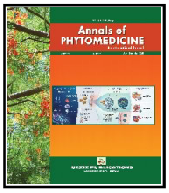
Annals of Phytomedicine 14(2): 252-262, 2025

DOI: http://dx.doi.org/10.54085/ap.2025.14.2.25

Annals of Phytomedicine: An International Journal
http://www.ukaazpublications.com/publications/index.php

Print ISSN : 2278-9839 Online ISSN : 2393-9885



Review Article : Open Access

A comprehensive review on protein power for stronger bones with reference to Indian context

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Article Info

Article history
Received 15 August 2025
Revised 16 September 2025
Accepted 17 September 2025
Published Online 30 December 2025

Keywords
Bone health
Bone mineral density
Muscles
Osteoporosis
Protein
Vegetarian diet

Abstract

Bone health is an emerging public health concern in India, particularly among ageing populations and women. While calcium and vitamin D have traditionally dominated the discourse, growing evidence highlights dietary protein as a critical factor in maintaining bone structure, supporting muscle mass and enhancing calcium absorption. This review synthesizes global and Indian research on the relationship between protein intake and bone outcomes, with a special focus on Punjab, a region marked by unique dietary patterns and a high prevalence of vegetarianism. It explores physiological mechanisms, regional nutritional trends and existing research gaps. Addressing protein adequacy through context-specific interventions could significantly improve skeletal health and positions of Punjab as a potential model for protein-focused public health strategies across India.

1. Introduction

Bone health is a vital component of overall well-being, influencing mobility, quality of life and the risk of chronic conditions such as osteoporosis and fractures. In India, the burden of low bone mineral density (BMD) is rising steadily, particularly among postmenopausal women and the elderly. Despite the tropical climate and high sun exposure, vitamin D deficiency remains widespread, increasing the risk of poor bone health. Nutritional factors, particularly calcium and vitamin D, have traditionally dominated the discourse on skeletal health; however, emerging evidence underscores the importance of dietary protein as a key contributor to bone maintenance and repair.

Proteins support bone health not only through their structural role in collagen synthesis but also by enhancing calcium absorption, muscle strength and insulin-like growth factor-1 (IGF-1) activity. However, both the quantity and quality of protein intake are crucial for obtaining these benefits. In India specifically in Punjab, dietary patterns often include a heavy reliance on cereal-based proteins, which may be lower in essential amino acids compared to animal sources. Additionally, vegetarianism is common due to cultural and religious preferences, potentially influencing protein adequacy and bone outcomes.

Adequate dietary protein intake is increasingly recognized as a vital factor in maintaining bone health among older adults (Groenendijk *et al*., 2024). The interdependence of muscle and bone tissues means that improvements in muscle strength through sufficient protein consumption may indirectly benefit bone mineral density by enhancing mechanical loading. Evidence from both observational and interventional studies indicates that protein intake above the population reference intake (PRI) of 0.83 g/kg/day is associated with improved bone mineral density (BMD) and a reduced risk of fractures in older populations. For example, individuals with higher protein consumption (approximately 1.1 g/kg/day) demonstrated significantly higher lumbar spine and hip BMD and a 64% lower risk of vertebral fractures over a five year period compared to those with lower intake. Moreover, an 18 months intervention with whey protein supplementation and resistance training led to significantly greater increases in BMD at the spine and hip in older men with osteoporosis and sarcopenia. These findings support the inclusion of higher protein intake ideally 1.0 - 1.2 g/kg/day as part of a holistic dietary strategy for the prevention and management of osteoporosis in older adults.

The importance of dietary protein in maintaining skeletal integrity among older adults was observed in a study conducted by Weaver *et al*. (2021). A large prospective cohort study involving over 2,100 community dwelling White and Black adults aged 70-79 found that individuals with higher protein intake (≥15% of total energy intake) exhibited significantly greater bone mineral density (BMD) at the hip, lumbar spine and whole body compared to those with lower intake (<13%). This higher intake was also associated with a 64% reduced risk of vertebral fracture over five years, independent of age, sex, race, physical activity, calcium and vitamin D intake. The current recommended dietary allowance (RDA) of 0.8 g/kg/day may be insufficient for optimal bone health in older populations and that higher protein consumption could serve as a modifiable nutritional strategy to prevent osteoporosis and reduce fracture risk. Punjab

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presents a unique regional case for exploring the relationship between protein intake and bone health. Despite relatively better economic indicators compared to other Indian states, nutritional imbalances still continue. Diets rich in carbohydrates and low in high-quality proteins are common and lifestyle factors such as physical inactivity and limited nutritional awareness may further increases bone health challenges.

This review aims to synthesize the current scientific evidence on the role of dietary protein in bone health with a particular focus on the Punjabi population. It explores the physiological mechanisms, dietary trends, regional data gaps and potential interventions that could guide future research and public health strategies.

2. Physiology of bone health and the role of protein

Bone is a dynamic tissue that undergoes continuous remodelling throughout life. This process involves the coordinated actions of osteoblasts (bone-forming cells) and osteoclasts (bone-resorbing cells) which are regulated by hormonal, mechanical and nutritional factors. Peak bone mass is typically achieved in early adulthood, after which bone resorption gradually begins to outpace bone formation increasing the risk of fractures, particularly in older adults (Rizzoli *et al*., 2014).

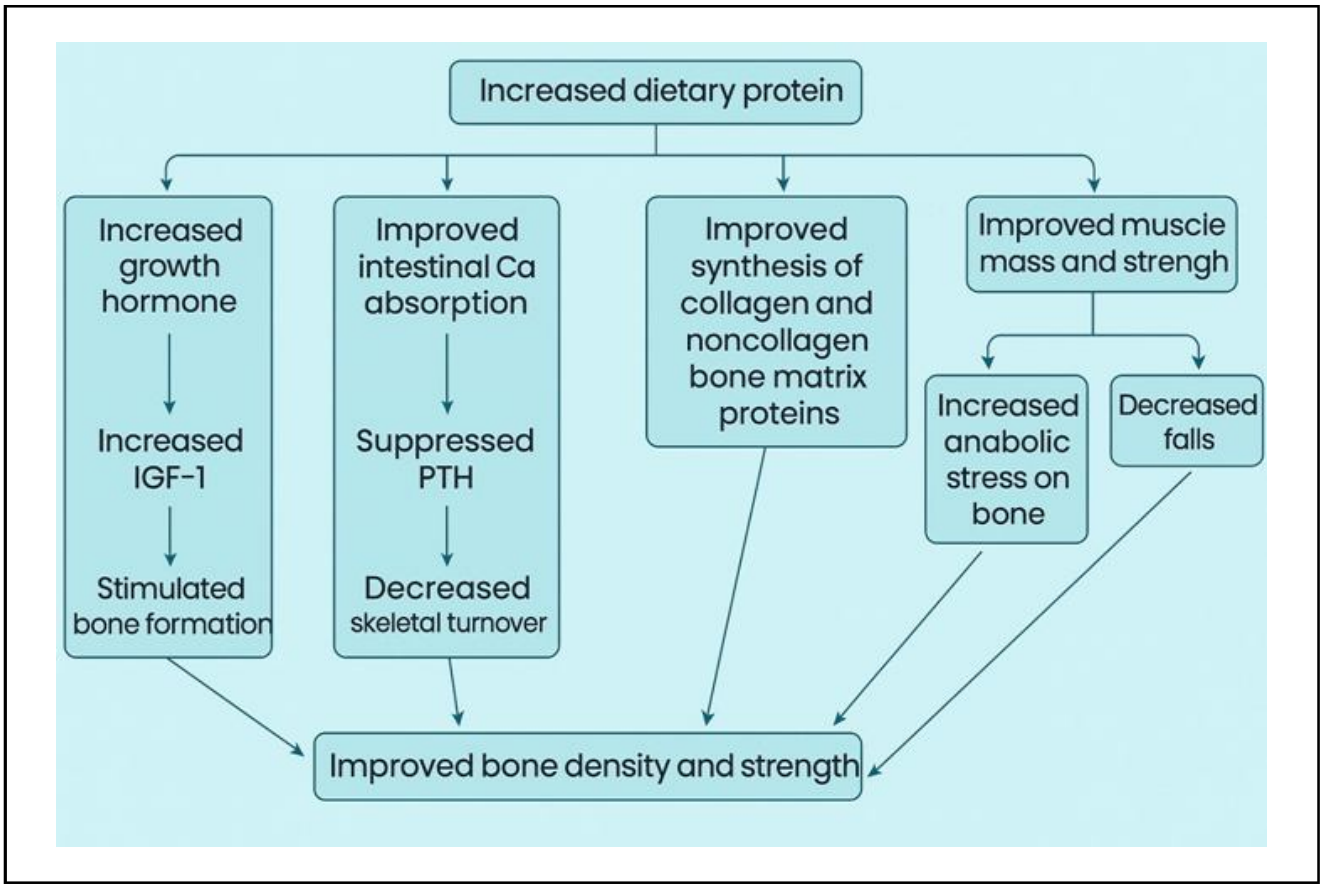

Figure 1: Potential mechanism by which increased dietary protein impacts bone health. (Gaffney- Stomberg *et al.*, 2009 and Surdykowski *et al*., 2010)

Protein plays a critical role in maintaining skeletal integrity, not only as a structural component of bone matrix but also as a regulator of bone remodelling (Figure 1). Among the key protein families involved in bone biology, 14-3-3 proteins have emerged as versatile regulators influencing the differentiation and activity of osteoblasts, osteoclasts and chondrocytes. Specific isoforms, such as 14-3-3ε and 14-3-3θ, have been shown to enhance osteogenic differentiation and facilitate mechano-transduction in osteocytes, respectively, thereby supporting bone formation and adaptation to mechanical stress. Moreover, 14-3-3 proteins modulate transcription factors like MITF and interact with signalling pathways such as PI3K/Akt and Wnt/β-catenin, which are crucial for osteoclastogenesis and chondrogenesis. These multifaceted roles underscore the importance of 14-3-3 proteins as central nodes in bone metabolic regulation, highlighting their potential as therapeutic targets for bone degenerative diseases and as biomarkers for bone health (Zhou *et al*., 2024).

3. Biomarkers and protein effects

Ballard *et al*. (2005) explored the impact of protein supplementation combined with a 6-month strength and conditioning programon markers of bone turnover and insulin-like growth factor I (IGF-I) in healthy young adults. Fifty-one participants (aged 18-25) received either a protein supplement (2.2 g/kg/day) or an isocaloric carbohydrate supplement (1.1 g/kg/day), alongside a structured exercise regimen involving alternating resistance training and running. The study reported a significantly greater increase in plasma IGF-I levels in the protein group compared to the carbohydrate group (p =

0.01), along with a trend toward higher bone alkaline phosphatase (BAP), indicating enhanced bone formation. Additionally, urinary N-telopeptide of collagen cross-links (NTx) a marker of bone resorption was also significantly higher in the protein group (p = 0.04), though it declined in both groups over time. These biomarker shifts suggest that protein supplementation during exercise promotes a favourable bone remodelling environment, possibly through IGF-I mediated pathways. Importantly, despite the modest acid load of the protein supplement, adequate calcium intake (up to 1850 mg/day) in both groups may have mitigated any acidogenic effects, reinforcing the argument that high protein diets do not compromise bone health when calcium intake is sufficient. This study adds mechanistic support to the anabolic role of protein in bone maintenance particularly during physical stress and remodelling.

Table 1: Role of proteins in several aspects of bone physiology

S. No.	Major role in physiology	Mechanism	References
1.	Structural role	Approximately 50% of bone volume and one-third of bone mass are composed of protein, primarily in the form of collagen. Collagen provides the framework upon which minerals such as calcium and phosphorus are deposited giving the bone its strength.	Heaney and Layman (2008)
2.	Supports muscle mass	Protein is essential for skeletal loading and balance. Stronger muscles reduce fall risk and promote bone strength through mechanical stimulation making protein intake double important for fracture prevention.	Darling *et al.* (2009); Bauer *et al.* (2013)
3.	Hormonal influence	Dietary protein stimulates the production of insulin-like growth factor 1 (IGF-1), a hormone that promotes bone formation and reduces bone resorption.	Dawson-Hughes *et al.* (2007)
4.	Physiological and nutritional influence	Relationship between protein and bone health is influenced by age, sex, total nutrient intake, and protein source (plant vs. animal). In older adults, especially postmenopausal women, protein may help mitigate age-related bone loss and the development of sarcopenia. However, the benefits depend not only on the quantity but also on the bioavailability and amino acid composition of the protein consumed.	Paddon-Jones *et al.* (2008)
5.	Calcium absorption and metabolism	Different levels of dietary protein affect intestinal calcium absorption and hormonal markers of bone metabolism in young women. Protein intake influences calcium absorption in the intestines and reabsorption in the kidneys.	Kerstetter *et al.* (1998)

In Punjab and similar regions in India, the predominance of plant-based diets, coupled with low total protein consumption, may impair optimal bone remodelling and regeneration. Understanding these physiological underpinnings is essential for contextualizing the nutritional needs and dietary patterns of the local population.

Kerstetter *et al.* (1998) conducted a study where seven healthy participants followed two isocaloric diets (low protein: 0.7 g/kg/day and high protein: 2.1 g/kg/day) under tightly controlled metabolic conditions. Using a dual stable isotope method, the authors found that fractional calcium absorption was significantly higher on the high-protein diet (26% ± 3%) compared to the low-protein diet (19% ± 2%, p = 0.05). Importantly, the low-protein diet induced secondary hyperparathyroidism, with significant increases in serum PTH and 1,25-dihydroxy vitamin D within four days. This hormonal shift was interpreted as a compensatory response to reduced calcium absorption from the intestine under low-protein conditions. Despite a modest increase in urinary calcium on the high-protein diet, the authors concluded that improved calcium absorption and greater glomerular filtration rate not bone loss likely explained the elevated urinary calcium. This experimental evidence challenging the belief that high-protein diets harm bone by inducing calcium loss, instead showing that insufficient protein intake may impair calcium economy and increase bone resorption via hormonal dysregulation. While earlier theories suggested that high protein intake could lead to calcium loss due to increased acid load, recent studies indicate that adequate protein may enhance calcium retention and positively affect bone mineral density (BMD) when calcium intake is sufficient.

4. Role of dairy in bone health

Minerals are also vital for maintaining health and longevity, supporting functions such as bone development, nerve transmission, hormone production and heart regulation. Macro- and microelements contribute to the structure of bones and teeth (*e.g.,* Ca, P, F, Mg, Mn, B) while microelements like Cu, Fe, Mn, Mg, Se, and Zn are essential components of various enzymes (Priyanka *et al.*, 2025). Dairy foods are a primary source of calcium (50-60%) and high-quality protein (20-30%) in Western diets and their avoidance is consistently associated with reduced BMD and elevated fracture risk. Rizzoli (2022) underscores the central role of dairy products in both bone mass accrual during growth and preservation of bone strength in later life. The review consolidates evidence from both randomized controlled trials and observational studies showing that dairy consumption particularly milk, cheese and fermented products like yogurt is positively associated with bone mineral content, IGF-I production and bone microarchitecturein children and adults. Importantly, casein and whey proteins in milk not only supply essential amino acids but also stimulate IGF-I which enhances calcium absorption and promotes bone modelling. Fermented dairy products provide additional benefits by delivering probiotics and bioavailable micronutrients with several studies showing that yogurt intake

correlates with reduced hip fracture risk and better muscle-bone function. Hip fracture risk reductions of up to 26% with regular yogurt intake. While evidence on long-term fracture reduction in adulthood is mixed for milk alone, fermented dairy consistently shows protective associations. Regular intake of dairy products is a practical and effective strategyto support skeletal health across the lifespan especially in populations with limited dietary diversity or plant-based diets.

Proteins derived from dairy sources, such as whey protein and milk basic protein (MBP), may play a beneficial role in bone health. A clinical study involving 66 post-menopausal women conducted at the University of Illinois, found that 40 g isolated soy protein (ISP) per day (containing 90 mg total isoflavones) significantly increased (approximately 2%) both bone mineral content and density in the lumbar spine after 6 months (Pushpangadan *et al*., 2014).

A systematic review and meta-analysis evaluated nine randomized controlled trials and found that MBP supplementation significantly reduced urinary N-terminal telopeptides (NTx) a key marker of bone resorption especially when supplementation exceeded 12 weeks. Additionally, whey protein was shown to significantly increase levels of insulin-like growth factor-1 (IGF-1) a hormone that stimulates bone formation and enhances osteoblast activity. However, the analysis did not find consistent improvements in bone mineral density (BMD) at the lumbar spine or hip. While protein supplementation may not directly increase BMD in the short term, it can favourably influence bone turnover markers indicating a potential long-term benefit in maintaining skeletal health (Khodadadi *et al*., 2024). In a study conducted by Yamini *et al*. (2023), 100-500 mg/kg of ethanolic extract of pomegranate seed was found to Increase bone formation markers and alkaline phosphatase activity by 32 and 69%. Also improved growth of tibia and bone mineral density (BMD) was observed.

Role of milk proteins and their derived peptides in bone metabolism go well beyond their traditional nutritional value as sources of amino acids and calcium (Bu *et al*., 2021). It is evident from both in vitro and in vivo studies showing that milk proteins especially casein and whey fractions positively influence osteoblast activity inhibit osteoclastogenesis and enhance calcium bioavailability. Numerous factors such as bone morphogenetic protein-2 (BMP-2) are known to affect osteoblast differentiation and activity (Giaze *et al*., 2017) Components such as lactoferrin (LF), osteopontin (OPN), osteoprotegerin (OPG) and milk basic protein (MBP) have been shown to directly stimulate bone formation markers like RUNX2, ALP, and OCN, while simultaneously downregulating bone resorption markers like RANKL and TRAP. Importantly, bioactive peptides derived from these proteins during gastrointestinal digestion retain or even enhance these functions. For example, caseinophosphopeptides (CPPs) not only bind calcium efficiently and improving its absorption but also promotes osteoblast proliferation and differentiation. MBP supplementation in clinical trials has shown significant improvements in BMD and reduced bone resorption markers in both pre and postmenopausal women. Furthermore fermented milk products enriched with probiotics such as *Lactobacillus helveticus* have been demonstrated to improve bone mineral content (BMC) and bone strength in animal models (Bu *et al*., 2021). This review reinforces the concept that milk proteins function as bioactive agents interacting with key signalling pathways such as Wnt/β-catenin, TGF-β/BMP, and PI3K/Akt to modulate the bone remodelling process. These findings support the inclusion of high quality dairy protein as a strategic dietary component in osteoporosis prevention and management frameworks, especially in populations at high risk of dietary protein deficiency.

5. Beyond protein: Supporting nutrients for bone integrity

The synergistic roles of vitamins K and D in promoting bone health through improved calcium metabolism. Aaseth *et al*. (2024) provide the mechanisms by which vitamin K, particularly vitamin K2 (menaquinone), activates bone-specific proteins like osteocalcin and matrix Gla protein (MGP) by γ-carboxylation. These activated proteins help incorporate calcium into the hydroxyapatite matrix of bone and inhibit vascular calcification. Theinsufficient vitamin K status leads to under carboxylated osteocalcin (ucOC) which is associated with reduced BMD and increased fracture risk. Several randomized controlled trials and meta-analyses confirm that vitamin K2 supplementation (especially MK-4 and MK-7) improves lumbar spine BMD and reduces fracture risk in postmenopausal women, particularly when co-administered with vitamin D and calcium. Moreover, the molecular effects of K2 include Wnt/β-catenin pathway activation, SXR receptor modulation, and inhibition of RANKL all of which favour bone formation over resorption. While calcium and vitamin D remain central to bone health the addition of vitamin K especially in populations with suboptimal status may enhance the effectiveness of osteoporosis prevention strategies. These insights are especially relevant in Indian settings where vitamin D insufficiency and limited intake of fermented rich foods may compromise bone outcomes despite adequate calcium intake. Consumption of millets or whole grains with pulses or legumes is associated with alleviating non-communicable diseases, as they consist of good quality protein, minerals (iron and calcium) in addition to dietary fiber, phenols and antioxidants (Joshi *et al*., 2024).

There is a vital role of dietary protein, particularly when combined with adequate calcium, in maintaining bone strength and reducing fracture risk in older adults. A large-scale, two-year cluster randomized controlled trial found that supplementation with dairy-based protein and calcium significantly reduced the incidence of fractures and falls among institutionalized elderly residents. Participants who received an additional 12 g/day of protein and 562 mg/day of calcium through milk, yoghurt and cheese achieved an average intake of 1.1 g protein/kg body weight and 1142 mg calcium/day. Compared to controls, the intervention group experienced a 33% reduction in all fractures, a 46% reduction in hip fractures and an 11% reduction in falls with no difference in mortality. These results demonstrate that improving protein and calcium intake through accessible foods like dairy products can be an effective, non-pharmaceutical strategy to enhance bone health and reduce injury risks in aging populations (Iuliano *et al*., 2021).

6. Dietary protein intake in India and Punjab

India faces a unique nutritional paradox: while undernutrition persists in several regions, there is also a rise in non-communicable diseases due to poor quality diets. Protein intake remains a critical concern particularly because a significant proportion of the Indian population follows a predominantly cereal-based vegetarian diet. This dietary pattern often leads to an inadequate intake of high-quality protein, which may compromise both muscle and bone health. According to

the Indian Council of Medical Research (2020), the recommended dietary allowance (RDA) for protein is approximately 0.8-1.0 g/kg body weight per day for adults. However, data from national surveys such as the National Nutrition Monitoring Bureau (2017) and National Family Health Survey (2021), indicate that large segments of the population fall short of this requirement especially among rural and lower income groups.

6.1 Punjab: A regional view

Punjab is often considered a relatively affluent state with better food security compared to many parts of India. However nutritional transition shift from traditional diets to more processed, high-calorie and low nutrient foods which led to dietary imbalances. Despite the state's agricultural wealth and dairy consumption, recent data suggest that protein quality and distribution across meals are suboptimal. Ministry of Health and Family Welfare *et al*. (2019) and The Comprehensive National Nutrition Survey (CNNS) (2016-2018) highlighted that protein adequacy in North India is uneven, with Punjab showing moderate intake levels but a heavy reliance on plant-based sources, such as wheat and legumes. While dairy consumption is relatively high, intake of meat, fish, and eggs is low due to cultural and religious practices. This leads to lower intake of essential amino acids such as lysine and methionine, which are crucial for effective collagen synthesis and bone matrix development.

Jain and Verma (2018) in Ludhiana, Punjab, offers valuable insight into how targeted dietary interventions can influence bone health in postmenopausal women. The study involved 60 women aged 45-55 years who were classified as osteopenic or osteoporotic based on their bone mineral density (BMD) measured *via* DEXA scans. Over a four-month period, the participants received twice-monthly nutrition counselling (NC) sessions focused on improving dietary intake of key nutrients such as calcium, vitamin C, iron and phosphorus. Post-intervention results showed a statistically significant improvement in both serum calcium levels (from 7.82 mg/dl to 8.99 mg/dl) and BMD T-scores (from 2.2 to 2.01), alongside a reduction in the percentage of osteoporotic women (from 33.3% to 20%). Dietary assessments revealed a notable increase in the consumption of milk and milk products, green leafy vegetables and fruits, while intake of sugar and visible fats declined. Although, protein intake showed only a marginal increase (from 48.18 g to 49.05 g/day), the overall dietary pattern shifted toward a more nutrient-rich profile, reinforcing the interconnected role of macronutrients and micronutrients in bone health. The effectiveness of localized, nutrition based educational interventions in improving bone outcomes among high-risk populations and underscores the importance of region-specific data in designing public health strategies for skeletal health improvement in Indian women.

6.2 Factors influencing protein intake in Punjab

6.2.1 Cultural and religious beliefs

A significant portion of the Punjabi population is vegetarian, especially among women and the elderly which limits access to complete proteins.

6.2.2 Gender disparity

Women, especially in rural households, often consume less protein than men, partly due to cultural norms and food distribution practices.

6.2.3 Socioeconomic status

Although Punjab fares better than other states, protein-rich foods like pulses, dairy, and meat are still under-consumed among economically disadvantaged groups.

6.2.4 Urbanization

The shift to urban lifestyles has increased consumption of refined foods while reducing traditional nutrient-dense preparations.

These factors contribute to protein-energy malnutrition and micronutrient deficiencies that indirectly affect bone health by limiting the availability of building blocks required for bone remodelling and maintenance. Given the interplay between protein intake and skeletal health understanding and addressing regional dietary patterns is essential to develop targeted nutrition interventions for populations in Punjab and beyond.

7. Evidence from research

Numerous studies across the globe and within India have explored the role of dietary protein in bone health providing insights that can inform regional health interventions. While much of the evidence comes from global studies recent regional data suggest that protein intake both in quantity and quality significantly influences bone mineral density (BMD) and fracture risk especially in older populations. Sefton *et al*. (2020) investigated the impact of whey protein (WP) supplementation on bone metabolism during Army initial entry training (IET), a high-stress physical regimen known to increase musculoskeletal injury (MSI) risk. Over a 9-week period, 90 healthy male soldiers were assigned to receive either a daily WP shake (38.6 g protein/day). The researchers assessed serum biomarkers including P1NP (a marker of bone formation), CTX (a marker of bone resorption), vitamin D and calcium at baseline and post-training. Although, both bone formation and resorption markers were elevated at baseline suggesting pre-existing bone stress no significant differences were observed between the WP and placebo group for any marker across time. Notably, vitamin D levels increased slightly due to outdoor training exposure while serum calcium remained marginally below optimal levels throughout. Regression analysis revealed that age and fat mass were negatively associated with bone formation while age was the sole significant predictor of bone resorption highlighting physiological factors over supplementation in predicting bone metabolism. Despite previous evidence suggesting whey protein benefits bone health, the authors conclude that in young, under-fueled recruits with high baseline bone turnover, short-term supplementation may be insufficient to elicit measurable changes. This study underscores the need for adequate total caloric intake, timing, and baseline nutrient status when assessing the efficacy of protein on skeletal outcomes.

PROTAGE study group (Bauer *et al*., 2013) an international expert panel convened by the European Union Geriatric Medicine Society (EUGMS), issued evidence-based recommendations calling for significantly higher protein intake in older adults than the current RDA. Their position paper emphasizes that the RDA of 0.8 g/kg/day is insufficient to maintain muscle mass, prevent sarcopenia and support functional recovery in older individuals. The group recommends a daily intake of 1.0 to 1.2 g/kg body weight for healthy older adults, increasing to 1.2-1.5 g/kg/day for those with chronic or acute diseases, and up to 2.0 g/kg/day in cases of severe illness,

injury or malnutrition. The recommendations highlight the age-related decline in anabolic responsiveness often termed "anabolic resistance," which requires larger per-meal protein doses (25-30 g per meal) with around 2.5-2.8 g of leucine to stimulate muscle protein synthesis effectively. Contrary to persistent myths, the report confirms that higher protein intake does not harm renal function in healthy older adults. Additionally, the position paper underscores the synergistic effects of dietary protein and resistance training advice for both as part of a comprehensive strategy to prevent frailty, osteoporosis and disability. These recommendations serve as a robust framework for developing context specific dietary protein guidelines especially in aging populations in India where protein intake often falls below global recommendations.

7.1 Global evidence

Several large-scale studies and meta-analyses have concluded that higher dietary protein intake especially from animal sources is associated with increased bone mineral density (BMD) and reduced fracture risk. Darling *et al*. (2009) synthesized data from 23 studies and concluded that higher protein intake was associated with a 0.6-1.5% increase in BMD at key sites like the lumbar spine and femoral neck particularly when calcium intake was also adequate. A randomized controlled trial (RCT) by Dawson-Hughes *et al*. (2007) on 120 elderly participants showed that daily protein supplementation of 20 g resulted in a significant 8% increase in bone turnover markers such as serum osteocalcin and Insulin-like growth factor 1 (IGF-1), indicating improved bone formation. Heaney and Layman (2008) provide a synthesized view of the complex relationship between dietary protein and bone health challenging that high protein intake especially from animal sources adversely affects bone. While high protein diets with increased urinary calcium excretion and bone resorption, this paper clarifies that suchcalciumloss is often offset by enhanced intestinal calcium absorption when adequate calcium is consumed. The protein plays a dual role by providing thecollagen matrix essential for bone structureandstimulating IGF-1, a key hormone in bone formation.

Bone health should be viewed as part of a musculoskeletal continuum, where muscle mass, strength and bone mineral density decline in parallel with aging all of which are positively influenced by protein intake. Moderate to high protein intakes (1.0-1.5 g/kg/day) do not negatively affect bone metabolism when dietary calcium is sufficient. Furthermore the acid-base balance of the diet often used to critique high protein diets is better managed by increasing intake of alkalinizing fruits and vegetables rather than reducing protein. Overall, a recalibration of public health nutrition advice is required for higher protein recommendations particularly in aging populations vulnerable to sarcopenia and osteoporosis. In postmenopausal women higher protein intake (1.2 g/kg body weight/day) led to a 13-16% reduction in the risk of hip fractures over 5 years compared to lower protein intakes (Heaney and Layman, 2008).

Kedzia *et al*. (2023) evaluates the nuanced impact of dietary protein-both plant and animal on osteoporosis risk, bone mineral density (BMD) and biochemical bone markers. The article synthesizes data from recent randomized controlled trials, cohort studies and meta-analyses, concluding that protein quantity and quality both modulate skeletal outcomes depending on physical activity levels, energy balance and hormonal status. Protein intake above 1.2 g/kg/day was linked to reduce BMD in sedentary postmenopausal women whereas individuals engaging in regular physical activity showed either neutral or beneficial bone effects. The review emphasizes that high protein intake does not inherently increase calcium loss, as greater intestinal calcium absorption and physiological adaptation balance urinary excretion. Biomarkers like IGF-1, CTX and P1NP were variably influenced by the type and timing of protein intake, with dairy proteins and calcium-fortified products showing superior outcomes in postmenopausal women compared to soy-based plant proteins. However, soy isoflavones still demonstrated potential benefits, especially in estrogen-deficient states though their impact was dependent on processing and bioavailability. Importantly, the authors caution against high protein intake in the absence of adequate physical activity or micronutrient sufficiency, noting that protein without exercise may enhance bone resorption markers. The balanced protein intake (both plant and animal), coupled with sufficient energy, calcium and vitamin D is essential for bone health especially in older adults, postmenopausal women and individuals with problems like kidney or cardiovascular disease.

7.2 Evidence from Indian context

Research from India, though limited, provides compelling evidence regarding the role of protein in bone health. Several studies have highlighted the protein deficiency in the Indian diet and its consequences for bone health particularly in postmenopausal women and the elderly. Paul *et al*. (2008) conducted a study on postmenopausal women in South India and found that women with higher protein intake (>1.0 g/kg body weight/day) had 4-8% higher BMD at the spine and hip compared to women consuming < 0.8 g/kg body weight/day. This study also indicated that protein intake accounted for approximately 10-12% of the variance in BMD levels in this cohort.

A cross-sectional study by Karkada *et al*. (2020) on 1,200 elderly individuals in rural India found that only 33% of participants met the recommended protein intake (0.8 g/kg body weight/day). This group had a 10-15% lower BMD compared to those with adequate protein intake, and the incidence of osteoporosis was three times higher among individuals with protein intake <0.6 g/kg body weight/day.A study on postmenopausal women in North India by Pandey *et al*. (2019) showed that low dietary protein (<0.7 g/kg body weight/day) was linked to a 5-6% decrease in BMD at the femoral neck and lumbar spine and a 12% higher risk of fractures compared to those with adequate intake.

The Journal of the Association of Physicians of India has emphasized the critical importance of increasing dietary protein intake among Indian adults, particularly those with chronic conditions such as type 2 diabetes (Mohan *et al*., 2023). The expert panel, comprising endocrinologists, nephrologists and dietitians noted that protein intake in India is significantly below recommended levels especially in vegetarian populations. This deficiency contributes not only to metabolic imbalances but also to muscle wasting and sarcopenia, which are key risk factors for osteoporosis and fractures. The panel recommended raising dietary protein intake to 19-20% of total energy intake or 1.0-1.2 g/kg body weight/day, particularly for those at risk of or living sarcopenia. The consensus also highlighted the importance of high quality proteins, protein timing and distribution throughout the day and advocated for policy level changes to promote awareness and accessibility to affordable protein-rich foods.

Shivakumar, Minocha and Kurpad (2018) sheds critical light on the evolving understanding of protein quality, amino acid requirements and digestibility in India with profound implications for national nutrition policies. Using modern stable isotope tracer techniques, their findings suggest that the requirements for indispensable amino acids (IAA) such as lysine, leucine and methionine are significantly higher than earlier FAO/WHO recommendations especially in undernourished populations and those exposed to parasitic infections. The authors discuss the limitations of the outdated nitrogen balance method, advocating instead for direct amino acid balance and the indicator amino acid oxidation (IAAO) method as more accurate approaches. Particularly important is the shift from the older protein digestibility corrected amino acid score (PDCAAS) to the newer digestible indispensable amino acid score (DIAAS), which accounts for digestibility of each amino acid. Using invasive dual isotope tracer methods, studies in South Indian adults and children revealed that commonly consumed plant-based foods like rice, finger millet and mung bean had lower digestibility (especially for lysine and methionine) compared to animal-source proteins like eggs and meat. Despite India's traditional reliance on cereal-based diets, these findings underscore the need to diversify protein sources, improve agricultural yields of pulses, and reframe food subsidy policies that currently prioritize cereals over higher-quality proteins. This research forms the biochemical and public health foundation for redefining protein adequacy not just in terms of quantity, but also in bioavailability and amino acid completeness making it highly relevant for addressing hidden hunger and childhood stunting across India.

Traylor, Gorissen and Phillips (2018) challenges the adequacy of the current recommended dietary allowance (RDA) for protein intake 0.8 g/kg/day for older adults growing evidence of age-related anabolic resistance and increased protein needs to preserve muscle mass. Drawing from nitrogen balance and stable isotope studies, the authors argue that older adults require at least 1.2 g/kg/day to support skeletal muscle synthesis and prevent sarcopenia. This conclusion is supported by data from the indicator amino acid oxidation (IAAO) method which indicates higher estimated average requirements (EAR) and RDA values in elderly populations. Even distribution of protein intake across meals rather than the typical skewed pattern with low-protein breakfasts was shown to more effectively stimulate muscle protein synthesis (MPS). Importantly, the article also dispels common concerns about high-protein diets harming bone or kidney health, stating that there is no scientific basis for such claims when protein intake is within the physiological range and accompanied by adequate calcium and vitamin D. These findings underscore the need for updated, age-specific protein guidelines to better support musculoskeletal health in ageing populationin India where current intake often fails to meet even the basic RDA.

7.3 Punjab-specific data

In Punjab, the overall protein intake tends to be moderate, but there are significant regional disparities. A survey of dietary patterns across Punjab in 2021 indicated that average protein intake in urban populations was 1.0-1.2 g/kg body weight/day, which meets the Indian RDA for protein. However, in rural populations, the average intake dropped to 0.6-0.8 g/kg body weight/day, which is considered inadequate for bone health. Dairy products, which are rich in complete proteins, make up about 40% of the protein intake in Punjab. However, meat, fish, and eggs contribute to only 5-8% of protein intake, leading to potential amino acid deficiencies (especially methionine and lysine). Vegetarian diets, common in both rural and urban areas have led to concerns regarding the quality of protein. The absence of meat and limited variety in legumes often results in insufficient intake of essential amino acids. Protein from plant sources in Punjab typically from lentils, beans and wheat is found to be low in bioavailability meaning less effective absorption and use by the body.

Khinda *et al*. (2022) investigated the prevalence and independent predictors of osteoporosis and osteopenia in 672 postmenopausal women from Punjab, India. Using dual-energy X-ray absorptiometry (DEXA) scans at the lumbar spine and femoral neck, the study reported a prevalence of 30.5% for osteoporosis and 44.2% for osteopenia, confirming a significant burden of low bone mass in this demographic. Through multivariable regression analysis, the study identified higher systolic blood pressure (SBP>120 mmHg), elevated triglycerides (TG>150 mg/dl), poor sleep quality (Pittsburgh Sleep Quality Index score $\geq$5) and elevated C-reactive protein (CRP>3 mg/l) as independent risk factors for both conditions. Higher CRP emerged as the most potent predictor, tripling the odds of osteoporosis (OR = 2.77; 95% CI: 2.18-3.56). In contrast, a BMI > 30 kg/m² was found to be protective, reducing the risk of both osteoporosis and osteopenia. The multifactorial nature of bone health in Indian women, where metabolic, inflammatory and lifestyle factors interact with nutritional variables. While dietary protein intake was not directly assessed, the idea that systemic inflammation often by poor diet and inactivity plays a critical role in accelerating bone loss highlighting the need for integrated approaches to osteoporosis prevention in Punjab.

A strong connection between dietary habits, physical activity and bone health in Indian women aged 40-60 years in Ludhiana, Punjab is illustrated by Munshi, Kochhar and Garg (2015). Among the 139 women assessed 43% were found to be at risk of osteoporosis with early menopause (47-55 years), poor protein intake and sedentary lifestyle emerging as prominent contributors. The study employed a multi-pronged assessment including BMD measurements, serum calcium and phosphorus levels and 24 h dietary recall. Results revealed significantly low intakes of pulses, fruits and vegetables, alongside inadequate protein consumption (mean intake 47 g/day vs RDA of 53-57 g/day). These were positively correlated with decreased BMD and serum calcium ($p\geq0.05$). Despite adequate intake of milk and cereals, BMD scores remained low suggesting that protein quality and dietary diversity play a more crucial role than just quantity. Additionally, more than 85% of women reported minimal physical activity, further compounding the risk of bone deterioration. The nutrition alone is insufficient unless complemented by regular physical activity and sun exposure, both of which were lacking in this cohort. Dietary interventions focusing on high-quality proteins, physical activity promotion, and lifestyle education are urgently needed to mitigate osteoporosis risk among pre and postmenopausal women in northern India.

Khinda *et al*. (2021) offers compelling biochemical evidence for the link between chronic low-grade inflammation and osteoporosis risk among Punjabi women. 300 postmenopausal women from Punjab, categorizing participants based on DEXA scans into osteoporotic and non-osteoporotic groups. Serum C-reactive protein (CRP) and nitric oxide (NO) levels using ELISA and found that women with CRP levels>3 mg/l had a 2.29 times greater risk of osteoporosis compared to those with lower CRP. In contrast, NO levels showed

non-significant association with BMD. Linear regression further confirmed that higher CRP levels were significantly and negatively correlated with BMD at both lumbar spine and femoral neck. This suggests that systemic inflammation, as indicated by elevated CRP is an independent and powerful biochemical determinant of bone loss in Punjabi postmenopausal women. It introduces CRP as a potential clinical biomarker for osteoporosis screening in Indian women and supports broader literature linking inflammation to accelerated bone resorption. These findings highlight the multi factors of osteoporosis, suggesting that even in populations with acceptable dietary calcium or protein intake, underlying inflammation may silently compromise skeletal integrity.

A study conducted in the border belt region of Tarn Taran, Punjab, highlights the severe burden of compromised bone health among rural adult women which examined 70 females aged 21-66 years from low-income backgrounds revealing high rates of hypocalcemia (70%) and hyperuricemia (58.6%). The mean serum calcium level was 8.25 ± 0.62 mg/dl, below the optimal reference range (8.5-10.5 mg/dl), indicating widespread calcium deficiency despite the availability of dairy in the region (Dhillon and Kumar, 2020). The average BMI was 24.7 ± 4.6 kg/m², with over 43% of women falling into overweight, pre-obese, or obese categories. Importantly, despite varying education levels, no significant difference was found in serum calcium levels across education groups, suggesting that nutrition knowledge and access alone may not be sufficient to improve bone health outcomes. These findings suggest a double burden of malnutrition, where poor-quality diets lead to both obesity and micronutrient deficiencies. The study provides critical evidence for the urgent need to design nutrition and bone health interventions tailored to rural Punjabi women, incorporating both protein-rich and calcium-dense foods alongside lifestyle modifications.

Remer *et al*. (2014) examined the dietary protein and acid load in relation to bone health. In comparison to earlier assumptions that high protein intake may be detrimental due to increased urinary calcium losses this review emphasizes that higher protein intake is actually associated with anabolic effects on bone, primarily through increased circulating IGF-1 levels. However, the bone-protective effects of protein are influenced by the acid-base balance of the diet. Protein rich diets can lead to a higher dietary acid load, especially when derived from sulphur containing amino acids (*e.g.,* methionine, cysteine), which increases net acid excretion (NAE) and potentially compromises calcium retention. Acid-induced bone resorption is not merely due to calcium loss but also results from changes in theendocrine-metabolic environment, such as elevated cortisol and reduced IGF-1 signalling under subtle metabolic acidosis. If a high-protein intake is accompanied by sufficient alkaline-producing foods (*e.g*., fruits, vegetables, potassium-rich sources) the acid load is neutralized, and the bone-forming benefits of protein. The future dietary strategies for bone health must assess both protein intake and net endogenous acid production (NEAP) together rather than in isolation. This integrated approach is especially relevant in settings like India where protein intakes are low and acid-base balance may be disrupted by high cereal and low fruit-vegetable consumption.

Shams-White *et al*. (2018) conducted under the National Osteoporosis Foundation, rigorously examined the effects of animal versus plant protein intake on bone mineral density (BMD), bone mineral content (BMC) and bone turnover markersin healthy adults. The review analyzed seven randomized controlled trials (RCTs) primarily comparing isoflavonerich soy protein with various animal derived proteins in postmenopausal women. Meta-analyses revealed no statistically significant differences in changes in lumbar spine (LS), femoral neck (FN), total body (TB) or total hip (TH) BMD between plant and animal protein groups. Specifically, the pooled net changes for LS BMD (0.24%, 95% CI: -0.80% to 1.28%), TB BMD (-0.24%, 95% CI: -0.81% to 0.33%) and FN BMD (0.13%, 95% CI: -0.94% to 1.21%) were minimal and not statistically significant. Likewise, bone turnover markers such as bone-specific alkaline phosphatase (BSAP) and N-telopeptide (NTX) showed no consistent differences between groups. The adequate calcium intake and energy balance, neither soy protein nor animal protein demonstrated superior effectson adult bone health. However, there is a major limitation: plant protein in all included studies was limited to soy leaving open questions about other plant protein like legumes, pulses and grains, especially in non-Western diets. This evidence underscores the equivalence of well-balanced animal and soy-based protein sources for skeletal outcomes but highlights the need for more culturally diverse trialsexamining broader plant protein profiles.

Darling, Millward, and Lanham-New (2009) interprets decades of conflicting data into more understanding about relationship between dietary protein and bone health. Historically, high protein especially from animal sources was viewed due to its potential to increase physiological acidity *via* sulphur containing amino acids, thereby enhancing bone resorption and urinary calcium loss. However, this emphasizes that these catabolic effects are dependent and may be mitigated when protein intake is accompanied by adequate dietary calcium, fruits and vegetables which help buffer acid load. At the same timeanabolic pathways dominate when dietary protein stimulates IGF-1 secretion, which promotes osteoblast activity, muscle mass retention and calcium absorption. The net effect of protein on bone is shaped by whole-diet quality, calcium adequacy, protein source (animal vs. plant) and acid-base balance rather than protein intake alone. For example, a high protein potassium ratio or low calcium intake can shift the impact toward catabolism. Observational and intervention studies yield mixed results some show BMD gains or maintenance with higher protein intake while others find no significant impact particularly in non-frail or healthy adults. Dietary protein is beneficial for bone health when part of a nutrient-dense, balanced diet and not inherently harmful especially if calcium and alkali intake are sufficient. This integrative perspective is particularly relevant in the India where cereal-heavy, low-protein and low-alkaline diets may exacerbate both protein deficiency and acid load-related bone loss.

Plant-based protein sources like soy, lentils, and pulses can support bone health they are often lower in amino acids that are crucial for bone collagen synthesis compared to animal-based proteins (Henkel *et al*., 2016). This can pose challenges for populations reliant on plant-based diets especially in regions like Punjab where vegetarianism is common.Animal protein has been shown to improve bone health by providing a complete amino acid profile and studies suggest that daily consumption of 1-2 servings of dairy and 1-2 servings of lean meat can boost bone strength by up to 10-15% in postmenopausal women and the elderly.

8. Challenges and gaps in research and practice

Despite growing awareness of the importance of protein for bone health, multiple structural, behavioral, and scientific challenges

continue to hinder progress in addressing this issue effectively in India and Punjab. These challenges span across data collection, policy, dietary practices and public health. Lamina *et al*. (2025) studied the impact of dietary protein intake on bone disease, kidney function, and sarcopenia across 81 unique studies published between 2000 and 2024. Despite the breadth of research, only 13 studies met criteria for low to moderate risk of bias, and even fewer specifically assessed bone health. For bone outcomes, four randomized controlled trials (RCTs) and one cohort study were included, but the strength of evidence across outcomes such as bone mineral density (BMD), bone mineral content (BMC), and bone turnover markers was rated as insufficient. While one RCT showed a slight benefit of protein intake on total body BMC, most studies reported no significant differences in lumbar spine, hip, or femoral neck BMD between high- and low-protein groups. Similar inconsistencies were found for bone turnover markers, such as osteocalcin and procollagen type I N-terminal propeptide. Importantly, only one eligible study included children or adolescents, highlighting a significant research gap in early-life bone health. The authors conclude that current evidence is too limited and inconsistent to support changes in dietary reference intakes (DRIs) for protein based on bone or renal outcomes, and call for more robust, long term and age diverse trials. This systematic review reinforces the need for study in India where baseline protein intakes and dietary patterns differ markedly from Western populations.

8.1 Limited longitudinal and interventional studies

One of the most critical gaps is the lack of long-term, large-scale, region-specific studies exploring how protein intake influences bone health outcomes (such as fracture risk, BMD decline, or osteoporosis progression). Most available studies in India are cross-sectional which limits the ability to infer causality. Very few randomized controlled trials (RCTs) have been conducted on Indian populations, especially in rural areas and among women who are at high risk for both protein deficiency and osteoporosis.

8.2 Inadequate protein assessment in National surveys

- National nutrition surveys like NFHS, CNNS, and NNMB often focus on total caloric intake and micronutrient deficiencies but give insufficient attention to protein intake patterns especially protein quality and amino acid adequacy.
- Protein quality indicators such as the digestible indispensable amino acid score (DIAAS) are not commonly used in Indian dietary assessments.
- Disaggregated data by age, gender, and geographic region (*e.g.,* Punjab) are either limited or outdated, hampering localized intervention planning.

8.3 Cultural and dietary barriers

In Punjab as in much of India cultural and religious norms significantly shape dietary choices:

- High prevalence of vegetarianism limits access to complete proteins. As per NFHS-5, about 69% of women and 63% of men in Punjab consume meat, fish or eggs less than once a week.
- Protein-rich foods like soy, eggs and dairy are sometimes perceived as "heavy" or unsuitable for daily consumption especially among elderly or sick individuals.
- Women and girls often face intra-household food distribution inequalities receiving less protein-rich foods compared to men.

8.4 Socioeconomic inequalities

Even in a relatively prosperous state like Punjab, economic disparities affect access to diverse protein sources:

- A household survey (2021) found that only 38% of low-income families in rural Punjab could afford to consume animal-source protein more than twice a week.
- Rising costs of pulses and dairy products have made quality plant-based proteins less accessible to marginalized populations.

8.5 Knowledge and policy gaps

- Protein is often overlooked in national and state level nutrition policies which focus more on micronutrients like iron, iodine and vitamin A.
- Public awareness campaigns rarely emphasize the link between protein and bone health. A gap that needs urgent attention especially for ageing populations and adolescent girls.

9. Conclusion

Dietary protein plays a pivotal role in maintaining bone health, especially among aging populations and postmenopausal women. While calcium and vitamin D have long been prioritized in bone health strategies, emerging evidence supports a more integrated approach that includes high-quality protein intake to enhance bone mineral density, muscle mass, and overall skeletal integrity. In India, where protein intake is often inadequate and skewed toward low-bioavailability plant sources, addressing protein gaps is essential for effective osteoporosis prevention. Punjab presents a compelling case study for this issue. Despite relatively better economic indicators and higher dairy consumption, the region exhibits significant disparities in protein intake, particularly among rural and vegetarian populations. Cultural norms, dietary transitions and gender-based food allocation further compound these challenges. However, Punjab's mixed dietary patterns, strong agricultural base and increasing health awareness also make it a promising model for piloting protein-centered public health interventions. By recognizing Punjab's unique nutritional landscape and leveraging its strengths, India can develop scalable, context-specific strategies to improve bone health nationwide. Integrating protein-focused education, targeted policy reforms and stakeholder collaboration will be crucial in transforming skeletal health outcomes, not just in Punjab, but across nutritionally vulnerable regions in India.

Acknowledgements

The authors acknowledge all authors of the original articles cited in this review. This work received no specific grant from any funding agency.

Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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Citation **Singh Ekonkar, Kaur Amarjeet, Kaur Harleen, Kaur Sukhmandeep and Kaur Sehajveer (2025). A comprehensive review on protein power for stronger bones with reference to Indian context. Ann. Phytomed., 14(2):252-262. http://dx.doi.org/10.54085/ap.2025.14.2.25.**