Healthy Lifestyle Patterns and Vitamin D Status in Adult Women: A Comprehensive Review of Nutritional, Behavioral, and Age-Related Determinants

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ABSTRACT

Background: Vitamin D deficiency remains a pervasive yet under-recognized public health concern among adult women worldwide, with implications spanning skeletal integrity, metabolic function, reproductive health, and healthy ageing. While individual determinants such as dietary intake, sunlight exposure, and physical activity have been examined independently, the synergistic influence of composite lifestyle patterns on vitamin D status remains insufficiently characterized.

Objective: This comprehensive review synthesizes current evidence linking nutritional, behavioral, environmental, and age-related lifestyle factors with vitamin D status in adult women, and proposes a conceptual framework for a composite healthy lifestyle approach.

Methods: To identify relevant literature, we systematically searched PubMed/MEDLINE, Web of Science, Scopus, and Embase for articles published from 2014 to 2025. We used search terms related to vitamin D status, lifestyle habits, and women's health. The review included observational and interventional studies that reported serum 25-hydroxyvitamin D (25(OH)D) levels in relation to modifiable lifestyle factors among adult women.

Results: Evidence consistently demonstrates that dietary patterns rich in fortified foods, adequate outdoor physical activity, healthy body composition, and sufficient sleep are independently associated with favorable vitamin D status. However, the magnitude of these associations varies significantly across reproductive life stages, with postmenopausal women exhibiting attenuated cutaneous synthesis and altered metabolic responses. Composite lifestyle indices, though limited in number, suggest a dose-response relationship between overall lifestyle quality and vitamin D sufficiency.

Conclusions: Vitamin D status in adult women reflects a multidimensional interplay of nutritional, behavioral, environmental, and age-related factors. An integrated healthy-lifestyle framework may offer superior predictive value compared to isolated determinants, warranting prospective validation and age-stratified intervention research.

Keywords: Vitamin D; 25-hydroxyvitamin D; women's health; composite lifestyle score; diet; sunlight exposure; physical activity; obesity; ageing

INTRODUCTION

Vitamin D, a fat-soluble secosteroid hormone, occupies a central position in human physiology extending far beyond its classical role in calcium homeostasis and skeletal mineralization. Contemporary evidence

implicates vitamin D signaling in immune modulation, cardiovascular function, glucose metabolism, neuromuscular performance, and reproductive biology[1],[2]. Despite the availability of cutaneous synthesis through ultraviolet B (UVB) radiation and dietary sources, vitamin D deficiency; defined as serum 25-hydroxyvitamin D [25(OH)D] concentrations below 20 ng/mL (50 nmol/L), affects an estimated one billion individuals globally, with women representing a disproportionately affected demographic[3].

The heightened vulnerability of women to vitamin D insufficiency is multifactorial. Biological factors including greater adiposity, hormonal fluctuations across the reproductive lifespan, and reduced cutaneous synthetic capacity with ageing converge with sociocultural determinants such as clothing practices, indoor occupational patterns, caregiving responsibilities, and dietary restrictions[4],[5]. In many low- and middle-income countries, cultural norms limiting women's outdoor mobility and sun exposure compound nutritional inadequacies, creating a persistent deficiency burden even in sun-rich geographies[6],[7].

Concurrently, modern lifestyle transitions, characterized by sedentary occupations, increased screen time, processed food consumption, disrupted sleep architecture, and urban confinement, have fundamentally altered the behavioral landscape within which vitamin D status is determined[8],[9]. These shifts affect women differentially across life stages: young adult women navigating academic and early-career demands, middle-aged women balancing occupational and domestic responsibilities, and postmenopausal women confronting accelerated bone loss and metabolic changes[10],[11].

Critically, the existing literature has predominantly examined vitamin D determinants in isolation, assessing dietary intake without concurrent evaluation of physical activity, or measuring sun exposure without accounting for body composition or sleep patterns[12],[13]. This reductionist approach obscures the interactive and potentially synergistic effects of co-occurring lifestyle behaviors. Emerging evidence from composite lifestyle indices in cardiovascular and metabolic research suggests that aggregated health behavior scores capture risk more accurately than any single factor[14],[15]. Whether this principle extends to vitamin D status in women remains an open and consequential question.

Furthermore, the modulatory role of age and reproductive life stage on the lifestyle–vitamin D relationship has received insufficient attention. Physiological changes including declining renal 1α-hydroxylase activity, reduced dermal 7-dehydrocholesterol concentrations, and shifting body composition across the female lifespan may fundamentally alter the efficacy of lifestyle-based strategies for maintaining adequate vitamin D status[16],[17].

This comprehensive review aims to synthesize current evidence linking nutritional, behavioral, environmental, and age-related lifestyle factors with vitamin D status in adult women. Specifically, this review: (i) examines dietary and nutritional determinants of vitamin D status; (ii) evaluates behavioral and environmental factors including sunlight exposure, physical activity, adiposity, sleep, and substance use; (iii) analyzes age-stratified evidence across the female reproductive lifespan; and (iv) proposes a conceptual framework for a composite healthy lifestyle approach to vitamin D sufficiency, identifying critical research gaps and future directions.

METHODS AND SEARCH STRATEGY

Search Strategy

This comprehensive literature review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to minimize selection bias and ensure reproducibility. The systematic search was conducted between January and March 2026 using four electronic databases: PubMed/MEDLINE, Scopus, Web of Science, and Embase. The search encompassed studies published from January 2004 through December 2025 to capture contemporary evidence reflecting modern lifestyle patterns. Google Scholar was utilized as a supplementary source for grey literature and reference tracking.

The Boolean search strategy combined three conceptual domains:

Vitamin D biomarkers: ("Vitamin D" or "25-hydroxyvitamin D" or "25(OH)D" or "cholecalciferol" or "vitamin D deficiency" or "vitamin D status")

Lifestyle determinants: ("lifestyle" or "diet" or "nutrition" or "dietary pattern" or "sunlight" or "sun exposure" or "physical activity" or "sedentary behavior" or "obesity" or "body mass index" or "body composition" or "sleep" or "smoking" or "alcohol")

Population: "women" or "female" or "adult women" or "postmenopausal" or "reproductive age" or "pregnant"

Inclusion and Exclusion Criteria

Inclusion criteria: (a) original observational studies (cross-sectional, cohort, case-control) or randomized controlled trials reporting serum 25(OH)D concentrations; (b) study populations comprising adult women (above 18 years); (c) assessment of at least one modifiable lifestyle factor in relation to vitamin D status; (d) publication in English in peer-reviewed journals.

Exclusion criteria: (a) studies exclusively involving male participants, children, or adolescents; (b) animal or in vitro studies; (c) case reports, editorials, and conference abstracts without full-text availability; (d) studies focusing solely on pharmacological vitamin D supplementation without lifestyle assessment; (e) studies lacking quantitative vitamin D measurement.

Data Extraction and Synthesis

Two independent reviewers screened titles and abstracts, followed by full-text assessment of eligible articles. Data extracted included: author, year, country, study design, sample size, age range, vitamin D assay methodology, lifestyle factors assessed, and principal findings. Discrepancies were resolved through consensus. The methodological quality of included observational studies was assessed using the Newcastle-Ottawa Scale (NOS), with studies scoring above 7 classified as high quality.

Given the heterogeneity in study designs, populations, and outcome definitions, a narrative synthesis approach was adopted, organized thematically around lifestyle domains and age strata. To assess the quality of the evidence and mitigate the risk of bias, the methodological quality of included observational studies was assessed using the Newcastle-Ottawa Scale (NOS), with studies scoring above 7 classified as high quality. Discrepancies in quality assessment were resolved through discussion with a third reviewer.

Principles of Evidence Interpretation

- Systematic reviews, meta-analyses, and authoritative consensus/guideline documents are used to define the overall evidence pattern.
- Women-specific primary studies are used to examine dietary, behavioral, cultural, and age-related differences.
- Randomized trials are used to distinguish modifiable exposure effects from observational associations where possible.
- Cross-sectional findings are described as associations rather than causal effects.
- Different biochemical thresholds for vitamin D deficiency are not treated as directly interchangeable.
- The strength of evidence is considered when proposing components of a future Composite Healthy Lifestyle Score.

Vitamin D Metabolism and Women's Health

Vitamin D is acquired through two principal pathways: cutaneous synthesis of previtamin D_3 from 7-dehydrocholesterol upon UVB exposure (290–315 nm), and dietary absorption of vitamin D_2 (ergocalciferol) or D_3 (cholecalciferol) in the small intestine[18]. Both forms undergo hepatic 25-hydroxylation to 25(OH)D—the primary circulating biomarker—followed by renal 1α-hydroxylation to the biologically active 1,25-

dihydroxyvitamin D [1,25(OH)$_2$D], which mediates genomic and non-genomic effects through the vitamin D receptor (VDR) expressed in over 30 tissues[19].

In women, adequate vitamin D status supports calcium absorption and bone mineralization, reducing fracture risk particularly during postmenopausal bone loss[20]. Beyond skeletal health, vitamin D influences ovarian steroidogenesis, endometrial receptivity, and pregnancy outcomes, with deficiency associated with increased risks of preeclampsia, gestational diabetes, and bacterial vaginosis[21],[22]. Emerging evidence further links vitamin D sufficiency to favorable metabolic profiles, reduced systemic inflammation, and preserved muscle function, factors critical for healthy female ageing[23],[24].

The regulation of vitamin D metabolism is uniquely sensitive to lifestyle exposures: sun-dependent cutaneous synthesis is modulated by behavioral patterns (outdoor time, clothing, sunscreen use), while dietary contributions depend on food choices, fortification policies, and cultural dietary practices[25]. This positions vitamin D as an integrative biomarker of overall lifestyle quality, particularly relevant to women whose daily routines are shaped by intersecting biological, social, and environmental factors.

Nutritional and Dietary Determinants

Dietary Vitamin D Sources and Intake Patterns

Natural dietary sources of vitamin D are limited, with fatty fish (salmon, mackerel, sardines), cod liver oil, egg yolks, and UV-exposed mushrooms representing the richest options[26]. In the absence of routine fortification, dietary vitamin D intake in most populations falls substantially below recommended levels. Studies across diverse geographies consistently report median dietary vitamin D intakes of 2–5 μg/day among adult women, well below the 15–20 μg/day recommended by most national guidelines[27].

Fortified foods, particularly dairy products, plant-based milk alternatives, breakfast cereals, and orange juice; contribute significantly to vitamin D intake in countries with mandatory or voluntary fortification policies (e.g., United States, Canada, Finland, Australia)[28]. However, in many Asian, African, and Middle Eastern contexts where fortification is absent or limited, dietary vitamin D remains critically inadequate, particularly among women with restricted dietary diversity[29],[30].

Dietary Patterns and Vitamin D Status

Beyond individual nutrients, overall dietary patterns influence vitamin D status through multiple mechanisms. Western dietary patterns characterized by processed foods, refined carbohydrates, and low dairy or fish consumption are consistently associated with lower 25(OH)D concentrations[31]. Conversely, Mediterranean-style patterns emphasizing fatty fish, olive oil, dairy, and vegetables demonstrate positive associations with vitamin D sufficiency[32].

Vegetarian and vegan dietary patterns present specific challenges for vitamin D adequacy, as the primary natural sources are animal-derived. Studies among vegetarian women report 20–40% lower 25(OH)D levels compared to omnivorous counterparts, though this gap narrows with fortified food consumption and adequate sun exposure[33], 36]. Dietary diversity scores, encompassing variety across food groups, emerge as significant predictors of vitamin D status in women from low-income settings, where monotonous starch-based diets predominate[34].

Calcium, Micronutrient Interactions, and Supplementation

Adequate calcium intake synergizes with vitamin D in maintaining skeletal health, and concurrent deficiency of both nutrients is prevalent among women in South Asian, African, and Middle Eastern populations. Magnesium, zinc, and vitamin K2 serve as cofactors in vitamin D metabolism, and their dietary insufficiency may impair 25(OH)D utilization even when circulating levels appear adequate[35].

Vitamin D supplementation represents a direct intervention strategy, with daily doses of 1,000–2,000 IU effectively raising 25(OH)D concentrations in deficient individuals[36]. However, adherence to supplementation among women is variable, influenced by health literacy, cost, side-effect concerns, and the absence of acute symptomatic deficiency[37]. Supplementation should be viewed as complementary to, rather than substitutive of, lifestyle-based strategies for sustained vitamin D adequacy.

Behavioral, Environmental, and Anthropometric Factors

Sunlight Exposure and Cutaneous Synthesis

Sunlight exposure remains the predominant determinant of vitamin D status for most populations, contributing an estimated 80–90% of circulating 25(OH)D under optimal conditions[38]. Effective cutaneous synthesis requires direct UVB exposure to uncovered skin (face, arms, legs) for approximately 10–30 minutes, depending on latitude, season, time of day, skin pigmentation, and age[39].

Among adult women, sun exposure behaviors are profoundly shaped by occupational patterns, domestic responsibilities, cultural clothing practices, and urban built environments. Studies from the Middle East, South Asia, and North Africa consistently identify full-body clothing (hijab, niqab, burqa) as a major determinant of vitamin D deficiency, with covered women exhibiting 2–3-fold higher odds of deficiency compared to those with greater skin exposure[40],[41]. However, this relationship is modifiable through targeted sun exposure of hands and face, timing adjustments, and dietary compensation.

Seasonality significantly modulates vitamin D status, with nadir concentrations observed in late winter and peak levels in late summer across temperate latitudes. Urban women, particularly those in indoor occupations with limited outdoor break time, demonstrate reduced UVB exposure regardless of geographic latitude. Sunscreen use (SPF ≥30), while essential for skin cancer prevention, reduces cutaneous vitamin D synthesis by >95% when applied comprehensively[42], creating a clinical tension that requires balanced public health messaging.

Physical Activity and Sedentary Behavior

Physical activity influences vitamin D status through both direct and indirect pathways. Outdoor physical activity: walking, cycling, gardening, sports—simultaneously increases UVB exposure and promotes musculoskeletal health, creating a synergistic benefit for vitamin D-dependent outcomes[43]. Cross-sectional studies consistently report higher 25(OH)D concentrations among physically active women compared to sedentary counterparts, with effect sizes ranging from 2–6 ng/mL differences in mean concentrations[44],[45].

However, the independent contribution of physical activity beyond sun exposure remains debated. Indoor exercise (gym-based training, yoga, swimming in enclosed facilities) may improve muscle function and body composition without augmenting vitamin D synthesis. Sedentary behavior, prolonged sitting, and excessive screen time (>4 hours/day) are independently associated with lower 25(OH)D levels, likely reflecting reduced outdoor time and concurrent unhealthy dietary patterns[46],[47].

The domestic and caregiving roles that characterize many women's daily routines present both barriers and opportunities. Household physical activity (cleaning, cooking, childcare) may not achieve the intensity thresholds for metabolic benefit but does involve indoor movement with minimal sun exposure. Community-based interventions promoting outdoor walking groups, park-based exercise, and active transportation represent contextually appropriate strategies for enhancing vitamin D status among women with limited leisure time[48].

Adiposity and Body Composition

The inverse association between adiposity and circulating 25(OH)D is among the most consistent findings in vitamin D epidemiology. Obese women (BMI ≥30 kg/m²) exhibit 20–35% lower 25(OH)D concentrations compared to normal-weight counterparts, with a dose-response relationship across the BMI spectrum[49],[50].

Proposed mechanisms include volumetric dilution of vitamin D in expanded adipose tissue, sequestration of fat-soluble vitamin D in lipid stores reducing bioavailability, and adipocyte-mediated inflammatory pathways impairing hepatic 25-hydroxylation[51],[52].

Waist circumference and body fat percentage may be more informative indicators than BMI alone, particularly among women with sarcopenic obesity or central adiposity patterns characteristic of postmenopausal metabolic changes[53]. Weight loss interventions (bariatric surgery, caloric restriction) demonstrate paradoxical effects: while reducing adipose sequestration, rapid weight loss may transiently release stored vitamin D, complicating interpretation of post-intervention levels.

The obesity- vitamin D relationship carries particular relevance for women given higher population-level adiposity prevalence, hormonal interactions with adipose tissue, and the compounding effects of vitamin D deficiency on insulin resistance, polycystic ovary syndrome (PCOS), and pregnancy complications[54].

Sleep, Circadian Rhythms, and Daily Activity Pattern

An emerging and underexplored determinant of vitamin D status is sleep architecture and circadian behavioral patterns. Vitamin D receptors are expressed in hypothalamic regions governing sleep-wake regulation, and observational studies report associations between vitamin D deficiency and short sleep duration (<6 hours), poor sleep quality, and excessive daytime sleepiness[55],[56].

The directionality of this relationship remains unclear: vitamin D deficiency may impair sleep regulation, while poor sleep may reduce outdoor activity and sun exposure the following day, creating a bidirectional feedback loop[57]. Shift work, prevalent among women in healthcare, manufacturing, and service sectors, disrupts circadian rhythms and limits daytime sun exposure, with preliminary evidence suggesting lower 25(OH)D concentrations among night-shift workers[58].

Screen-based sedentary leisure (television, smartphones, computers) displaces outdoor activity and is associated with irregular sleep timing, creating a clustered lifestyle pattern detrimental to vitamin D status[59]. The integration of sleep hygiene into lifestyle-based vitamin D interventions represents a novel and promising frontier.

Smoking, Alcohol, and Other Modifiable Behaviors

Smoking is associated with lower 25(OH)D concentrations through multiple mechanisms: impaired hepatic hydroxylation, increased catabolism via CYP24A1 induction, reduced outdoor physical activity, and concurrent poor dietary quality[60]. Among women, smoking prevalence varies dramatically by geography and socioeconomic status, with significant implications for vitamin D status in populations where female smoking is increasing.

Excessive alcohol consumption (>2 drinks/day) impairs hepatic 25-hydroxylation and is associated with lower vitamin D status, though moderate consumption shows inconsistent relationships[61]. Caffeine intake may modestly influence vitamin D receptor expression, though clinical significance remains uncertain[62]. These behavioral factors, while less directly influential than diet, sun exposure, and adiposity, contribute to the overall lifestyle milieu shaping vitamin D status.

Age-Stratified Perspectives Across the Female Lifespan

Young Adult Women (18–35 Years)

Young adulthood represents a critical window for peak bone mass consolidation, making vitamin D sufficiency particularly consequential. However, this demographic exhibits paradoxically high deficiency prevalence (40–70% in many populations), driven by indoor academic or occupational routines, sedentary leisure patterns, irregular dietary habits, and cosmetic sun avoidance[63],[64].

Lifestyle determinants in this age group are predominantly behavioral: physical inactivity, inadequate dietary diversity, insufficient sun exposure due to screen-based leisure, and suboptimal sleep. Interventions targeting outdoor physical activity, fortified food consumption, and health literacy demonstrate particular efficacy in this demographic, where habits are still malleable[65].

Reproductive-age women planning pregnancy represent a subgroup of special concern, as preconception vitamin D status influences fetal skeletal development, immune programming, and pregnancy outcomes[66]. Preconception lifestyle counseling incorporating vitamin D optimization should be integrated into women's primary healthcare.

Reproductive-Age and Pregnant Women (25–40 Years)

Pregnancy and lactation dramatically increase the physiological demand for vitamin D, as the maternal skeleton must supply calcium for fetal skeletal mineralization (Cashman et al., 2016 [3]). Vitamin D deficiency during pregnancy has been linked to preeclampsia, gestational diabetes, preterm birth, and low birth weight (Harinarayan et al., 2007 [11]; Khan et al., 2024 [40]).

Lifestyle factors during this life stage are uniquely constrained. Pregnant women often reduce outdoor physical activity due to fatigue, physical discomfort, or medical advice, and dietary patterns may shift due to nausea, food aversions, or cultural food taboos [Author, Year]. In many South Asian and Middle Eastern cultures, pregnant women are encouraged to remain indoors and avoid sun exposure, further compounding the risk [Author, Year]. Home Science and community health professionals play a vital role in designing culturally sensitive prenatal nutrition and lifestyle programs that address these barriers.

Middle-Aged and Perimenopausal Women (36–50 Years)

The perimenopausal transition introduces hormonal changes (declining estrogen, irregular cycles) that interact with vitamin D metabolism and bone turnover. Women in this age group often face compounded lifestyle challenges: peak occupational demands, caregiving responsibilities for children and ageing parents, reduced leisure time for outdoor activity, and stress-related dietary changes[67],[68].

Evidence suggests that the protective effect of healthy lifestyle patterns on vitamin D status remains robust in this age group, though the relative contribution of individual factors may shift. Dietary quality and body weight management become increasingly important as cutaneous synthetic capacity begins to decline and metabolic changes promote central adiposity[69]. Community-based interventions addressing time-efficient outdoor activity, dietary modification, and stress management are particularly relevant.

Postmenopausal and Older Women (≥51 Years)

Post menopause represents the period of greatest vitamin D vulnerability. The combination of estrogen withdrawal (accelerating bone resorption), reduced dermal 7-dehydrocholesterol (decreasing cutaneous synthesis by up to 75%), declining renal 1α-hydroxylase activity, and lifestyle changes (reduced mobility, institutionalization, social isolation) creates a multifactorial deficiency risk[70],[71].

Lifestyle interventions in this demographic must be adapted to physiological realities. While outdoor activity and dietary optimization remain beneficial, the attenuated cutaneous and renal responses to vitamin D precursors mean that lifestyle modifications alone may be insufficient to achieve sufficiency, necessitating targeted supplementation alongside behavioral strategies[72],[73]. The age-stratified evidence collectively demonstrates that the relationship between lifestyle and vitamin D status is not static but evolves across the female lifespan, with implications for age-appropriate public health recommendations and intervention design.

Towards a Composite Healthy Lifestyle Framework

The central proposition of this review is that vitamin D status in adult women may be better understood by evaluating clusters of favorable or unfavorable behaviors rather than isolated predictors. This does not mean

that all lifestyle components are equally causal or should be equally weighted. Instead, the composite approach provides a framework for representing real-life behavioral clustering and testing cumulative associations.

Proposed Domains and Scientific Weight

Domain	Candidate Indicator	Evidence Strength	Role in Future Score
Dietary quality	Vitamin-D-rich/fortified foods, diet diversity, calcium-rich foods	Moderate	Core
Sun/outdoor behavior	Duration, timing, body surface exposed, clothing, season	Strong	Core
Physical activity	Total activity plus outdoor activity separately	Moderate	Core
Adiposity	BMI, waist circumference, body-fat measure	Strong association	Modifier/mediator or secondary component
Sleep/daily routine	Duration, quality, regularity	Emerging	Exploratory
Smoking	Current/non-use	Context-dependent for vitamin D	Optional
Alcohol	Population-appropriate category	Context-dependent	Optional
Vitamin D supplements	Dose, frequency, duration	Strong direct biochemical effect	Adjustment variable, not core behavior

Table 1. Proposed domains for a Female Vitamin D-Healthy Lifestyle Framework.

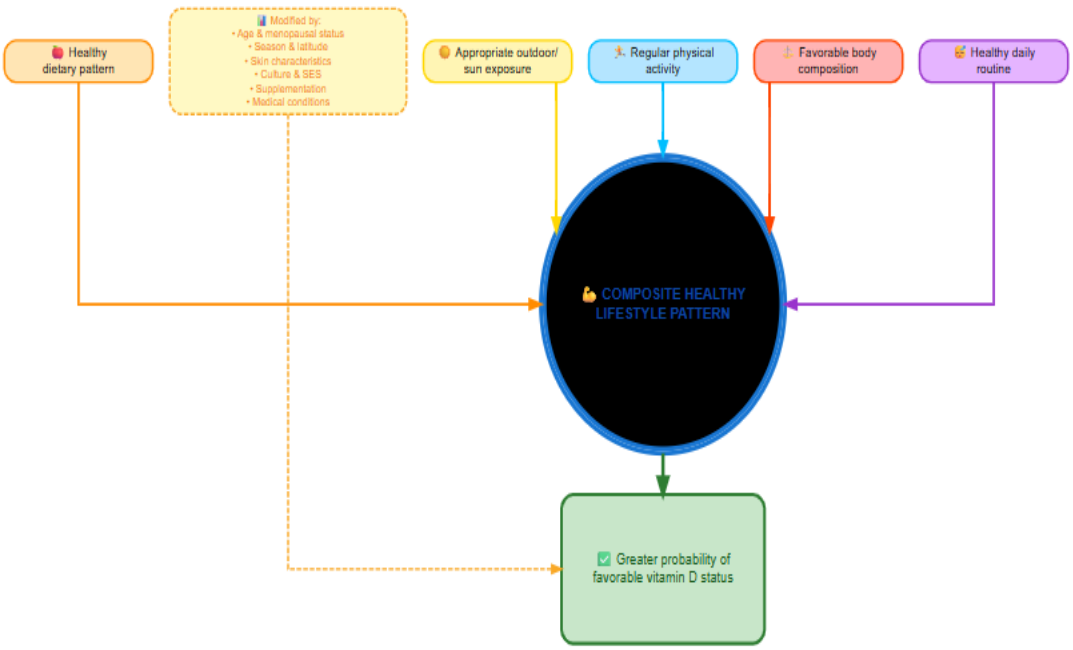

Figure 1. Proposed research framework; not a clinically validated diagnostic score.

Modified by age, menopausal status, season, latitude, skin characteristics, culture, socioeconomic status, supplementation, and medical conditions

Panoramic View of the Evidence

The matrix below opens a panoramic window onto the evidence, showcasing representative studies that shape the scientific argument of this review. It is curated for breadth and illustration rather than constructed as a PRISMA-defined included-study table.

Table 2. Representative Evidence Matrix: Study Design, Population, and Key Findings

Study	Design	Population	Key Contribution
Cui et al. 2023[74]	Pooled analysis	Global populations	Demonstrated substantial global/regional variation in vitamin D deficiency.
Siddiqee et al. 2021[75]	Systematic review/meta-analysis	South Asian adults	Confirmed high and heterogeneous burden in South Asia.
Cashman et al. 2016 [13]	Standardized population analysis	European populations	Showed how assay standardization and season alter prevalence estimates.
Demay et al. 2024[76]	Clinical practice guideline	Healthy populations	Updated approach to routine testing, supplementation, and thresholds.
Harinarayan et al. 2008 [29]	Cross-sectional	South Indian adults	Linked low dietary calcium/high phytate with low vitamin D; strong female burden.
Tripkovic et al. 2017[77]	Randomized fortification trial	South Asian/White European women	D3-fortified foods improved winter 25(OH)D more than D2.
Dunlop et al. 2021[78]	Systematic review/meta-analysis	Adults/children	Supported food fortification/biofortification for increasing 25(OH)D.
Grønborg et al. 2020[79]	Randomized controlled trial	Danish/Pakistani-origin women	Fortified foods improved winter vitamin D status.
de Santana et al. 2022 [18]	Women-specific observational study	Brazilian women	Integrated sunlight, diet, health, and lifestyle factors.
Alyahya. 2020[80]	Cross-sectional	Premenopausal Kuwaiti women	Low milk/fish intake and limited weekend sun exposure predicted deficiency.
Jaruratanasirikul et al. 2023[81]	Cross-sectional	Nonpregnant reproductive-age Thai women	Examined BMI, diet, sunlight, and socioeconomic factors.
Lhilali et al. 2023[82]	Cross-sectional	Moroccan women of childbearing age	Sun-exposure score related to vitamin D status.
Vičič et al. 2022[83]	Cross-sectional	Premenopausal/post menopausal women	Supplementation and time in sun were major predictors.

Khan et al. 2024[84]	Systematic review/meta-analysis	Intervention studies	Vitamin D improvement mainly associated with outdoor activity.
Farrell et al. 2022[85]	Longitudinal cohort	Healthy women	Physical activity and adiposity jointly related to 25(OH)D.
Abiri et al. 2024[86]	Women-focused review	Women	Most studies reported inverse vitamin D-adiposity relationships.
Tobias et al. 2023[87]	Randomized cohort analysis	Adults	Higher BMI was associated with a blunted biochemical response to supplementation.
Gao et al. 2018 [55]	Systematic review/meta-analysis	Adults	Low vitamin D was associated with sleep disorders, but causality remained uncertain.
Larsen et al. 2021[88]	Randomized trial	Vitamin-D-insufficient adults	Supplementation did not improve sleep outcomes.
Millen et al. 2010[89]	WHI analysis	Postmenopausal women	Multiple dietary, anthropometric, activity, and solar factors predicted vitamin D.
Kuwabara et al. 2024[90]	Nationwide cross-sectional	Young Japanese women	Developed ViDDPreS multidimensional prediction score.
Jeong et al. 2026[91]	Lifestyle screening study	Older women	Evaluated lifestyle-based questionnaire for vitamin D deficiency.
Naureen et al. 2020[92]	Systematic review	Adults	Prediction tools showed promise but variable sensitivity/specificity.
Sohl et al. 2014[93]	Prediction model	Older adults	Demonstrated feasibility of risk prediction using simple characteristics.

Note: 25(OH)D thresholds for deficiency varied across included studies (e.g., <20 ng/mL, <30 ng/mL, <30 nmol/L, and <50 nmol/L), and assay methodologies were not uniformly standardized, which may contribute to inter-study heterogeneity.

Synthesis of Evidence

The most consistent lifestyle-related evidence concerns actual sunlight/outdoor exposure, supplement use, and adiposity. Dietary vitamin D and food fortification have moderate-to-strong evidence as modifiable inputs, particularly in settings with low UVB availability or limited personal sun exposure. Outdoor physical activity is relevant but should not be interpreted independently of UVB exposure. Sleep and circadian behavior remain emerging associated domains.

A composite lifestyle score is attractive because it represents behavioral clustering, but equal weighting may obscure important differences in evidence strength. A scientifically robust score should therefore compare simple equal weighting with regression-derived or other data-driven weighting and should assess whether BMI belongs within the score or outside it as a mediator/modifier.

Age stratification should be treated as effect modification rather than a cosmetic subgroup analysis. The combination of behaviors that identifies deficiency in a 20-year-old may not be the same as that in a postmenopausal woman. Prediction models should therefore be validated by life stage.

Differentiating Evidence from RCTs and Observational Studies: It is critical to distinguish between observational associations and interventional efficacy. While observational studies robustly link lifestyle factors (e.g., outdoor activity, adiposity) to 25(OH)D status, they cannot establish causation. Reverse causation remains a plausible confounder; for instance, low vitamin D may contribute to metabolic dysfunction and weight gain, just as obesity causes volumetric dilution of vitamin D. Conversely, Randomized Controlled Trials (RCTs) and fortification studies (e.g., Tripkovic et al., 2017; Grønborg et al., 2020) provide causal evidence that targeted dietary fortification and outdoor physical activity interventions directly elevate serum 25(OH)D. Furthermore, methodological heterogeneity across studies, including variations in assay types (LC-MS/MS versus immunoassays), differing 25(OH)D deficiency thresholds (20 ng/mL versus 30 ng/mL), and the inherent recall bias in self-reported dietary and sun-exposure data, complicates direct pooling. Future research must prioritize standardized biochemical assays and objective exposure measurements (e.g., dosimeters for UVB exposure) to reduce this heterogeneity.

Practical Clinical and Public Health Guidance

Based on the synthesized evidence, the following practical recommendations are proposed for clinicians, dietitians, and public health planners to optimize vitamin D status in adult women:

Dietary Optimization: Women should be encouraged to consume vitamin D-rich foods, including fatty fish (salmon, mackerel), egg yolks, and UV-exposed mushrooms[94]. In regions with mandatory fortification, dairy products, plant-based milk alternatives, and fortified cereals should be emphasized[95]. For women following vegetarian or vegan diets, fortified foods or supplements are essential to bridge the dietary gap[96].

Safe Sun Exposure: Cutaneous synthesis remains the most efficient source of vitamin D. Women should be advised to obtain 10–30 minutes of midday sun exposure to the face, arms, and legs, 2–3 times per week, without sunscreen. This must be balanced with skin cancer prevention; prolonged exposure beyond the point of mild erythema should be avoided, and sunscreen (SPF ≥30) should be applied thereafter[97].

Supplementation Doses and Upper Limits: When lifestyle modifications are insufficient, supplementation is required. For deficient women, the Endocrine Society recommends 50,000 IU weekly for 8 weeks, followed by a maintenance dose of 1,500–2,000 IU daily[98]. The safe upper limit for adults is generally recognized as 4,000 IU/day to avoid hypercalcemia and toxicity, though higher doses may be used short-term under strict medical supervision.

Guidance for Special Populations:

- Pregnant and Lactating Women: Due to increased fetal and neonatal demands, pregnant women should maintain a daily intake of at least 600–2,000 IU of vitamin D, alongside adequate calcium, to prevent preeclampsia and support fetal skeletal mineralization[99].
- Postmenopausal and Older Women: Due to a 75% reduction in cutaneous synthetic capacity and declining renal hydroxylation, lifestyle modifications alone are often insufficient. Older women should rely on a combination of dietary intake and daily supplementation (800–2,000 IU) to maintain 25(OH)D levels >30 ng/mL for optimal bone and muscle health[100].
- Veiled Women and Those with High Skin Pigmentation: Women practicing full-body covering (e.g., hijab, burqa) and those with darker skin pigmentation (higher melanin content) require significantly longer sun exposure to synthesize equivalent amounts of vitamin D. For these groups, dietary fortification and routine supplementation (1,500–2,000 IU/day) are highly recommended as primary preventive strategies, as behavioral sun-exposure modifications may be culturally or physiologically impractical[101].

CONCLUSION

Vitamin D deficiency in adult women is not merely a nutritional shortfall. Still, it reflects the complex interplay among dietary patterns, sunlight exposure behaviors, physical activity levels, body composition, sleep architecture, and the physiological transitions that characterize the female lifespan. This comprehensive

review demonstrates that no single lifestyle factor operates in isolation; rather, vitamin D status emerges from the cumulative and interactive effects of multiple modifiable behaviors embedded within social, cultural, and environmental contexts.

The evidence supports a paradigm shift from reductionist, single-factor analyses toward integrated, composite lifestyle frameworks that capture the multidimensional determinants of vitamin D sufficiency. Such an approach aligns with the principles of Home Science and public health nutrition, emphasizing practical, household- and community-level interventions that address the root behavioral and environmental drivers of deficiency.

The scientific opportunity is to move beyond a single-risk-factor paradigm toward a rigorously validated composite lifestyle framework. Future studies should develop age-sensitive and culturally appropriate indices, explicitly account for season and supplement use, separate behavior from anthropometric outcomes, and prospectively test whether cumulative healthy lifestyle patterns predict vitamin D status.

However, the proposed composite lifestyle framework remains conceptual and requires rigorous empirical validation across diverse populations and life stages. Future research must prioritize longitudinal designs, age-stratified analyses, objective exposure measurement, and the integration of biological, behavioral, and socioecological perspectives. Only through such comprehensive inquiry can evidence-based, life-stage-appropriate strategies be developed to address the persistent burden of vitamin D deficiency among women worldwide.

Limitations of the Current Evidence: While this review synthesizes a broad array of literature, several limitations must be acknowledged. The predominance of cross-sectional and observational studies in the current literature precludes definitive causal inferences. Reverse causation is a notable risk, particularly regarding adiposity and physical activity. Additionally, the reliance on self-reported data for dietary intake and sun exposure introduces recall bias, and the lack of standardized 25(OH)D assays and uniform deficiency thresholds across studies creates methodological heterogeneity. Finally, while non-skeletal benefits of vitamin D (e.g., immune modulation, reproductive health) are highlighted, the evidence for these outcomes is less robust than for skeletal health, warranting cautious interpretation.

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