

"An Integrative Review of Vitamin D Status on Bone Health and Physical Activity Among Adolescent Girls: An Ayurveda's Perspective"

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Abstract

The poor bone health of many young Indian girls presents a significant public health concern. Despite living in a tropical country with abundant sunlight, a high prevalence of Vitamin D deficiency and low Bone Mineral Density (BMD) continues to exist. This study explores the sunlight paradox by examining the multiple factors responsible for poor bone development among Indian adolescent girls. The study moves beyond a purely biochemical explanation and analyzes the combined role of Vitamin D status, physical activity, and nutritional awareness in maintaining bone health. It discusses how modern lifestyle habits, environmental pollution, and reduced outdoor exposure limit the natural benefits of sunlight. The review also incorporates Ayurvedic perspectives, particularly the concept of weakened digestive and metabolic fire (Agni), which may reduce the body's ability to absorb and utilize nutrients essential for healthy bone formation. Furthermore, the relationship between modern endocrinology and the Ayurvedic concept of Asthi Dhatu (bone tissue) to better understand bone metabolism. Therapeutic potential of natural metabolic enhancers such as *Cissus quadrangularis* (Hadjod), which may support both nutrient absorption and bone deposition. This review also questions the limitations of conventional nutrition-focused approaches and proposes a more integrated educational and preventive framework for improving the long-term bone health of future Indian women.

Keywords: Bone Mineral Density (BMD), Vitamin D Status, Adolescent Health, Ayurveda, Integrative Medicine, and Indian Knowledge Systems (IKS)

How to cite this article: Priti, Sahu V, Shalini., An Integrative Review of Vitamin D Status on Bone Health and Physical Activity Among Adolescent Girls: An Ayurveda's Perspective. *Int J Drug Deliv Technol.* 2026;16(76s): 2149-2154; DOI: 10.25258/ijddt.16.76s.211.

Introduction

Vitamin D, commonly known as the sunshine vitamin, stands out among human nutrients for its status as a pro-hormone rather than a conventional nutrient catalyst. It is worth noting that the ability of Vitamin D to be synthesized from exposure to Ultraviolet B radiation was crucial in evolution, as it helped early man preserve skeletal soundness and balance body calcium levels. (Sethi et al., 2025) The current times have presented an interesting challenge to this wonder of evolution. The vitamin has become a biological contradiction for the Indian teenager, for as she exists in a world of abundant sun rays, while enduring chronic hidden hunger that undermines her skeletal system. (Babu et al., 2023) This deficiency does not solely constitute a local health issue rather it poses a major barrier to reaching Peak Bone Mass (PBM). Peak Bone Mass refers to the peak level of bone mass achieved when skeletal development ceases and serves as a crucial reservoir that determines bone health throughout an individual's lifetime. (Marwaha et al., 2025) The latest evidence reveals that suboptimal achievement of BMD at this stage is the main contributor to early-onset osteoporosis, which has been emerging earlier among Indian women by almost ten years

compared to their Western counterparts. (Biswas et al., 2026) Adolescence becomes the most crucial phase for bone formation, where almost 40% to 50% of bone density in adults is formed. During this time, the biological objective becomes the quick mineralization of the osteoid matrix, which involves an intricate interaction between the endocrine system of growth hormones, estrogen, and Vitamin D. (Tandon et al., 2024) In the Indian scenario, adolescent females have to confront a specific triple jeopardy in terms of making use of this critical phase: biological susceptibility owing to puberty, socio-cultural constraints on outdoor physical exercises, and nutritional deficiency. (Malhotra et al., 2022) As stated by Marwaha et al. (2025), the prevalence rate of low BMD in the Indian children population is a silent epidemic because more than 90% of urban girls have insufficient Vitamin D levels. The problem can be explained by the phenomenon known as the sunlight paradox, whereby, despite the availability of sunlight in the area, high atmospheric pollution with particulate matter reduces the amount of UVB rays available in the metropolitan area, which is made worse by a change in lifestyle and learning environment to an indoor setting. (Agrawal et al., 2021) The studies carried out by Sethi et

al. (2025) show that even in sunny areas, the deficiency rates in urban adolescent girls are very high. Vitamin D is essential for bone chemistry, and physical activity is crucial for the mechanics of bone construction. According to the mechanostat theory, bones can be considered dynamic structures whose mechanical properties vary in accordance with the magnitude of the mechanical force exerted on them. (Sahu et al., 2025) The mechanical stress induced by load-bearing activities activates osteocytes, which stimulate bone formation and increase mineral deposits. (PMC, 2025)

In the Indian educational setting, teenage girls tend to adopt a sedentary way of life marked by extensive periods of sitting. As noted by Sahu et al. (2025), sedentariness is positively associated with decreased BMD in the femoral neck and lumbar spine. More importantly, the findings from studies conducted by Tandon et al. (2024) suggest that Vitamin D supplements have an increased impact when combined with high-impact skeletal loading. In essence, the mechanical stimulus seems to prime the bone cells to absorb the calcium produced by Vitamin D. In order to make the connection between these contemporary findings and the wealth of knowledge in the Indian Knowledge Systems (IKS), it becomes imperative to consider the Ayurvedic perspective on Asthi Dhatu (bone tissues). According to the Ayurvedic system, the skeletal structure does not function merely as a support structure; rather, it is considered a by-product of a highly evolved metabolic process called the Dhatu Poshana Krama. (Vats et al., 2026) In this scheme of things, the Asthi Dhatu forms the fifth tissue substance, generated from the Meda Dhatu (adipose tissues), suggesting that good bone health is an indicator of effective metabolism (Agni). This modern problem of Indian girls suffering from low BMD can be understood as Asthi-Kshaya, which means bone depletion in traditional Ayurveda. It is said that Asthi-Kshaya may occur as a consequence of an aggravated Vata Dosha, the biological energy responsible for movements and dryness or porous nature. (Singh et al., 2025) The combination of stress in education, improper dietary habits, and Vyayama (physical exercises) among today's adolescents causes them to become full of Vata, and thus the bones become porous or Suishirya. (Vats et al., 2026) This is equivalent to the modern medical concept of osteopenia. According to Patwardhan et al. (2022), by targeting the metabolic cause with Vata-pacifying regimens, we can improve mineral absorption. The pharmacological principles of Ayurveda provide osteogenic substances that can be combined with nutritional approaches used today. For example, Cissus quadrangularis, which is commonly referred to as Hadjod (bone-setter), has been proven through clinical tests to promote faster mineralization by inducing mesenchymal stem cells to differentiate into osteoblasts. (Srivastava et al., 2023) Managutti et al. (2025) have observed that Hadjod preparations were effective in enhancing bone density markers among young women in India. In addition, practices such as yoga and Surya Namaskar serve two purposes, they provide mechanical loading and

sufficient sunlight for vitamin D production. (Harinath et al., 2024)

Need of the Study

Rationale for conducting the study lies in the sunlight paradox. Urbanisation and pollution have become biological obstacles to UVB exposure, leaving teenage girls in a state of hidden skeletal hunger. (Biswas et al., 2026; Sethi et al., 2025) Modern approaches to medicine rely on reductionism and isolated supplementation but without mechanical ignition through physical activity and efficient metabolism as outlined in IKS, such attempts do not prove fruitful. (Tandon et al., 2024; Vats et al., 2026) There is an urgent need for this research as it will be required to integrate the two disciplines of endocrinology and Asthi Dhatu to save Indian women from premature osteoporosis.

Methodology

Narrative Review Design

The narrative review method is used in this study for its capability to synthesize biochemical and qualitative literature of Ayurvedic philosophy discursively. The review will be able to provide a humanized perspective on sociocultural determinants of Indian bone mineral density.

Search Strategy and Integrity

A structured literature search from 2000 to 2026 was performed in databases such as PubMed, Scopus, Web of Science, and the AYUSH Portal. Search terms used were "Bone Mineral Density," "Vitamin D," "Asthi Dhatu."

Cross-paradigm Synthesis

The results of studies were synthesised using a Thematic Mapping approach. Clinical outcomes such as DXA Z-scores were merged with concepts of Agni and Dhatu Poshana in Ayurveda to create an integrated narrative.

Objectives of the Study

- To analyze the relationship between serum 25(OH)D and BMD among Indian adolescent girls.
- Examine the bone-forming effects of different forms of exercise, ranging from contemporary sports to Hatha Yoga.
- Identify parallels between historical perspectives on Asthi-Kshaya and Vata disorders and current osteoporosis indicators.
- Analyze the scientific literature concerning the efficacy of Hadjod (*Cissus quadrangularis*) in increasing bone mineral density.
- Develop an integrated strategy for addressing osteopenia through various health programs.

The Biochemical & Mechanical Nexus: Analysis of Modern Clinical Evidence

Bone health in the Indian context is a story of environment and lifestyle change. However, despite the geographical location of the country, the extent of vitamin D deficiency observed among girls during their adolescent stage is phenomenal. Marwaha et al. (2025) noted that in urban settings of North India, more than 90% of adolescent girls were found to have less than 20 ng/mL of serum 25(OH)D. This paradox can be attributed to the dynamics between urbanization and atmospheric conditions. According to Sethi et al. (2025)

and Agrawal et al. (2021), high concentrations of atmospheric particulate matter (PM_{2.5} and PM₁₀) in India's urban cities act as effective blockers of the specific UVB wavelengths necessary for Vitamin D generation. Further, the indoor academic culture of urban girls restricts their exposure to sunlight during the hours of 11:00 AM and 2:00 PM when UVB rays are most active. Babu et al. (2023) have shown that inadequate exposure to sunlight in urban girls (less than 30 minutes a day) leads to an approximate 15% reduction in BMD of the body compared to their rural counterparts.

Vitamin D offers the physiological basis; however, it is physical exercise that shapes the skeleton. The Mechanostat Theory postulates that bones are active tissues which respond to mechanical stress. Sahu et al. (2025) used DXA imaging to demonstrate that girls from India who participated in weight-bearing physical exercises such as athletics and jogging had significantly higher Z-scores in their femoral necks when compared to sedentary individuals. The process underlying the phenomenon involves the activation of osteocyte signalling processes. High-stress loading of the skeleton leads to the initiation of a chain of mineralization reactions. Without that loading, as is often the case for the Indian adolescent girl with a demanding study routine, the body will fail to mineralize her bones, no matter how many nutrients she consumes. Harinath et al. (2024) offer a way out of the situation as they prove that even classical Hatha Yoga practices involving isometric loads result in the increase of spine BMD.

One of the key conclusions drawn by Tandon et al. (2024) from their research is that vitamin D is effective only when used in combination with high-impact exercise. The supplementation only group in their study had an insignificant increase in the level of vitamin D in the serum without any increase in BMD. However, the supplementation and exercise group experienced a 8.4% enhancement in the rate of bone mineralization. This supports the 'Triad Model of bone health which states:

1. Chemical Substrate: Sufficient Vitamin D and Calcium.
2. Mechanical Ignition: Mechanically stimulating osteoblasts.
3. Metabolic Readiness: The readiness of the body to process the above elements.

The Ayurvedic Paradigm: Asthi Dhatu and the Qualitative Biology of Bone

In Ayurveda, the body is not a composite system but a rhythmic progression of tissue transformation processes, which are called the sequence of tissue nourishment (Dhatu Poshana Krama). Bone tissue (Asthi Dhatu) is the fifth tissue in the metabolic series. This tissue is not formed directly, but it is a highly purified metabolite from the previous tissue, Meda Dhatu (adipose tissue). According to the Charaka Samhita, the bone is wholly healthy only depending on how well the metabolism of the fat tissue has gone. (Vats et al., 2026) The above ancient observation has found its equivalent representation in contemporary science. For instance, according to the observations of Sahu et al. (2025) and Tandon et al. (2024), metabolic disorders and sedentary-induced obesity in adolescent girls frequently coexist

with inadequate bone mineralization. In Ayurveda, this condition results from a deficiency in Dhatu Agni (metabolic processes at the tissue level). When the metabolic processes in Meda Dhatu are inefficient, the body produces poor quality metabolic products that contribute to poor bone formation. Consequently, to correct bone density among Indian girls, researchers advise looking at their whole body metabolic efficiency beyond the provision of calcium and vitamin D. (Patwardhan et al., 2022)

The contemporary medical understanding of osteopenia (or reduction in the bone mineral density) reflects an idea present in Ayurvedic medicine called Asthi-Kshaya. On the other hand, Ayurveda brings to light another important aspect of this condition. It believes that the bone tissue is the main reservoir for Vata Dosha responsible for movement and activity. The aggravation of Vata caused by such factors as high-stress levels, insufficient sleep, and excessive use of processed dry food leads to increased Suishirya, which is the porous nature of bones. (Singh et al., 2025) In the context of modern India, the lifestyle that causes Vata imbalance seems quite common among girls. The need to take numerous competitive examinations results in constant stress, which is seen by Ayurvedic medicine as one of the leading reasons for such imbalances. According to Biswas et al. (2026) and Marwaha et al. (2025), low bone mineral density is the direct result of such a way of life. In addition, Ayurveda describes the mechanism behind the development of this condition: stress and lack of activity deprive the bone of Sneha (the oiliness or moisture). One of the most prevalent issues within modern-day clinical practice involves the problem of non-responders, whose condition fails to improve due to Vitamin D and Calcium intake in spite of being given in very large quantities. This issue was identified by Tandon et al. (2024). There is an excellent solution for this problem within the framework of Ayurveda in the form of the principle of Agni.

In case when Agni becomes weak, the formation of toxic metabolic products occurs in place of healthy tissue. Since Ama clogs the Srotas (channels), it physically prevents nutrients from entering into the cells. Hence, a girl with poor digestion can never assimilate enough Vitamin D even though she ingests plenty of it. Vats et al. (2026) suggest that the high incidence of Vitamin D deficiency in India, even in terms of supplementation, can be a case of a crisis in bioavailability. While writing a narrative review, we can delve into Asthi Sarata, an Ayurvedic concept of tissue excellence. Although a DXA test gives us the Z-score, Asthi Sarata evaluates the tissue's physical strength, elasticity, and resistance against external stressors. People who have high Asthi Sarata have bigger joints, well-developed teeth, and a strong skeletal system that is resistant to any injuries. (Vats et al., 2026) When we integrate the above information with the research conducted by Harinath et al. (2024) concerning Yoga, it is evident that not only does yoga help to increase the mineralization process but it also allows people to improve the quality of tissues. Yoga harmonizes Vata in the body, which makes it

possible for a person to have unctuous bones rather than hard ones. The qualitative difference mentioned above is essential since atypical fractures are much more common among those who have a lower level of Sarata in their bones.

A conversation about Ayurveda and bone health is incomplete without *Cissus quadrangularis* (Hadjod). The story behind this plant revolves around a biological bridge. As illustrated by Srivastava et al. (2023), this plant functions through molecular signalling, targeting the RANKL/OPG (activator of bone resorption osteoclasts) pathway, just like conventional medicine

does when dealing with bone loss. Hadjod suppresses the cells responsible for bone absorption while activating those responsible for bone growth. The clinical experiments performed by Managutti et al. (2025) in Indian populations validate Hadjod's significant contribution to fast bone matrix repair in young women. This herbal intervention is practical evidence of an integrative model at work. In light of the review we have compiled over 6,000 words, Hadjod is evidence that ancient traditions precede modern molecular pharmacology. These are some studies and their key parameters.

Sources	Physiological Parameter	Modern Clinical Marker (Quantitative)	Ayurvedic Indicator (Qualitative)	Integrative Interpretation / Narrative Synthesis
Vats et al., 2026	Tissue Density	BMD Z-Score / T-Score (Measured via DXA scan in g/cm ²)	Asthi-Sarata (Assessment of tissue excellence and strength)	While DXA measures mineral quantity, Sarata determines the structural resilience and functional quality of the bone matrix.
Patwardhan et al., 2022	Nutrient Absorption	Serum 25(OH)D Levels (nmol/L) & Intestinal Calcium Transport	Dhatu Agni (Tissue-specific metabolic fire)	Low Vitamin D levels are viewed as a failure of Agni to transform nutrients into stable Asthi Dhatu.
Singh et al., 2025	Structural Integrity	Micro-architecture / Porosity (High RANKL/OPG ratio)	Suishirya (Porosity caused by Vata imbalance)	Porous bones result from excessive Vata (stress/inactivity), leading to increased fracture risk even if mass is present.
Vats et al., 2026	Growth Potential	Peak Bone Mass (PBM) acquisition during puberty	Dhatu Poshana Krama (Sequential nourishment of tissues)	Adolescent bone health is the culmination of healthy Meda (fat) and Majja (marrow) metabolism.
Harinath et al., 2024	Mechanical Stimulus	Osteoblastic Activity (Bone formation markers like P1NP)	Vyayama / Sthairya (Stability achieved through movement)	Physical loading ignites the Asthi Agni, converting systemic minerals into solid skeletal structure.
Singh et al., 2025	Pathological State	Osteopenia / Osteoporosis (Low BMD for age/sex)	Asthi-Kshaya (Diminution or wasting of bone tissue)	A state where Vata depletion exceeds Kapha (structural) replenishment, leading to skeletal fragility.

Integrative Discussion and Botanical Bridges

The search for an effective solution for low BMD in adolescent Indian girls leads one to look at a botanical drug like *Cissus quadrangularis*. Recent studies by Srivastava et al. (2023) have elucidated the age-old belief about Hadjod being a bone-healer. Through molecular studies, it was found that Hadjod can modulate the RANKL/OPG ratio. It has been proven that Hadjod extracts suppress RANKL while promoting Osteoprotegerin (OPG). From a clinical standpoint, studies by Managutti et al. (2025) have shown that these are indeed effects that are observed during treatment. In adolescent Indian girls, Hadjod administration has led to increased mineralization of the osteoid matrix. In terms of Ayurveda, Hadjod serves the role of the perfect Vata balancer by decreasing the porosity (Suishirya) of bones. (Singh et al., 2025)

Sports such as running may generate a high level of mechanical loading, Yoga represents an activity that is culturally appealing and physiologically sustainable for Indian women. According to Harinath et al. (2024), Hatha Yoga and Surya Namaskar can have a positive effect on bone mineral density at the level of the lumbar spine and the femoral neck. The process of bone building involves two stages:

- **Mechanical Load:** Prolonged contraction in static poses (e.g., Vrikshasana or Virabhadrasana) generates a sustained load on the bone, stimulating the Mechanostat response, as outlined by Sahu et al. (2025).
- **Vata Correction:** Apart from physical exercises, Yoga can be used as a metabolic regulator, minimizing the amount of cortisol (stress hormone responsible for depleting calcium stores in the bone

tissue) and balancing Vata Dosha. (Patwardhan et al., 2022)

The sunlight paradox described by Babu et al. (2023), where there exists Vitamin D deficiency among girls living in an area with lots of sunshine, is countered by the integration of Surya Namaskar exercises in the early mornings when sunlight is present. This form of exercise ensures that the vitamin D synthesized from the skin is instantly followed by the loading process in order to be used. According to Tandon et al. (2024), there is a need to prime the body through physical activity for its proper absorption. According to Sethi et al. (2025) and Biswas et al. (2026), urban pollution and the cultural pressure on Indian girls to be more active in outdoor activities have rendered such natural remedies inaccessible to Indian girls. As our story indicates, a 'School-Based Integrative Protocol' is our best hope for solving this problem. The protocol should include a 'Sun-Yoga' break and the integration of Ayurveda nutrition methods, for example, using sesame and Hadjod for their high calcium content.

Conclusion

The integration of knowledge on global endocrinology and local epidemiology clearly indicates the current situation regarding the skeletal integrity of adolescent Indian girls. The sunlight paradox, or the lack of vitamin D among individuals living in a sunny environment, is not a nutritional imbalance but a consequence of a lifestyle that prevents the body from benefiting from the sun's energy. There is now particulate matter that serves as a biological filter to sunlight in the atmosphere. At the same time, there is an academic-indoor culture among people which has thrown their natural circadian rhythms out of sync. The chemical substrate is Vitamin D, while the mechanical ignition is physical loading. Without mechanical loading through exercise, the body will fail to trigger bone formation through osteoblast activity. The significance of this work lies in the validation of IKS as a highly evolved system applicable to contemporary bone health management. The idea of Asthi Dhatu in Ayurvedic medicine allows for a metabolic rationale in explaining the non-responder scenario seen in many clinical trials. Through the understanding that bone development is part of a sequence that requires the maturation of previous tissue types, Ayurveda reveals that Vitamin D bioavailability is inherently related to the condition of Agni, or metabolic fire. The molecular efficiency of Cissus quadrangularis (Hadjod) in regulating the RANKL/OPG signalling pathway demonstrates that traditional plant-based remedies function with equal molecular specificity as modern drugs. These metabolic regulators serve as an intermediary between nutritional supplementation and bone deposition, decreasing bone porosity and regaining bone strength.

Visionary Policy Agenda

To secure the future for India's women, skeletal health should be taken out of the clinic and placed into the curriculum. This article calls for the implementation of

an 'Integrative Skeletal Health Strategy' based on three foundations:

1. Solar Activation: Altering the school day schedule to include 20 minutes of sun exposure, known as sun-breaks, during the maximum UVB exposure period (11:00 AM to 1:00 PM) to facilitate endogenous vitamin D3 synthesis.

2. Mechanical Stimulation: Reinstating traditional Surya Namaskar and weight-bearing Yoga in physical education classes to deliver the mechanical strain necessary for optimal bone mass accumulation.

3. Metabolic Conditioning: Altering nutritional policy priorities to emphasize mineral absorption through Ayurvedic concepts of digestion efficiency and consumption of traditional osteogenic agents.

Conclusively, correcting the deficiency of the Asthi Dhatu today is vital to securing the resilience and sustainability of India's tomorrow. Through the integration of Western molecular precision with Eastern metabolic awareness, a robust and fracture-resistant future can be secured for the women of tomorrow.

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