.[17,33,34]

Mixed interventions combining micronutrient supplementation with broader dietary improvements, such as multivitamins or macronutrient optimization, have shown significant promise in improving both growth and overall health. These interventions are particularly effective in populations with complex nutritional needs, such as HIV-infected adolescents or those recovering from chronic illnesses.[76,80,88] By addressing multiple deficiencies simultaneously, these strategies not only enhance growth outcomes but also support broader developmental milestones. Clinical applications include integrating nutritional interventions into broader public health strategies and school-based programs to ensure sustained benefits.[85,88]

Finally, emerging trends, such as the increasing adoption of plant-based diets in high-income countries, highlight new challenges in adolescent nutrition. Dietary shifts that reduce intake of critical vitamins like A, D, and B12 must be carefully managed to avoid micronutrient deficiencies that impair growth and development.[44,45] Similarly, low-protein, high-calorie diets pose risks for metabolic health and growth, particularly in urbanizing populations with access to processed foods.[64,66] Addressing these challenges requires proactive dietary planning, public education, and continued research into the long-term effects of dietary patterns on pubertal growth.[67,68,69]

CONCLUSION

Pubertal growth represents a vital developmental milestone, critically dependent on adequate nutrition. This review highlights that both undernutrition and overnutrition can adversely affect pubertal timing, growth velocity, and final adult height. Protein intake—especially from high-quality sources—plays a central role in supporting growth, while balanced caloric intake ensures hormonal regulation and skeletal development. Micronutrients such as iron, zinc, vitamin D, and calcium are equally essential for bone health, hemoglobin synthesis, and endocrine function during puberty.

Nutritional interventions, particularly when tailored to individual needs and local dietary deficiencies, are effective in improving growth outcomes. Evidence from global studies suggests that timely supplementation, balanced macronutrient intake, and integrated public health programs are essential for mitigating stunting, promoting catch-up growth, and ensuring healthy

pubertal progression. Emerging dietary transitions and double burdens of malnutrition in both low- and high-income countries require proactive, evidence-based strategies to optimize adolescent health.

Authors' Contributions

A.S. conceptualized and designed the review, supervised manuscript development, and critically revised the content. F.A., S.A., N.A., and N.H. contributed to the literature review, data collection, and drafting of the manuscript. A.E. and S.E. participated in data interpretation, manuscript editing, and critical revision. N.A.A. contributed to synthesis of evidence, drafting, and final formatting. N.S. provided expertise in public health perspectives, data analysis, and review of environmental and socioeconomic factors. A.K. assisted in literature review, pharmacologic considerations, and final proofreading. All authors reviewed and approved the final version of the manuscript for submission.

Conflict of interest

The authors declare no conflicts of interest related to this work.

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