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Review

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Strategies for preventing bone loss in populations with insufficient calcium and vitamin D intake

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ABSTRACT

Calcium and vitamin D are essential nutrients for maintaining skeletal health, yet deficiencies in these nutrients are particularly widespread in regions such as Asia and Africa. Inadequate intake of these nutrients in these areas has been associated with diminished bone integrity and a rising incidence of osteoporosis. This review examines the underlying mechanisms of bone loss driven by calcium and vitamin D deficiencies, emphasizing their crucial roles in bone metabolism. It also presents strategies to improve nutrient intake, such as fortification of staple foods and supplementation, along with lifestyle modifications including increased physical activity, sun exposure, and dietary education, to prevent bone loss effectively. Special consideration is given to vulnerable populations, including older adults, individuals with limited sun exposure, and those with dietary restrictions, who are at higher risk of deficiency. The review further evaluates public health strategies, including government-initiated fortification and educational programs, as essential measures for tackling widespread nutrient deficiencies. Lastly, it explores future avenues for addressing calcium and vitamin D deficiencies, including the potential role of digital health tools, personalized nutrition, and innovative public health policies to alleviate the global burden of bone-related diseases.

Keywords: Bone diseases; calcium; vitamin D deficiency; dietary intervention

INTRODUCTION

Bone health is vital for overall physical well-being throughout life, with its maintenance depending largely on the balance between bone formation and resorption. These processes are significantly influenced by nutritional intake and lifestyle choices [1]. Calcium and vitamin D are key nutrients in bone metabolism, where calcium acts as a primary structural component [2], and vitamin D enhances the body's ability to absorb calcium and regulate its levels [3]. Together, these nutrients help maintain bone density and structural integrity. A deficiency in either nutrient disrupts these processes, leading to bone loss.

Globally, calcium deficiency poses a serious public health issue, especially in regions such as Asia, Africa, and Latin America, where access to calcium-rich foods is limited due to economic and dietary constraints [4,5]. Additionally, certain cultural factors, such as lactose

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intolerance among specific ethnic groups [6,7], may limit the consumption of dairy products, a primary calcium source in many diets. The lack of calcium intake can lead to reduced bone mineral density and, over time, increase the risk of conditions such as osteoporosis and fractures [8].

Similarly, vitamin D deficiency is a widespread issue, particularly in South Asia and the Middle East. In South Asia [9], the deficiency is prevalent due to several factors, including limited dietary sources of vitamin D, as most diets are plant-based and lack fortified foods or fish rich in vitamin D. In the Middle East, cultural practices such as wearing clothing that covers most of the body, even in sunny climates, contribute to insufficient sun exposure, further exacerbating the problem [10].

The impact of calcium and vitamin D deficiencies on public health is profound, contributing to widespread occurrences of bone diseases such as osteoporosis [11]. This condition, characterized by reduced bone density and structural deterioration, heightens the risk of fractures, especially in the hip and spine, which are associated with significant healthcare costs, morbidity, and mortality [12,13]. As the global population ages, addressing these nutritional deficiencies becomes increasingly crucial to reducing the incidence of osteoporosis and related bone conditions.

This review focuses on scientifically supported strategies to mitigate bone loss in populations with inadequate calcium and vitamin D intake. With the aging global population, the growing health concern of skeletal decline requires practical solutions, including dietary interventions, supplementation, and lifestyle modifications, to improve bone health and reduce the burden of bone-related diseases.

PATHOPHYSIOLOGY OF BONE LOSS RELATED TO CALCIUM AND VITAMIN D DEFICIENCY

Bone health is maintained through a delicate balance between bone formation and resorption, processes primarily regulated by the activity of osteoblasts and osteoclasts. Calcium and vitamin D play critical roles in these processes, and deficiencies in either, along with an inadequate dietary pattern, can disrupt bone homeostasis, leading to bone loss and increased fragility. A well-balanced diet that includes sufficient intake of these nutrients is essential for maintaining bone health and preventing skeletal deterioration [14].

When dietary calcium intake is insufficient, the body compensates by increasing bone resorption through elevated parathyroid hormone (PTH) levels, which accelerates osteoclast activity and reduces bone mineral density (BMD). In adults aged 50 and older, calcium and vitamin D deficiency is linked to higher PTH levels, contributing to increased bone loss [15]. Similarly, another study shows that calcium supplementation in postmenopausal women suppresses PTH, helping to preserve BMD [16,17]. Vitamin D plays a crucial role in maintaining calcium balance by enhancing calcium and phosphorus absorption from the gastrointestinal tract. When vitamin D levels are insufficient, calcium absorption decreases, leading to lower serum calcium levels, which triggers PTH release and increases bone resorption. Additionally, vitamin D deficiency impairs the function of osteoblasts, the cells responsible for bone formation, leading to reduced bone formation and increased bone loss [18,19]. In particular, the combined effect of calcium and vitamin D deficiencies exacerbates the deterioration of

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bone health. While calcium deficiency alone increases bone resorption, inadequate vitamin D further compounds the issue by limiting calcium absorption and impairing bone formation. This imbalance of increased resorption and decreased formation significantly weakens the skeletal structure, leading to conditions such as osteoporosis [20,21].

Postmenopausal women and older adults are particularly vulnerable, as age-related declines in hormone levels, particularly estrogen, contribute to skeletal aging by accelerating bone resorption and decreasing bone formation [22]. Additionally, reduced skin synthesis of vitamin D with age further exacerbates bone loss, leading to faster rates of skeletal deterioration [3]. Over time, the chronic imbalance between bone formation and resorption in postmenopausal women and older adults, driven by calcium and vitamin D deficiencies, leads to decreased BMD and deterioration of bone microarchitecture. This increases the risk of hip and vertebral fractures, common in individuals with osteoporosis, which significantly contribute to morbidity, reduced quality of life, and higher mortality rates in these populations [23].

DIETARY STRATEGIES TO INCREASE CALCIUM AND VITAMIN D INTAKE

Inadequate intake of calcium and vitamin D, which are crucial for maintaining bone density and strength, is a significant health concern. Calcium is vital for maintaining the structure of bones, while vitamin D enhances the absorption and mineralization of calcium. Deficiencies in these nutrients accelerate bone resorption and impair formation, highlighting the need for dietary strategies to prevent bone loss in at-risk populations.

Maintaining sufficient calcium intake is essential for preventing bone loss and supporting BMD. The daily recommended calcium intake differs based on factors such as country, gender, and age. For adults, typical recommendations range from 700–1,000 mg/day. For individuals over 50, especially women, the recommended intake increases to 800–1,200 mg/day to support bone health [24,25]. This can be achieved through diet, with key dietary sources of calcium including dairy products like milk, cheese, and yogurt, which are among the most concentrated sources of calcium. For non-dairy options, foods like leafy green vegetables (e.g., kale, broccoli), legumes, almonds, and sesame seeds provide significant calcium. In regions with limited dairy consumption, calcium-fortified plant-based milks and cereals offer viable alternatives to meet calcium needs. In addition, when dietary intake is insufficient, calcium supplementation may be necessary. Commonly used forms, such as calcium carbonate and calcium citrate, can further help improve calcium intake in individuals with dietary restrictions. It has been reported that calcium citrate is more easily absorbed, particularly in individuals with low stomach acid [26], while calcium carbonate has also been shown to have no absorption issues when taken with meals [27]. Additionally, concerns about lead contamination in calcium carbonate supplements have been reported, posing a further limitation in its use as a calcium source [28]. In light of these concerns, eggshell powder has emerged as a good alternative calcium source, offering high bioavailability with minimal risk of lead contamination [29].

Vitamin D is essential for the absorption of calcium in the intestines and is key to the process of bone mineralization. Inadequate levels of vitamin D hinder the body's ability to effectively absorb calcium from the diet, resulting in weakened bones. The Institute of Medicine (IOM)

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recommends a daily intake of 600–800 IU of vitamin D for adults, with the upper end of this range being advised for older individuals aged 70 and above [24]. Increasing vitamin D intake through food is important, but the sources are limited. Rich natural sources of vitamin D include fatty fish like salmon, mackerel, and sardines, as well as egg yolks and mushrooms. Additionally, many countries fortify foods like milk, cereals, and orange juice with vitamin D to prevent deficiencies. If dietary intake remains insufficient, especially in individuals with limited sunlight exposure or dietary restrictions, supplements may be necessary. Ensuring optimal vitamin D levels over 20–30 ng/mL (50–75 nmol/L) is crucial for maintaining bone health as reported earlier [3,24,30].

Vitamin D is synthesized in the skin through sunlight exposure [31]. The amount of sun exposure needed for the body to synthesize sufficient vitamin D varies depending on several factors, including skin type, geographical latitude, season, time of day, and the extent of sun exposure. A general recommendation is to get sun exposure between 10 a.m. and 3 p.m., when ultraviolet (UV) rays are strongest, for about 10–20 min, 3–4 times a week [32]. Exposing 20% of the body surface to sunlight for this duration, roughly equal to 0.5 minimal erythemal dose (MED), can lead to the production of around 1,400–2,000 IUs of vitamin D3 [33]. Studies also suggest that vitamin D synthesis can still occur when using sunscreen with a sun protection factor (SPF) of 15 [34]. However, for individuals who do not engage in outdoor activities, live in high-latitude regions, or have cultural practices that limit sun exposure, vitamin D supplements can be a valuable alternative as discussed previously [35].

Vitamin D supplements are available in 2 primary forms: ergocalciferol (vitamin D2) and cholecalciferol (vitamin D3). There are reports that ergocalciferol, sourced from plants and fungi, is less stable in storage and more prone to degradation during cooking and baking than cholecalciferol. Consequently, vitamin D3 is generally regarded as more effective at increasing and maintaining blood vitamin D levels [36]. The primary treatment goal for vitamin D supplementation is to achieve and maintain serum 25-hydroxyvitamin D (25[OH]D) levels of at least 30 ng/mL (75 nmol/L), as this is generally considered sufficient for optimal bone health and calcium metabolism [24]. In cases of confirmed vitamin D deficiency, some experts recommend higher doses, typically ranging from 1,000 to 2,000 IU per day, under medical supervision to restore adequate levels [37]. In addition, vitamin D supplementation can be taken in various forms—daily, weekly, or monthly—depending on the dosage and individual patient needs. In more severe deficiency cases, an initial high-dose regimen (e.g., 50,000 IU weekly for 8–12 weeks) may be prescribed, followed by a maintenance dose once sufficient serum levels are achieved [3,38,39]. While calcium and vitamin D supplementation are generally safe when taken as recommended, excessive calcium supplementation [40] may lead to kidney stones or vascular calcification, and excessive vitamin D supplementation [38] may result in hypercalcemia or contribute to vascular calcification in some cases. Therefore, regular monitoring of serum calcium and 25(OH)D levels is essential to ensure safety and effectiveness, particularly for individuals on high-dose regimens or with pre-existing health conditions.

Additionally, other nutrients such as magnesium [41], phosphorus [42], and vitamin K [43] are also related to bone health. Magnesium deficiency can impair bone mineralization and disrupt calcium metabolism, resulting in weaker bones and a higher risk of osteoporosis. Studies have shown that magnesium deficiency is associated with increased bone resorption and influences the levels of PTH, which plays a crucial role in maintaining calcium balance in the body [44]. Phosphorus homeostasis is regulated by the bone-kidney-intestine network

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through complex, coordinated endocrine feedback loops involving PTH, fibroblast growth factor 23, and vitamin D. These pathways work together to maintain optimal phosphorus levels by controlling its absorption, excretion, and mobilization from bone. [45]. The ratio of calcium-to-phosphorus intake is widely recognized as important for bone health [42]. For instance, excessive phosphorus intake from processed foods, which are prevalent in modern diets, particularly in developed countries, can disrupt the calcium-phosphorus balance and negatively affect bone mineralization [46]. To address this, practical strategies include reducing the consumption of phosphate-additive-rich processed foods and raising awareness of food labeling. Similarly, while animal protein is beneficial for bone health, excessive intake may increase urinary calcium excretion; thus, a balanced approach incorporating both plant and animal protein sources is recommended [47,48]. Moreover, moderating the intake of caffeine [49] and sodium [50,51] is essential, as both can adversely impact calcium metabolism, particularly in populations with low calcium intake, where the negative effects may be more pronounced. Vitamin K also plays a vital role in bone health by modifying osteocalcin, a protein responsible for binding calcium to the bone matrix, which is necessary for proper bone mineralization [52]. A deficiency in vitamin K can lead to decreased bone density and a higher risk of fractures [53]. Research indicates that high-dose supplementation of vitamin K1 and K2 can improve bone strength, particularly in the femoral neck, and reduce the incidence of clinical fractures [54]. This highlights the importance of adequate vitamin K intake not only for maintaining bone density but also for enhancing bone strength and preventing fractures.

Therefore, calcium and vitamin D are the most critical nutrients for maintaining skeletal health, as they are fundamental to bone formation and strength. However, other micronutrients, such as magnesium and vitamin K, also play essential supportive roles in bone metabolism and should not be overlooked. A well-balanced intake of calcium, vitamin D, and these additional micronutrients is key to ensuring optimal bone density and preventing fractures, making all of them crucial for maintaining overall bone health.

Fig. 1 summarizes the proposed strategies for ensuring adequate intake of calcium, vitamin D, and related micronutrients as described above.

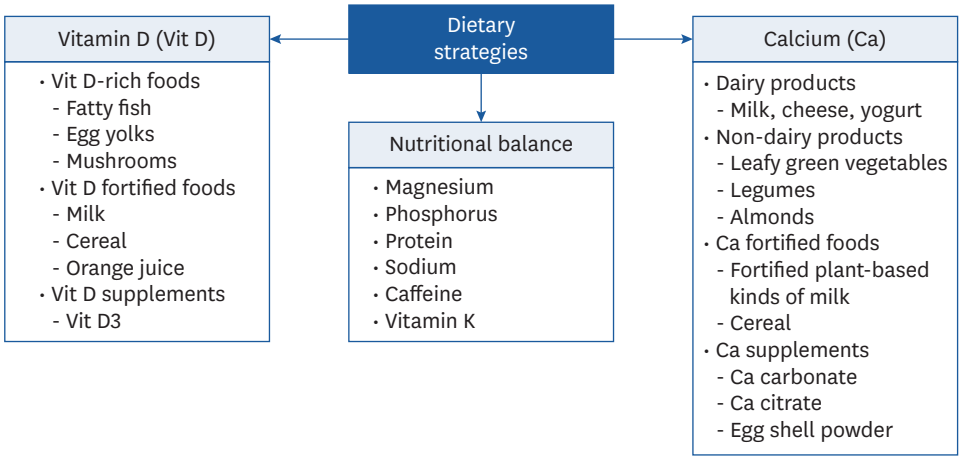

Fig. 1. Strategies for ensuring adequate intake of calcium, vitamin D, and related micronutrients.

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LIFESTYLE AND BEHAVIORAL APPROACHES TO PREVENT BONE LOSS

To prevent bone loss in populations with insufficient calcium and vitamin D intake, lifestyle and behavioral approaches can complement dietary and supplementation strategies. These approaches include promoting sun exposure to enhance vitamin D biosynthesis, encouraging physical activity and exercise, and implementing lifestyle modifications aimed at reducing risk factors for bone loss. Additionally, balance and flexibility exercises, along with fall prevention measures for older adults, are essential for supporting bone health and reducing the risk of osteoporosis and osteoporotic fractures as suggested in **Fig. 2**.

As a complement to dietary vitamin D intake, outdoor activities are encouraged to promote vitamin D biosynthesis in the skin through sunlight exposure several times a week. The duration depends on skin type, time of day, and geographic location as discussed earlier. People living in regions with limited sunlight (e.g., high latitudes) or those with darker skin may need longer exposure to generate sufficient vitamin D. For individuals unable to obtain adequate sun exposure, UV lamps that simulate sunlight can help stimulate vitamin D production [55]. This may be especially useful during winter months or for individuals living in areas with limited sunlight. Research has shown that tanning is associated with optimal vitamin D status and higher bone mineral density, highlighting the importance of UV exposure for maintaining adequate vitamin D levels and supporting bone health [56].

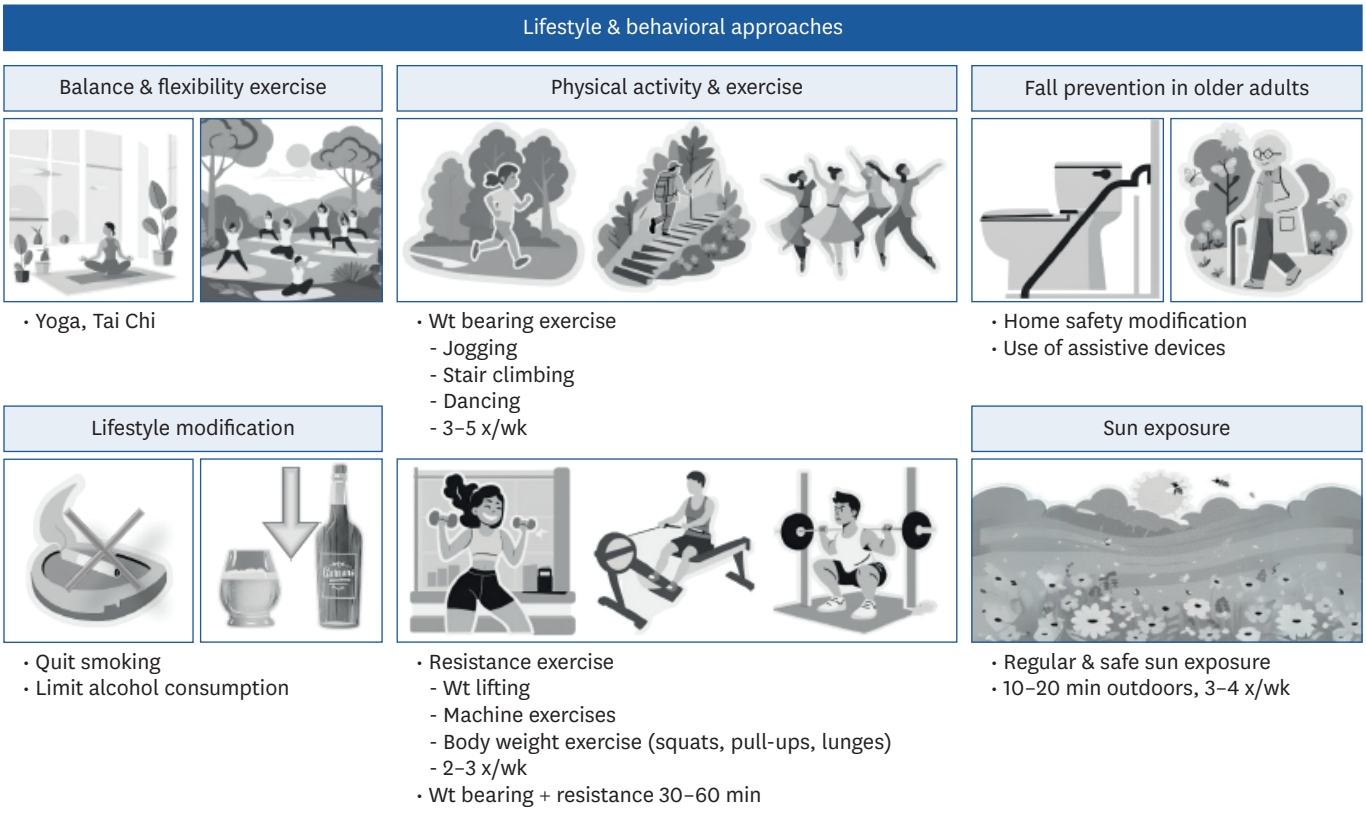

Fig. 2. Suggested lifestyle and behavioral approaches to prevent bone loss in populations with insufficient calcium and vitamin D intake.

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Weight-bearing exercises such as jogging, stair climbing, and dancing, increase the mechanical load on bones, prompting the body to build and strengthen bone tissue [57,58]. Resistance exercises, such as weight lifting, machine exercises [59], and bodyweight exercises, including squats, pull-ups, and lunges, are known to promote bone formation and slow the progression of bone loss [59,60]. Therefore, combining regular exercise with sufficient calcium and vitamin D intake enhances the effectiveness of dietary strategies in preventing bone deterioration. It is recommended to engage in 30–60 min of weight-bearing and resistance exercises at least three times per week, as these activities help strengthen bones, improve bone density, and increase muscle mass. In addition, activities like yoga [61] and tai chi [62] improve physical mobility and balance, which help lower the risk of falls and fractures in older adults. Falls are a significant cause of fractures in populations with weakened bones, and improving balance can mitigate this risk.

Lifestyle modifications such as quitting smoking and moderate alcohol intake are aimed at reducing risk factors for bone loss. Smoking has been found to decrease bone density and impair the body's ability to absorb calcium [63]. It also accelerates bone resorption, increasing the risk of fractures [64]. Therefore, quitting smoking is a beneficial lifestyle change for improving bone health. Additionally, excessive alcohol consumption is associated with lower bone density and a higher risk of fractures [65,66]. Limiting alcohol intake to moderate levels (no more than one drink per day for women and 2 drinks per day for men) can help preserve bone health.

To prevent falls in older adults, home safety modifications and the use of assistive devices can be highly beneficial. For those at higher risk of fractures, creating a safer home environment is crucial in reducing fall risks. Effective measures include installing grab bars in bathrooms, using non-slip mats, ensuring adequate lighting, and removing trip hazards. Additionally, utilizing assistive devices such as canes, walkers, or hip protectors can provide extra stability and help protect against fractures, particularly for individuals with reduced mobility or balance issues [67,68].

SPECIAL CONSIDERATIONS IN VULNERABLE POPULATIONS

Older adults, low-income populations, individuals with limited sun exposure, ethnic groups with high rates of lactose intolerance, and pregnant or breastfeeding women are considered vulnerable populations for skeletal health issues as shown in **Fig. 3**. Special consideration is needed for these groups to ensure they receive adequate nutrients, such as calcium and vitamin D, to support bone health and prevent conditions such as osteopenia, osteoporosis, and fractures.

Older adults, particularly post-menopausal women, experience a significant decline in estrogen levels, which leads to increased bone resorption and reduced calcium absorption [69]. Additionally, decreased vitamin D synthesis due to reduced skin capacity and kidney function [31,37] exacerbates these effects, heightening the risk of osteoporosis. For these groups, ensuring adequate dietary intake of calcium and vitamin D is critical to maintain bone health, with supplements serving as a supportive measure to reduce fracture risk when dietary intake is insufficient. In addition, ensuring a safe environment to prevent falls is crucial, as even minor falls can lead to severe fractures in individuals with weakened bones.

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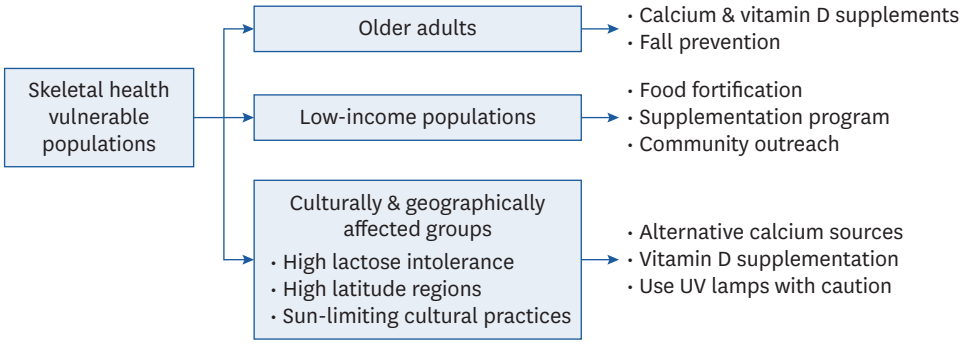

Fig. 3. Special considerations for vulnerable populations in supporting skeletal health.
UV, ultraviolet.

Measures include installing handrails, improving home lighting, and providing mobility aids such as walkers.

Low-income individuals often face barriers in accessing calcium-rich foods [70,71] or vitamin D supplements [72], making it vital for public health policies to focus on increasing the affordability and accessibility of fortified foods and offering low-cost or free supplementation programs. Educational programs and community-based initiatives also play a key role in raising awareness about bone health and nutrition, particularly in underserved populations. Research has shown that adults with low osteoporosis knowledge often have inadequate calcium intake [73], emphasizing the need for community-based efforts to improve awareness and encourage sufficient calcium consumption.

Culturally and geographically affected groups are particularly vulnerable to maintaining bone health due to challenges in accessing sufficient calcium and vitamin D. For ethnic groups with high rates of lactose intolerance, such as Asians and Africans [6,74], public health recommendations should prioritize alternative calcium sources, including fortified plant-based milks and non-dairy calcium-rich foods such as leafy greens, tofu, and nuts. In high-latitude regions [75] or among populations following cultural practices that limit sun exposure, such as wearing clothing that covers most of the body [76], vitamin D deficiency is prevalent. Similarly, individuals with limited UV exposure, such as those living or working in buildings or underground settings [77], higher doses of vitamin D supplementation or alternatives like UV lamps may be necessary [33]. Furthermore, individual differences in sun exposure, influenced by factors such as geographic location, skin type, and lifestyle, underscores the importance of personalized vitamin D supplementation strategies [3]. These tailored approaches can effectively address specific needs, reducing the risk of vitamin D deficiency and its negative impact on bone health.

PUBLIC HEALTH APPROACHES AND POLICY IMPLICATIONS

A comprehensive public health approach is essential for effectively preventing bone loss in populations deficient in calcium and vitamin D. Key strategies include food fortification, supplementation programs, nutrition education, and preventive healthcare services, as illustrated in **Fig. 4**.

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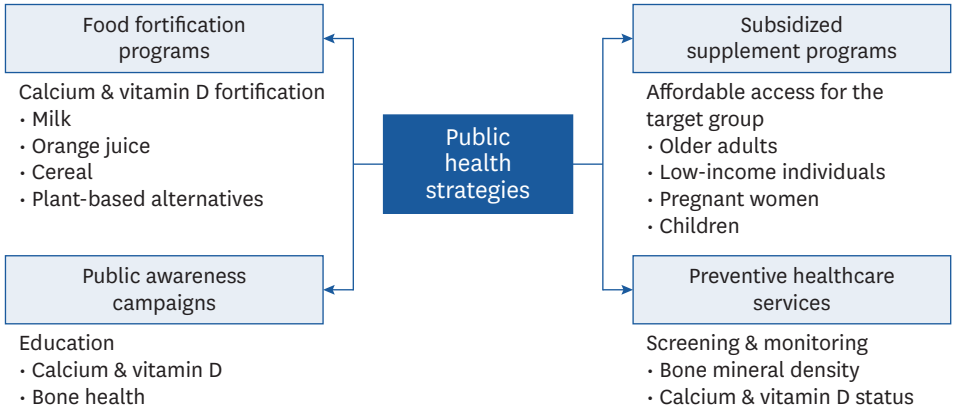

Fig. 4. Public health strategies for preventing bone loss in calcium and vitamin D deficient populations.

Food fortification ensures that populations with limited access to calcium- and vitamin D-rich foods meet their nutritional requirements, as these nutrients are often insufficient in many diets [78,79]. Governments and public health organizations can implement fortification of common foods, such as milk, cereals, and plant-based alternatives, with calcium and vitamin D. Successful implementation of these programs requires national guidelines focused on supporting vulnerable populations, particularly those in low-income communities or regions with limited sun exposure. Regular monitoring and quality control are crucial to maintaining the appropriate nutrient levels and ensuring the efficacy of fortification efforts. Randomized controlled trials (RCTs) have demonstrated that food-based fortification approaches for nutrients like calcium and vitamin D have not reported significant adverse effects [80], making them a safe and effective method for addressing deficiencies.

In addition to fortification, subsidized supplement programs are vital for improving access to calcium and vitamin D, particularly among at-risk groups such as older adults, low-income individuals, pregnant women, and children. These programs can be delivered through public health clinics, community centers, or schools, ensuring that vulnerable populations receive the necessary nutrients. Similar to the U.S. Supplemental Nutrition Assistance Program [81], such initiatives can address nutrient deficiencies and improve bone health outcomes in these groups. Prioritizing support for calcium and vitamin D supplements should be a key focus in national healthcare policies, particularly in regions with high rates of osteoporosis or deficiencies, as previously recommended [79,82]. This strategic focus would provide essential support to at-risk populations, helping to mitigate the risk of bone-related health complications and improve overall skeletal health outcomes.

Education and public awareness campaigns also play a pivotal role in preventing skeletal loss due to calcium and vitamin D deficiencies. A previous study has shown that nutrition education interventions can effectively increase calcium intake and prevent bone loss, particularly in postmenopausal women [83]. These efforts, along with preventive healthcare interventions including regular bone mineral density screenings and monitoring of calcium and vitamin D levels, are particularly important for high-risk populations. European guidelines emphasize the importance of early detection and monitoring to prevent osteoporosis and related complications [84], underscoring the need for timely interventions to support long-term skeletal health outcomes.

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As discussed, this integrated approach of fortification, supplementation, education, and regular health monitoring is critical for mitigating the risk of bone-related health issues and enhancing overall public health. By addressing nutrient deficiencies and ensuring timely interventions, particularly for high-risk populations, this comprehensive strategy contributes significantly to improving skeletal health and preventing complications such as osteoporosis.

FUTURE APPROACHES FOR CALCIUM AND VITAMIN D DEFICIENCY

In the future, ensuring adequate calcium and vitamin D intake for skeletal health can be more effectively achieved through personalized nutrition and precision health approaches, integrating digital health tools, and developing global policies and awareness initiatives. These strategies will enable tailored dietary recommendations, improved monitoring of nutrient intake, and a broader understanding of bone health on a global scale, fostering better health outcomes and preventing bone-related complications such as osteoporosis.

As research advances, there is an increasing emphasis on personalized nutrition strategies that are tailored to individual needs based on genetic, environmental, and lifestyle factors. Studies have shown that calcium and vitamin D can be more effectively managed by considering specific genetic variants that influence nutrient metabolism [85-87]. This targeted approach allows for more precise dietary recommendations and supplementation strategies, leading to better health outcomes for individuals with unique genetic profiles [88]. By incorporating genetic data into nutritional planning, interventions can be more accurately designed to address deficiencies and optimize nutrient levels, particularly in at-risk populations.

Globally, calcium fortification practices vary, with fortification often being voluntary in many countries. In contrast, the United Kingdom mandates calcium fortification of wheat flour, ensuring that fortified flour significantly contributes to the nation's overall calcium intake [89]. This policy underscores the potential of fortification programs to improve public health outcomes without relying solely on individual choices or market trends. However, research suggests a need for a more rigorous evaluation of fortification programs, especially in areas where multiple micronutrient initiatives overlap, to ensure high-quality evidence supports these efforts [89]. For vitamin D fortification, it is critical to ensure that fortification processes do not negatively affect the nutrient's properties and stability. As demonstrated in the fortification of yogurt with vitamin D3, no negative impact on physicochemical and sensory properties was observed, and vitamin D3 loss was minimized with opaque packaging [90]. This highlights the need for further research on vitamin D fortification from various perspectives, including the development of improved packaging technologies to enhance its stability. Continued innovation in fortified food development is essential to address calcium and vitamin D deficiencies, particularly for populations with limited access to these nutrients.

Digital health tools, such as apps that track dietary intake, sun exposure, and physical activity, should be developed to help individuals more effectively monitor their calcium and vitamin D status. A meta-analysis showed that while mHealth-supported interventions for managing osteoporosis reduced pain and disability, they did not significantly improve calcium and vitamin D intake [91], highlighting the need for more advanced solutions to address this gap. As previously discussed regarding the potential and limitations of artificial intelligence (AI) in nutritional research [92], incorporating AI-based recommendations into

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these tools could further enhance their ability to personalize supplement doses and dietary plans. By leveraging real-time data on dietary habits, sun exposure, and physical activity, this approach could optimize calcium and vitamin D intake, ultimately supporting long-term bone health.

Telehealth, including phone or video consultations, can also be effectively utilized in osteoporosis management. As reported in studies on the advantages and disadvantages of telehealth use for osteoporosis management [93], it offers improved accessibility to care, especially for those in rural or underserved areas, while allowing for remote monitoring and assessments. However, challenges such as technology access and the need for in-person evaluations in certain cases remain considerations for its broader implementation.

Education and outreach programs should play an important role in future public health strategies, with attention given to educating both healthcare providers and the public about the importance of bone health across the lifespan and practical ways to meet calcium and vitamin D needs. Such programs must be culturally and regionally appropriate to effectively reach vulnerable populations.

CONCLUSIONS

In conclusion, addressing calcium and vitamin D deficiencies is crucial for maintaining skeletal health, particularly in regions where inadequate intake has contributed to an increased incidence of osteoporosis and compromised bone integrity. Implementing food fortification and supplementation in populations with limited dietary access to these nutrients is an essential strategy to mitigate these deficiencies. A comprehensive approach, integrating nutritional interventions, supplementation, and lifestyle modifications, alongside public health initiatives such as government-led fortification programs and educational campaigns, is necessary for effective bone loss prevention. Special consideration should be given to vulnerable populations, including older adults and individuals with limited sun exposure or dietary restrictions. Furthermore, the integration of personalized nutrition, digital health solutions, and forward-thinking public health policies offers a promising pathway to reducing the global impact of bone-related disorders and improving overall bone health.

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