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Effect of vitamin D supplementation on bone health in Black, Asian and other non-White Ethnic adults: a systematic review and meta-analysis

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Abbreviations

BALP, bone-specific alkaline phosphatase

BMD, bone mineral density

BTM, bone turnover marker

CTX, C-terminal crosslinked telopeptide of type 1 collagen

- 23 IQR, interquartile range
- 24 IU, international unit
- 25 MeSH, Medical Subject Heading
- 26 OC, osteocalcin
- 27 PICP, procollagen type I C-terminal propeptide
- 28 PINP, procollagen type I N-terminal propeptide
- 29 PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses
- 30 RCT, Randomised Controlled Trial
- 31 RoB-2, Risk of Bias-2
- 32 SMD, standardised mean difference
- 33 TRAP 5b, tartrate-resistant acid phosphatase 5b

Abstract

Background: Evidence on the effects of vitamin D supplementation on bone health is inconsistent, and no systematic review has focused specifically on non-White ethnic populations, who are at higher risk of vitamin D deficiency.

Objective: To evaluate the effects of vitamin D supplementation on bone health in non-White adults.

Methods: CENTRAL, MEDLINE, AMED, EMBASE, EMCARE, CINAHL, and APA PsycInfo were searched from inception to September 2025. Randomised controlled trials involving all ethnic groups other than White adults receiving vitamin D supplementation of any dose or route were included. Outcomes were bone mineral density (BMD), bone turnover markers (BTMs), and fractures. Data were narratively synthesised, with meta-analyses conducted for BTMs using random-effects models. Risk of bias was assessed using the Cochrane Risk-of-Bias 2 tool.

Results: Twelve trials (13 articles) involving 8,023 participants aged 18–90 years were included. Study populations comprised Black Africans, South Asians, South Koreans, and Chinese. Intervention duration ranged from 3 months to 5.3 years, with vitamin D doses from 400–6,400 IU/day. Of eight studies assessing BMD, only one study conducted in South Asians, reported significantly higher femoral neck and trochanter BMD after 12 months of vitamin D supplementation (400 IU/day) compared with placebo ($p < 0.001$). The primary meta-analysis showed significantly higher BALP concentrations in the vitamin D supplementation groups than in the control groups (SMD 0.96, 95% CI 0.09–1.83; $p = 0.031$), with substantial heterogeneity ($I^2 = 97.1\%$). However, after excluding one clinically distinct study in which both groups received risedronate, the pooled effect was attenuated and no longer statistically significant (SMD 0.64, 95% CI -0.14–1.41). Only one study examined fractures ($n = 5,106$) and found no significant difference between groups.

59 **Conclusion:** Evidence supporting vitamin D supplementation for improving bone health in
60 non-White adults remains limited.

61 **Keywords:**

62 Vitamin D; ethnicity; bone health; bone mineral density; bone turnover marker; fracture

63

Introduction

Vitamin D (vitD) plays a critical role in maintaining bone health through regulation of calcium and phosphorus metabolism (1). VitD status is assessed by serum 25-hydroxyvitamin D [25(OH)D] concentrations (2). Although there is no universally accepted definition of deficiency (3), there is a broad consensus that concentrations below 25 nmol/L (10 ng/mL) represent a serious public health concern (4).

Low serum 25(OH)D concentrations trigger secondary hyperparathyroidism, increasing bone resorption and leading to skeletal complications such as rickets in children (5) and osteomalacia in adults (2). VitD deficiency is prevalent worldwide and disproportionately affects individuals with darker skin pigmentation, including Black African, Black Caribbean, and South Asian populations, due to reduced cutaneous synthesis resulting from higher melanin content (4). In the UK, mean 25(OH)D concentrations were substantially lower among Black and South Asian adults than White adults (6). Similar disparities have been reported in the USA (7). However, African Americans exhibit similar (8) or higher bone mineral density (BMD) (9) and a lower or similar risk of fragility fractures than White Caucasians (10, 11). This “vitamin D paradox” in the American Black population (12) suggests that optimal vitD thresholds may differ by ethnicity, although the vitamin D paradox observed in Black populations may not be universally applicable to other ethnicities.

Previous systematic reviews and meta-analyses regarding the effects of vitD supplementation on bone mineral density (BMD) (13-16), fracture risk (17, 18), and bone turnover markers (BTMs) (19) generally did not stratify outcomes by ethnicity and were conducted predominantly in White Caucasian populations. Consequently, the effectiveness of vitD supplementation for improving bone health in Black, Asian, and other underrepresented

ethnic populations remains unclear. The present systematic review and meta-analysis aimed to assess the effects of vitD supplementation on bone health outcomes, including BMD, fracture risk and BTMs in non-White ethnic adults.

Methods

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (20) and was prospectively registered on the PROSPERO International Prospective Register of Systematic Reviews (CRD42022356933). The final search was conducted up to September 2025, extending the search period beyond September 2022 as specified in the original registration. No other changes to the registered methods were made.

Eligibility criteria

Peer-reviewed, full publications in English that met the criteria reported in Table 1 were eligible for inclusion. Eligibility criteria were set out using the Population, Intervention, Control, Outcomes and Study design (PICOS) framework (21). Apart from the exclusion criteria shown in Table 1, studies were excluded if they were available only in abstracts, conference proceedings, editorials, dissertations, in languages other than English, or no clear results were reported.

Search strategy

We searched for articles using Medical Subject Headings (MeSH) terms, keywords, and index terms combined with Boolean operators “AND” and “OR”. Truncation and wildcards (*) were used to detect words with differences in spelling. The databases MEDLINE, AMED, EMBASE, EMCARE, and APA PsycInfo via Ovid, Cochrane CENTRAL, and CINAHL

(EBSCOhost), were searched from inception until September 2025. The full search strategy is provided in Supplementary Document S1.

Study selection

All identified articles were imported into EPPI-reviewer software (22) and duplicates were removed. Two reviewers independently screened the titles and abstracts to exclude studies that did not meet the eligibility criteria. Full texts of the remaining articles were retrieved. The primary reviewer (JYS) screened all the full texts, and three other reviewers (KM, HD, SH) each screened one-third of the studies independently. Any disagreements were resolved through discussion.

Data extraction

A data extraction form was used to extract quantitative data from included papers by HD and JYS and was cross-checked independently by KM and SH. The extracted information included study reference, first author and publication year, and country of the study, study population (age, ethnicity etc.), sample size (at the beginning and the end of study), attrition, intervention (dose, period and cumulative dose), comparator (placebo or control), outcome measures relating to bone health, results and adverse effects. Ethnicity was defined according to the classifications reported by the authors of the included studies. The cumulative vitD dose over the intervention periods was calculated based on 30 days per month and the weekly dose was converted to daily dose before calculating.

Quality assessment

A quality assessment using Cochrane Risk of Bias-2 (RoB-2) assessment tool for RCTs (23) was conducted to assess the risk of bias in all included trials by three reviewers (JYS, KM, SH) with disagreements resolved through further discussion among the reviewers. The tool

assesses five domains (randomisation process; deviations from intended interventions; missing outcome data; measurement of the outcome; selection of the reported result) plus overall bias, and each trial was classified as being at high risk, some concerns, or low risk of bias.

Data synthesis

Descriptive statistics were used to present characteristics of the included studies in a table. The results were reported based on the outcomes of BMD, fracture and BTMs separately with narrative description. A meta-analysis was not conducted for BMD because most included studies reported outcomes only in graphical format and did not provide sufficient numerical data. Although data digitization was considered, the limited availability of accompanying variance measures and the potential for extraction error were judged to compromise the reliability of pooled estimates. Consequently, the findings were synthesised narratively. Only one study investigated the outcome of fractures. Therefore, meta-analysis was only performed for BTMs.

Meta-analysis and assessment of heterogeneity and publication bias for BTMs

The meta-analyses on BTMs were performed using the statistical software Jamovi (version 2.2.5, the Jamovi Project) and were carried out using the standardised mean differences (SMD). A random-effects model was fitted to the data. The amount of heterogeneity (i.e., τ^2), was estimated using the DerSimonian-Laird estimator (24). In addition to the estimate of τ^2 , the Q-test for heterogeneity (25) and the I^2 statistic (26) were reported. The Begg rank correlation test and the Egger's regression test, using the standard error of the observed outcomes as predictor, were used to check for the publication bias. These analyses were conducted in R (version 4.5.3; R Foundation for Statistical Computing, Vienna, Austria). However, it is important to note that Egger's test might have limited ability to identify

publication bias in analyses with a small number of studies (27). Due to the small number of studies, no subgroup analysis was conducted.

Where numerical outcome data required for meta-analysis were not reported, the study was excluded from the relevant quantitative synthesis, and its findings were synthesised narratively.

All statistical tests were two-sided, and $p < 0.05$ was considered statistically significant. Exact p -values and 95% confidence intervals (95% CIs) were reported where available.

Results

Search results

Figure 1 shows the PRISMA flow chart. A total of 1,365 articles were retrieved, and 758 articles were identified after excluding 607 duplicates. After screening the titles and abstracts, 629 articles failed to meet the inclusion criteria and were excluded, and 129 articles were selected for full-text screening, of which 116 articles were excluded due to multiple reasons. Hence, 12 trials reported in 13 papers were included in this review.

Trial characteristics

Table 2 summarises the data from the 12 RCTs in 13 papers that were published between 2005 and 2025. Two papers are from the same study (11, 28) (6a and 6b in Table 2). Only data comparing vitD supplementation with the corresponding control or placebo group are presented in Table 2. The studies were conducted in various countries, in the USA ($n = 6$) (9, 11, 28-31), New Zealand ($n = 1$) (32), Denmark ($n = 2$) (33, 34), South Korea ($n = 2$) (35, 36), Bangladesh ($n = 1$) (37) and China ($n = 1$) (38). Study populations included Black Africans ($n = 6$) (9, 11, 28-31), South Asians ($n = 4$) (32-34, 37), South Koreans ($n = 2$) (35, 36), and

Chinese ($n = 1$) (38). The two South Korean studies (35, 36) used patients with osteoporosis, while all other studies were on generally healthy people. Eight studies (66.7%) included females only (9, 29-34, 37) and four studies (33.3%) included both males and females (11, 28, 35, 36). All 13 papers included 8,023 participants aged from 18 to 90 years.

Intervention characteristics

Four out of 13 studies had bone health as their primary outcomes (29, 30, 33, 36), five as secondary outcomes (31, 32, 34, 35, 38), two were ancillary studies (11, 28) and two did not clearly state (9, 37). Most studies compared vitD supplementation with placebo. Exceptions included two studies comparing vitD plus risedronate with risedronate alone (35, 36), one comparing vitD plus calcium with calcium alone (30), and one used low dose of 400 IU/day as control (9). Daily supplementation was used in all studies except for two (35, 36) that provided vitD3 supplementation weekly. All studies provided vitD supplementation via tablet or capsule form except one via food fortification (34). All studies provided vitD3 supplementation except one that did not specify (37). Doses of vitD in the intervention groups ranged from 400 IU/day ($n = 2$) (33, 37), 800 IU/day ($n = 3$) (30, 33, 36), 1,000 IU/day ($n = 1$) (31), 1,200 IU/day ($n = 1$) (34), 2,000 IU/day ($n = 4$) (11, 28, 30, 38), 4,000 IU/day ($n = 1$) (32), to 6,400 IU/day ($n = 1$) (9). The age of study participants ranged between 18–90 years. Multiple doses were used in three studies, either at different stages of the intervention (29, 30), or in different intervention groups (33). Intervention durations varied from 3 months ($n = 1$) (34), 4 months ($n = 1$) (35), 6 months ($n = 2$) (9, 32), 12 months ($n = 3$) (33, 36, 37), 20 months ($n = 1$) (38), 24 months ($n = 2$) (28, 31), 36 months ($n = 2$) (29, 30), and a median of 5.3 years ($n = 1$) (11). The cumulative vitD doses were between 96,000 IU and 3,869,000 IU. All included studies showed a significant increase in serum 25(OH)D concentration in the vitD group (baseline range: 18.0–69.1 nmol/L; end of intervention: 40.0–117.0 nmol/L),

while no significant changes were observed in the placebo group, except in the study with vitD supplementation of 400 IU/day as comparator (9).

Attrition, calculated from pre- and post-trial participant numbers, ranged from 3% to 50%, though one study (11) did not report post-trial numbers. The adherence to the study supplementation was reported in one study as 95.2% at 6 months, 94.3% at 12 months and 93.0% at 24 months according to a self-reported questionnaire (28).

BMD

Table 3 summarises the studies that reported specific BMD outcomes. Of the 12 included studies, 8 measured BMD at various skeletal sites: spine ($n = 8$) (9, 28-31, 33, 36, 37), femoral neck ($n = 6$) (9, 28, 29, 31, 36, 37), total hip ($n = 5$) (9, 28, 30, 31, 36), whole body ($n = 5$) (9, 28-30, 33), trochanter ($n = 3$) (29, 31, 37), radius ($n = 2$) (29, 30), and total femur ($n = 1$) (29). Reporting formats varied across the studies including percentage change ($n = 4$) (29-31, 36), change in areal BMD (aBMD) ($n = 1$) (28), median (IQR) ($n = 1$) (33), and change in BMD ($n = 1$) (37). In addition, five studies reported BMD in figures (9, 29-31, 36).

Aloia et al. (30) studied 208 postmenopausal Black American women receiving 2,000 IU/day of vitD₃ plus 1,200 – 1,500 mg/day calcium for 36 months. Although serum 25(OH)D concentrations increased significantly to 70.8 nmol/L (95% CI, 66.4–76.1) following 800 IU/day supplementation and to 86.9 nmol/L (95% CI, 80.1–94.1) following 2,000 IU/day supplementation, no significant differences in BMD were observed at the total hip, non-dominant midradius, whole body, or spine compared with the calcium-only group. Similarly, Aloia et al. (29) followed 260 Black American women ≥ 60 years, providing vitD₃ at various doses to maintain serum 25(OH)D above 75 nmol/L (achieved in 90% of participants). Despite marked increases in serum 25(OH)D at 12, 24, and 36 months compared with

placebo, no significant differences were observed in BMD at the total femur, trochanter, femoral neck, spine, whole body, or radius. LeBoff et al. (28) investigated 67 Black American men (≥ 50 years) and women (≥ 55 years) given 800 IU/day vitD₃ for 24 months. No significant differences were observed in absolute changes in aBMD at the spine, hip, femoral neck, or whole body compared with placebo. Likewise, Nieves et al. (31), in 127 postmenopausal Black American women supplemented with 1,000 IU/day vitD₃ for 24 months, found no significant effects on BMD at the spine, total hip, femoral neck, or trochanter. The study by Wahlquist et al. (9) included Black, Hispanic and White women with either breastfeeding or formula feeding who took either 6,400 IU or 400 IU vitD₃ supplements daily for 6 months and found that the BMD of Black women at spine was 0.94 (0.13) at baseline ($n = 114$), 0.94 (0.12) at 3 months ($n = 74$), and 0.94 (0.14) at 6 months ($n = 57$). Similarly, the BMD at hip was 1.09 (0.12) at baseline ($n = 114$), 1.10 (0.12) at 3 months ($n = 74$), and 1.10 (0.13) at 6 months ($n = 57$); the BMD at whole body was 1.15 (0.09) at baseline ($n = 84$), 1.16 (0.08) at 3 months ($n = 68$), and 1.17 (0.09) at 6 months ($n = 51$). The results did not distinguish between the intervention and control groups, nor the statistical analysis between different time points.

In Asian populations, Andersen et al. (33) provided 400 IU or 800 IU/day vitD₃ for 12 months to 173 Pakistani women and men living in Denmark. No significant differences were observed in BMD at the whole body or spine, or in serum osteocalcin concentrations, between intervention and placebo groups. The study by Park et al. (36) conducted in 1,076 South Korean patients with osteoporosis found there was no significant difference in BMD change between risedronate + vitD₃ supplementation and risedronate only groups for 12 months. The study by Islam et al. (37) in Bangladeshi women reported significant changes in BMD after 12 months of 400 IU/day vitD supplementation at the femoral neck between intervention ($n = 40$) and placebo ($n = 35$) groups (0.012 ± 0.028 g/cm² and -0.010 ± 0.012

g/cm² respectively, $p < 0.001$). Similar results were observed at trochanter (0.002 ± 0.021 g/cm² and -0.017 ± 0.029 g/cm² respectively, $p < 0.001$). There was no significant change in BMD at lumbar spine.

BTMs

Eight of the 12 studies measured BTMs (Table 4) (29-35, 38). Apart from Andersen et al. (33), which reported median (IQR), all other studies presented results as mean (SD). Among the five studies that reported OC (Table 4), only three studies showed baseline values (32-34), of which one study used median (IQR) (33). The study by von Hurst et al. (32) reported the results separately for the pre-menopausal women and post-menopausal women separately, therefore, two entries were included in the meta-analysis of OC (Figure 2A) and CTX (Figure 2B). There were no significant differences in OC (SMD -0.55, 95% CI -1.58–0.49, $p = 0.303$) based on two studies (32, 34) (Figure 2A). However, the limited number of studies included in this meta-analysis limits interpretation of these findings. Five studies (29, 32, 34, 35, 38) including 996 participants reported CTX concentrations and no significant difference in CTX was observed between vitD and placebo groups (SMD 0.19, 95% CI -0.08–0.45, $p = 0.170$) (Figure 2B). Figure 2C shows that vitD supplementation significantly increased blood BALP concentrations with an SMD of 0.96 (95% CI, 0.09–1.83, $p = 0.031$) in four studies (29, 34, 35, 38) including 944 participants, although substantial heterogeneity was observed across all meta-analyses (OC: $I^2 = 88.7\%$, $p < 0.001$; CTX: $I^2 = 71.0\%$, $p = 0.004$; BALP: $I^2 = 97.1\%$, $p < 0.001$).

As Chung et al. (35) differed clinically from the other studies included in the BALP meta-analysis because both the intervention and control groups received risedronate, an antiresorptive medication that may independently influence BTMs, a sensitivity analysis was conducted excluding this study. The pooled effect estimate was attenuated from an SMD of

0.96 (95% CI 0.09–1.83) to 0.64 (95% CI -0.14–1.41) ($I^2 = 97.1\%$, $p < 0.001$), and the result was no longer statistically significant. This finding indicates that the statistical significance of the primary BALP meta-analysis was sensitive to the inclusion of Chung et al. (35). Details of the meta-analysis results, including the BALP sensitivity analysis are presented in the supplementary document S2.

Fracture

Only one study measured fracture (11). The study provided vitD3 2,000 IU/day for a median of 5.3 years in 5,106 generally healthy Black adults (men ≥ 50 years and women ≥ 55 years). The results showed the fracture frequency was 53 among 2,553 participants in the vitD3 group and 59 out of 2,553 participants in the placebo with a hazard ratio for total fractures 0.89 (95% CI 0.62–1.30).

Adverse effect

Five studies (11, 29, 30, 35, 36) reported adverse effects of vitD3 supplementation in comparison with the control groups. However, none of these studies reported a significant difference in adverse effects between intervention and control groups. The commonly reported side effects include hypercalcaemia, kidney stones, or gastrointestinal symptoms by LeBoff et al. (11), myalgia, dyspepsia and fractures by Park et al. (36), and gastrointestinal discomfort, hypercalcaemia, hypocalcaemia or renal impairment by Chung et al. (35).

Association of serum 25(OH)D concentrations with BMD and BTMs

Two studies (30, 38) reported the association of serum 25(OH)D concentrations with BMD or BTMs. There was no linear correlation of BMD change with the mean serum 25(OH)D level over the course of the intervention (3 years) (30), while the study by Yao et al. (38) found a

significant positive association between changes in 25(OH)D and changes in BALP, PINP, and TRAP5b ($r = 0.07\text{--}0.16$, $p \leq 0.020$).

Publication bias assessment

None of the three markers showed statistical evidence of publication bias, although the publication-bias tests were likely underpowered given the small number of included studies (Table 5). However, these findings should be interpreted with caution because each meta-analysis included six or fewer studies, limiting the power of both visual (funnel plots were shown in supplementary document S2) and statistical assessments of publication bias.

Risk-of-bias assessment

Results of the RoB-2 assessment are shown in Table 6. Among the 12 studies included in the review, eight were assessed to have a low risk of bias (28, 29, 32-35, 37, 38), while four were regarded as having a high risk of bias (9, 30, 31, 36).

Discussion

This systematic review provides limited evidence that vitD supplementation improves BMD or prevents fracture in non-White populations. Only one included trial (37) found significant increases in BMD among Bangladeshi women at the femoral neck and trochanter (vitD3 400 IU/day, 12 months), whereas other included studies used much higher vitD3 doses (800 IU–2,000 IU/day) and longer intervention periods (24–36 months), consistently found null effect. The meta-analyses showed vitD supplementation had no significant effect on OC and CTX, while the evidence on BALP concentrations was not robust as the pooled effect was no longer significant after excluding the study by Chung et al. (35).

Findings from previous meta-analyses on the effects of vitD supplementation on BMD have been inconsistent. Bolland et al. (39) found no between-group differences in BMD at any site

(range -0.16% to 0.76% over 1–5 years) based on 41 RCTs, while Reid et al. (14) reported a small benefit of vitD supplementation on BMD only at the femoral neck (WMD 0.8%, 95% CI 0.2–1.4) on 13 RCTs, though with considerable heterogeneity ($I^2 = 67\%$, $p < 0.001$). A recent systematic review and meta-analysis (13) showed that vitD supplementation significantly improved BMD at the lumbar spine (SMD 0.06, 95% CI 0.01–0.12) on 34 RCTs and femoral neck (SMD 0.25, 95% CI 0.09–0.41) on 30 RCTs and increased femoral neck BMD (SMD 0.79, 95% CI 0.24–1.35) across eight studies on 2,223 non-White participants. However, several included studies among the 8 studies (40–42) did not report separate results for the non-White groups.

Mounting evidence has demonstrated differences in BMD across ethnic groups (43). American Black adults, despite having significantly lower serum 25(OH)D concentrations compared with White Caucasians, typically exhibit higher BMD, lower prevalence of osteoporosis, reduced fracture and fall risk, and slower rates of bone loss than White or Asian adults (44, 45). This “vitamin D paradox in Black Americans” may partly reflect a lower physiological requirement for calcium and vitD to maintain bone health in this population (12). The present review supports this by finding no effect of vitD supplementation on BMD in Black adults and other ethnic populations with the exception of one study conducted among Bangladeshi women (37), which reported a significant improvement in BMD despite using the lowest vitamin D dose among the included studies and having a relatively small sample size.

Few studies compared the effect of vitD supplementation on White and other ethnic populations in one single study. The only such trial included in this review reported no significant differences in areal BMD (aBMD) at the spine ($p = 0.83$), total hip ($p = 0.81$), femoral neck ($p = 0.54$), or whole body ($p = 0.15$) between White ($n = 259$ – 282) and Black ($n = 23$ – 28) after two years of vitD supplementation at 2,000 IU/day (28). However, the

interpretation of these findings is limited due to the small sample size of the Black subgroup and the lack of baseline 25(OH)D and aBMD data reported by ethnicity. Further research directly comparing the effects of vitD supplementation across diverse ethnic groups is therefore warranted.

Only one study that reported fracture outcomes in the current research found no significant difference in fracture incidence between vitD supplementation (2,000 IU/day) and placebo during a median follow-up of 5.3 years (hazard ratio [HR] 0.89, 95% CI 0.62–1.30; $n = 5,106$) in Black American adults (11). The trial also reported no difference in fracture frequency between White and Black groups. A large RCT ($n = 21,315$ aged 60–84 years) in Australia reported similar results after vitD supplementation at 60,000 IU per month (equivalent to 2,000 IU/day) for up to 5 years (46). A systematic umbrella review of meta-analyses concluded that vitD supplementation alone does not appear to prevent fractures, whereas combined supplementation with calcium is more likely to be effective (17). However, another meta-analysis including 32 studies found that daily vitD supplementation of 800–1,000 IU, either alone or with calcium, significantly reduced osteoporotic fracture risk (risk ratio [RR] 0.80, 95% CI 0.63–1.00; and RR 0.88, 95% CI 0.78–1.00, respectively) (18). Taken together, these inconsistent findings highlight ongoing uncertainty regarding the anti-fracture efficacy of vitD, particularly when used alone, and also emphasise the need for further research focused on various ethnic populations.

Moreover, no significant correlation was observed between mean serum 25(OH)D concentrations and changes in BMD over three years of vitD₃ supplementation (800 IU/day in years 1 and year 2, and 2,000 IU/day in year 3) in 208 Black American postmenopausal women (30). These findings suggest that supplementation dose or achieved serum 25(OH)D levels may not be the primary determinants of BMD response. Some evidence indicates that the combination of vitD supplementation with calcium is superior to vitD alone in improving

BMD (47-49). Vitamin K is another micronutrient that has been demonstrated to be beneficial for bone health when taken along with vitD supplementation (50, 51) via activating proteins such as osteocalcin that facilitate calcium deposition into the bone matrix (52, 53).

BTMs provide early indicators of bone remodelling and may precede detectable changes in BMD (54). BALP, OC, and PINP are key BTMs for bone formation, while CTX is for bone resorption (55). A recent meta-analysis (19) reported significant reductions in CTX (MD: -0.038, $n = 22$) and OC (MD: -0.610, $n = 24$), following vitD supplementation in women aged ≥ 18 years, while no significant change was found in BALP levels ($n = 6$) or PINP ($n = 17$), without specific data on ethnicities. In addition, the relationship of BTMs and BMD after vitD supplementation needs to be further investigated. Few studies assessed both BMD and BTMs in the same study. Only three out of the 12 studies in the current research measured both BMD and BTMs (29, 30, 33). However, none of them investigated the association between BTMs and BMD.

To our knowledge, this is the first systematic review to synthesise data specific to non-White populations, thus addressing a critical gap in the literature. However, the small number of eligible studies and modest sample sizes (67–260 participants per trial), particularly among studies included in the meta-analyses, limit the generalisability, precision, and robustness of the pooled estimates. Therefore, these findings should be interpreted cautiously. The small number of studies also limited the reliability of statistical assessment of publication bias and precluded meaningful subgroup analyses to explore potential sources of heterogeneity. Two studies conducted in patients with osteoporosis (35, 36) evaluated the incremental effect of vitD supplementation in the context of antiresorptive treatment (risedronate) that suppresses bone remodelling and independently alters BTMs, which confounds the vitD signal. Therefore, the two studies may not be directly comparable with studies conducted in generally healthy adults without clinical treatment. The inability to conduct meta-analysis due

to heterogeneity in outcome reporting indicates the necessity of reporting outcome measures in mean and SD format where appropriate. Exclusion of non-English language studies may have led to missed evidence, and the poor quality of several included trials further restricts interpretation. Overall, the generalisability of these findings is limited because the available evidence was derived from a small number of studies involving only a few non-White ethnic populations, predominantly Black Americans. Consequently, the results may not be applicable to all ethnic minority groups or to populations with different health characteristics, highlighting the need for more diverse, adequately powered RCTs.

This systematic review found insufficient evidence to support the efficacy of vitD supplementation alone for improving bone health in non-White populations. Future trials should prioritise inclusion of diverse ethnic groups, report outcomes separately by ancestry, and include association between BTMs and BMD.

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1. Kato S. The function of vitamin D receptor in vitamin D action. *J Biochem.* 2000;127(5):717–22.
2. Chang S, Lee H. Vitamin D and health -The missing vitamin in humans. *Pediatr Neonatol.* 2019;60:237–44.
3. Amrein K, Scherkl M, Hoffmann M. Vitamin D deficiency 2.0: an update on the current status worldwide. *Eur J Clin Nutr.* 2020;74(11):1498–513.
4. Ames BN, Grant WB, Willett WC. Does the High Prevalence of Vitamin D Deficiency in African Americans Contribute to Health Disparities? *Nutrients.* 2021;13(2):499–522.
5. Chanchlani R, Nemer P, Sinha R. An Overview of Rickets in Children. *Kidney Int Rep.* 2020;5(7):980–90.
6. Sutherland JP, Zhou A, Leach MJ, Hyppönen E. Differences and determinants of vitamin D deficiency among UK biobank participants: A cross-ethnic and socioeconomic study. *Clin Nutr.* 2021;40(5):3436–47.
7. Gallagher JC, Jindal PS, Smith LM. Vitamin D supplementation in young White and African American women. *J Bone Miner Res.* 2014;29(1):173–81.
8. Wei W, Shary JR, Garrett-Mayer E. Bone mineral density during pregnancy in women participating in a randomized controlled trial of vitamin D supplementation. *Am J Clin Nutr.* 2017;106:1422–30.
9. Wahlquist AE, Blanke HH, Asghari G, et al. Factors Affecting Postpartum Bone Mineral Density in a Clinical Trial of Vitamin D Supplementation. *J Womens Health (Larchmt).* 2024;33(7):887–900.
10. Bao Y, Xu Y, Li Z, Wu Q. Racial and ethnic difference in the risk of fractures in the United States: a systematic review and meta-analysis. *Sci Rep.* 2023;13(1):9481–9497.
11. Leboff MS, Chou SH, Ratliff KA. Supplemental Vitamin D and Incident Fractures in Midlife and Older Adults. *N Engl J Med.* 2022;387(4):299–309.
12. Brown LL, Cohen B, Tabor D. The vitamin D paradox in Black Americans: a systems-based approach to investigating clinical practice, research, and public health -expert panel meeting report. *BMC proceedings.* 2018;12:6–10.
13. Kazemian E, Pourali A, Sedaghat F. Effect of supplemental vitamin D3 on bone mineral density: a systematic review and meta-analysis. *Nutr Rev.* 2023;81:511–30.
14. Reid IR, Bolland MJ, Grey A. Effects of vitamin D supplements on bone mineral density: a systematic review and meta-analysis. *Lancet.* 2014;383(9912):146–55.
15. Winzenberg T, Powell S, Shaw KA, Jones G. Effects of vitamin D supplementation on bone density in healthy children: systematic review and meta-analysis. *BMJ.* 2011;342:c7254.
16. Wu F, Fuleihan GE, Cai G. Vitamin D supplementation for improving bone density in vitamin D-deficient children and adolescents: systematic review and individual participant data meta-analysis of randomized controlled trials. *Am J Clin Nutr.* 2023;118(3):498–506.
17. Chakhtoura M, Bacha DS, Gharios C. Vitamin D Supplementation and Fractures in Adults: A Systematic Umbrella Review of Meta-Analyses of Controlled Trials. *J Clin Endocrinol Metab.* 2022;107(3):882–98.
18. Kong SH, Jang HN, Kim JH, Kim SW, Shin CS. Effect of Vitamin D Supplementation on Risk of Fractures and Falls According to Dosage and Interval: A Meta-Analysis. *Endocrinol Metab (Seoul).* 2022;37(2):344–58.

19. Nasimi N, Jamshidi S, Askari A, et al. Effect of vitamin D supplementation or fortification on bone turnover markers in women: a systematic review and meta-analysis. *Br J Nutr*. 2024;1473–87.
20. Page MJ, McKenzie JE, Bossuyt PM. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ*. 2021;372:n71.
21. Amir-Behghadami M, Janati A. Population, Intervention, Comparison, Outcomes and Study (PICOS) design as a framework to formulate eligibility criteria in systematic reviews. *Emerg Med J*. 2020;37(6):387
22. Thomas J, Graziosi S, Brunton J, Ghouze Z, O'Driscoll P, Bond M, Koryakina A. *EPPI-Reviewer: advanced software for systematic reviews, maps and evidence synthesis*. EPPI Centre, UCL Social Research Institute, University College London; 2023. Available from: [EPPI-Reviewer](#).
23. Sterne J, Savovi J, Page MJ. RoB 2: a revised tool for assessing risk of bias in randomised trials. *BMJ*. 2019;366:l4898.
24. DerSimonian R, Laird N. Meta-analysis in clinical trials. *Control Clin Trials*. 1986;7(3):177–88.
25. Cochran WG. The combination of estimates from different experiments. *Biometrics*. 1954;10:101–29.
26. Higgins JPT, Thompson SG. Quantifying heterogeneity in a meta-analysis. *Stat Med*. 2002;21(11):1539–58.
27. Harrer M, Cuijpers P, Furukawa T, & Ebert D. *Doing Meta-Analysis with R: A Hands-On Guide* (1st ed.). Chapman and Hall/CRC.
28. Leboff MS, Chou SH, Murata EM. Effects of Supplemental Vitamin D on Bone Health Outcomes in Women and Men in the Vitamin D and Omega-3 Trial (VITAL). *J Bone Miner Res*. 2020;35(5):883–93.
29. Aloia J, Fazzari M, Islam S. Vitamin D supplementation in elderly black women does not prevent bone loss: a randomized controlled trial. *J Bone Miner Res*. 2018;33:1916–22.
30. Aloia JF, Talwar SA, Pollack S. A randomized controlled trial of vitamin D3 supplementation in African American women. *Arch Intern Med*. 2005;165:1618–23.
31. Nieves JW, Cosman F, Grubert E. Skeletal effects of vitamin D supplementation in postmenopausal black women. *Calcif Tissue Int*. 2012;91:316–24.
32. von Hurst PR, Stonehouse W, Kruger MC, Coad J. Vitamin D supplementation suppresses age-induced bone turnover in older women who are vitamin D deficient. *J Steroid Biochem Mol Biol*. 2010;121(1-2):293-6.
33. Andersen R, Mølgaard C, Skovgaard LT. Effect of vitamin D supplementation on bone and vitamin D status among Pakistani immigrants in Denmark: a randomised double-blinded placebo-controlled intervention study. *Br J Nutr*. 2008;100(1):197–207.
34. Grønborg IM, Tetens I, Andersen EW. Effect of vitamin D fortified foods on bone markers and muscle strength in women of Pakistani and Danish origin living in Denmark: a randomised controlled trial. *Nutr J*. 2019;18:1–12.
35. Chung HY, Chin SO, Kang MI. Efficacy of risedronate with cholecalciferol on 25-hydroxyvitamin D level and bone turnover in Korean patients with osteoporosis. *Clin Endocrinol (Oxf)*. 2011;74(6):699–704.
36. Park SY, Kang MI, Park HM. Efficacy of risedronate with cholecalciferol on bone mineral density in Korean patients with osteoporosis. *Arch Osteoporos*. 2009;15(1):3.

37. Islam MZ, Shamim AA, Viljakainen HT. Effect of vitamin D, calcium and multiple micronutrient supplementation on vitamin D and bone status in Bangladeshi premenopausal garment factory workers with hypovitaminosis D: a double-blinded, randomised, placebo-controlled 1-year intervention. *Br J Nutr.* 2010;104(2):241–7.
38. Yao P, Sun L, Xiong Q, Xu X, Li H, Lin X. Cholecalciferol Supplementation Promotes Bone Turnover in Chinese Adults with Vitamin D Deficiency. *J Nutr.* 2018;148(5):746–51.
39. Bolland MJ, Grey A, Avenell A. Effects of vitamin D supplementation on musculoskeletal health: a systematic review, meta-analysis, and trial sequential analysis. *Lancet Diabetes Endocrinol.* 2018;6(11):847–58.
40. Mason C, Tapsoba JD, Duggan C. Effects of vitamin D3 supplementation on lean mass, muscle strength, and bone mineral density during weight loss: a double-blind randomized controlled trial. *J Am Geriatr Soc.* 2016;64:769–78.
41. Mesinovic J, Mousa A, Wilson K. Effect of 16-weeks vitamin D replacement on calcium-phosphate homeostasis in overweight and obese adults. *J Steroid Biochem Mol Biol.* 2019;186:169–75.
42. Smith LM, Gallagher JC, Kaufmann M. Effect of increasing doses of vitamin D on bone mineral density and serum N-terminal telopeptide in elderly women: a randomized controlled trial. *J Intern Med.* 2018;284:685–93.
43. Noel SE, Santos MP, Wright NC. Racial and Ethnic Disparities in Bone Health and Outcomes in the United States. *J Bone Miner Res.* 2021;36(10):1881–905.
44. Tracy JK, Meyer WA, Flores RH, Wilson PD, Hochberg MC. Racial differences in rate of decline in bone mass in older men: the Baltimore men's osteoporosis study. *J Bone Miner Res.* 2005;20(7):1228–34.
45. Wright NC, Looker AC, Saag KG. The recent prevalence of osteoporosis and low bone mass in the United States based on bone mineral density at the femoral neck or lumbar spine. *J Bone Miner Res.* 2014;29(11):2520–6.
46. Waterhouse M, Ebeling PR, Mcleod D. The effect of monthly vitamin D supplementation on fractures: a tertiary outcome from the population-based, double-blind, randomised, placebo-controlled D-Health trial. *Lancet Diabetes Endocrinol.* 2023;11(5):324–32.
47. Voulgaridou G, Papadopoulou SK, Detopoulou P. Vitamin D and Calcium in Osteoporosis, and the Role of Bone Turnover Markers: A Narrative Review of Recent Data from RCTs. *Diseases.* 2023;11(1):29.
48. Yao P, Bennett D, Mafham M. Vitamin D and Calcium for the Prevention of Fracture: A Systematic Review and Meta-analysis. *JAMA Netw Open.* 2019;2(12):e1917789.
49. Weaver CM, Alexander DD, Boushey CJ. Calcium plus vitamin D supplementation and risk of fractures: an updated meta-analysis from the National Osteoporosis Foundation. *Osteoporos Int.* 2016;27(1):367–76.
50. Kuang X, Liu C, Guo X, Li K, Deng Q, Li D. The combination effect of vitamin K and vitamin D on human bone quality: a meta-analysis of randomized controlled trials. *Food Funct.* 2020;11(4):3280–97.
51. Aaseth JO, Finnes TE, Askim M, Alexander J. The Importance of Vitamin K and the Combination of Vitamins K and D for Calcium Metabolism and Bone Health: A Review. *Nutrients.* 2024;16(15):2420
52. Singh V, Jain S, Prakash S, Thakur M. Studies on the Synergistic Interplay of Vitamin D and K for Improving Bone and Cardiovascular Health. *Curr Res Nutr Food Sci.* 2022;10(3).

53. Van Ballegooijen AJ, Pilz S, Tomaschitz A, Gröbler MR, Verheyen N. The Synergistic Interplay between Vitamins D and K for Bone and Cardiovascular Health: A Narrative Review. *Int J Endocrinol.* 2017;2017:7454376.
54. Mobasser M, Tarverdizadeh N, Mirghafourvand M, Salehi-Pourmehr H, Ostadrahimi A, Farshbaf-Khalili A. The role of bone turnover markers in screening low bone mineral density and their relationship with fracture risk in the postmenopausal period. *J Res Med Sci.* 2023;28(1):54.
55. Schini M, Vilaca T, Gossiel F, Salam S, Eastell R. Bone Turnover Markers: Basic Biology to Clinical Applications. *Endocr Rev.* 2023;44(3):417–73.

422 Table 1. Inclusion and exclusion criteria using PICOS framework

Parameters	Inclusion criteria	Exclusion criteria
Population	Adult men or women, ≥ 18 years, Black and Asian, and other non-White ethnic groups	Studies in White Caucasians or no outcome measures were available separately for the ethnic minority groups.
Intervention	VitD supplementation alone or combined with other nutrients or ingredients that were also included in the control condition.	Studies in which the effect of vitD supplementation could not be separated from that of other co-interventions.
Control	Placebo or control	
Outcomes	BMD, BTMs and fractures	No bone health outcomes assessed
Study design	Randomised controlled trials (RCTs)	Case reports; observational studies; review articles

423 Abbreviations: BMD, Bone Mineral Density; BTM, Bone Turnover Marker; vitD, vitamin D.

Table 2. Summary of the included studies

Study No.	Ref	Study population	Sample size (Female/Male)		Attrition	Intervention	Comparator	Duration (months)	Outcome measures	Results	Adverse effects
			Start	End							
1	Aloia et al., 2005 (30) USA	Black American postmenopausal women not receiving hormone therapy. 50 - 75 years	208 (208/0)	148 (148/0)	28.8%	VitD3 capsules 800 IU daily for year 1-2 and 2,000 IU/day for year 3 plus calcium 1,200–1,500 mg/day Cumulative dose: 1,296,000 IU	VitD3 placebo plus calcium 1,200–1,500 mg/day	36	- % change in BMD at the total hip, non-dominant midradius, whole body, and spine. - BTM (OC and CrossLaps) - Relationship between serum 25(OH)D levels and rates of bone loss (primary outcome)	No effects	No
2	Aloia et al., 2018 (29) USA	Black American women without hormone replacement therapy, with serum 25(OH)D between 20-65 nmol/L; ≥60 years, mean age 68.2 years	260 (260/0)	184 (184/0)	29.2%	Various doses of vitD3 capsules individually to keep serum 25(OH)D above 75 nmol/L (90% of the active group maintained)	Placebo	36	- % change in BMD at the total femur, trochanter, femoral neck, spine, total body, and nondominant radius. - BTM (BALP, CTX)	No effects	No

						Cumulative dose: Unavailable			(BMD primary outcome)		
3	Andersen et al., 2008 (33)	Pakistani women (18.1– 52.7 years old) and men (17.9– 63.5 years) living in Denmark	173 (89/84)	127 (62/65)	26.7%	VitD3 400 IU or 800 IU/day	Placebo	12	- BMD at whole- body and lumbar spine - BTM (OC) (primary outcome)	No effects	Not reported
	Denmark					Cumulative dose: 144,000 IU, or 288,000 IU					
4	Chung et al., 2011 (35)	South Korean patients diagnosed with osteoporosis	164 (158/6)	142 (NA)	13.4%	Risedronate 35 mg + VitD3 5,600 IU/week	Risedronate (35 mg) alone weekly	4	- BTM (BALP, CTX) (secondary outcome)	No effects	No
	South Korea	≥19 years				Cumulative dose: 96,000 IU					
5	Grønberg et al., 2019 (34)	Pakistani women aged 18–50 years with low dietary vitD intake who lived in Denmark	72 (72/0)	70 (70/0)	2.8%	VitD3 1,200 IU/day through fortified yoghurt, cheese, eggs and crisp bread	Non-fortified foods	3	- BTM (OC, BALP, PINP, CTX) (secondary outcomes)	No effects	Not reported
	Denmark					Cumulative dose: 108,000 IU					

6a	LeBoff et al., 2020 (28)	General healthy adults, men ≥50 years and women ≥55 years including Black participants	67 (Black)	56 (Black)	16.4%	VitD3 2,000 IU/day	Placebo	24	- Change in aBMD at spine, hip, femoral neck and whole body (Ancillary study)	No effects	Not reported
	USA					Cumulative dose: 1,440,000 IU					
6b	LeBoff et al., 2022 (11)	General healthy adults, men ≥50 years and women ≥55 years including 5,106 Black participants	5106 (NA)	NA	NA	VitD3 2,000 IU/day	Placebo	median 5.3 years	- Hazard ratios for total fractures and in various skeletal sites (Ancillary study)	No effects	No
	USA					Cumulative dose: 3,869,000 IU					
7	Islam et al., 2010 (37)	Bangladeshi female garment workers aged 18–36 years	100 (100/0)	75 (75/0)	25.0%	VitD3 400 IU/day	Placebo	12	- Change in BMD at femoral neck, trochanter and lumbar spine	Significant increase in BMD change in intervention group compared with placebo group at femoral neck (0.012 ± 0.028 g/cm² vs. -0.010 ± 0.012 g/cm², <i>p</i> < 0.001), and at trochanter (0.002 ± 0.021 g/cm² vs. -0.017 ± 0.029 g/cm², <i>p</i> < 0.001)	Not reported
	Bangladesh					Cumulative dose: 144,000 IU					

8	Nieves et al., 2012 (31) USA	Black African American women aged ≥45 years with menopause or surgical ovariectomy, and 25(OH)D <50 nmol/L	127 (127/0)	103 (103/0)	18.9%	VitD3 1,000 IU/day Cumulative dose: 720,000 IU	Placebo	24	- % change in BMD at spine, total hip, femoral neck and trochanter - BTM (PICP and OC) (secondary outcomes)	No effects	Not reported
9	Park et al., 2009 (36) South Korea	South Korean patients with osteoporosis ≥19 years	1,076 (NA)	841 (796/45)	21.8%	Risedronate (35 mg) + VitD3 (5,600 IU) weekly (equivalent to 800/day) Cumulative dose: 288,000 IU	Risedronate (35 mg) alone weekly	12	- Change in BMD at the lumbar spine, femoral neck, and total hip (primary outcome)	No effects	No

10	von Hurst et al., 2010 (32) New Zealand	South Asian women aged >20 years with 25(OH)D <50 nmol/L from India (91%), Sri Lanka (6%) and Pakistan (3%) who lived in New Zealand	106 (106/0)	81 (81/0)	23.6%	VitD3 capsules 4,000 IU/day Cumulative dose: 720,000 IU	Placebo	6	- BTM (OC, CTX) (secondary outcomes)	OC was significantly lower in the vitD group than in the placebo group; CTX was only significantly lower in vitD3 group vs. placebo in postmenopausal women aged > 49 years	Not reported
11	Wahlquist et al., 2024 (9) USA	Lactating and nonlactating Black women with singleton pregnancies at 4–6 weeks postpartum	114 (114/0)	57 (57/0)	50%	VitD3 6,400 IU/day Cumulative dose: 1,152,000 IU	Placebo (VitD3 400 IU/day)	6	- BMD at hip, spine, femoral neck, and whole body	BMD values for all Black American women were reported at various skeletal sites without distinguishing between the intervention and control groups.	Not reported
12	Yao et al., 2018 (38) China	Chinese Han adults, aged 20–45 years with 25(OH)D <50 nmol/L, BMI between 18.5 and 28 kg/m ²	448 (307/141)	411 (NA)	8.3%	VitD3 2,000 IU/day Cumulative dose: 1,200,000 IU	Placebo	20	- BTM (PINP, BALP, β-CTX, TRAP5b) - Association of 25(OH)D with BTMs	- BALP concentrations were significantly higher in vitD3 group than in placebo - Significant	Not reported

(secondary
outcome)

positive
association
between
changes in
25(OH)D and
changes in
BALP, PINP,
and TRAP5b

Abbreviations: 25(OH)D, 25-hydroxyvitamin D; aBMD, areal bone mineral density; BALP, bone-specific alkaline phosphatase; BMD, bone mineral density; BMI, body mass index; CTX, C-terminal crosslinked telopeptide of type 1 collagen; IU, international unit; OC, osteocalcin; PICP, procollagen type I C-terminal propeptide; PINP, procollagen type I N-terminal propeptide; TRAP5b, tartrate-resistant acid phosphatase 5b; vitD, vitamin D.

Table 3. Studies that measured BMD

References	Unit of measures	Body location							Note
		Total hip	Radius	Whole body	Spine	Total femur	Trochanter	Femoral neck	
Aloia et al., 2005 (30)	% change in BMD	√	√	√	√				Data in figures
Aloia et al., 2018 (29)	% change in BMD		√	√	√*	√	√	√	Data in figures
Andersen et al., 2008 (33)	Median (IQR) of BMD			√	√				
Islam et al., 2010 (37)	Change in BMD				√		√	√	
LeBoff et al., 2020 (28)	Change in aBMD	√		√	√			√	
Nieves et al., 2012 (31)	% change in BMD	√			√		√	√	Data in figures
Park et al., 2009 (36)	% change in BMD	√			√			√	Data in figures
Wahlquist et al., 2024 (9)	Mean (SD) of BMD	√		√	√			√	Data in figures

*Baseline only; aBMD, areal bone mineral density; IQR, interquartile range; SD, standard deviation.

Table 4. Studies that measured bone turnover markers

References	Unit of measures	OC	CTX	BALP	PINP	CrossLaps	PICP	TRAP5b
Aloia et al., 2005 (30)	Mean (SD)	√*				√		
Aloia et al., 2018 (29)	Mean (SD)		√	√				
Andersen et al., 2008 (33)	Median (IQR)	√						
Chung et al., 2011 (35)	Mean (SD)		√	√				
Grønborg et al., 2019 (34)	Mean (SD)	√	√	√	√			
Nieves et al., 2012 (31)	Mean (SD)	√*					√	
von Hurst et al., 2010 (32)	Mean (SD)	√	√					
Yao et al., 2018 (38)	Mean (SD)		√	√	√			√

*Baseline only; BALP, bone-specific alkaline phosphatase; CTX, C-terminal crosslinked telopeptide of type 1 collagen; IQR, interquartile range; OC, osteocalcin; PICP, procollagen type I C-terminal propeptide; PINP, procollagen type I N-terminal propeptide; SD, standard deviation; TRAP 5b, tartrate-resistant acid phosphatase 5b.

Table 5. Publication Bias Assessment

	Test	Value	<i>p</i>
OC	Begg and Mazumdar Rank Correlation	$\tau = -0.333$	1.000
	Egger's Regression	$z = -1.391$	0.164
CTX	Begg and Mazumdar Rank Correlation	$\tau = 0.067$	1.000
	Egger's Regression	$z = -0.132$	0.895
BALP	Begg and Mazumdar Rank Correlation	$\tau = 0.000$	1.000
	Egger's Regression	$z = 0.346$	0.729

BALP, bone-specific alkaline phosphatase; CTX, C-terminal crosslinked telopeptide of type 1 collagen; OC, osteocalcin.

Table 6. Summary of risk-of-bias assessment of the included studies ($n = 12$)

Study reference	Weight	D1	D2	D3	D4	D5	Overall
Aloia et al., 2005 (30)	1	+	+	+	+	!	!
Aloia et al., 2018 (29)	1	+	+	+	+	+	+
Andersen et al., 2008 (33)	1	+	+	+	+	+	+
Chung et al., 2011 (35)	1	+	+	+	+	+	+
Grønberg et al., 2019 (34)	1	+	+	+	+	+	+
Islam et al., 2010 (37)	1	+	+	+	+	+	+
LeBoff et al., 2020 (28)	1	+	+	+	+	+	+
Nieves et al., 2012 (31)	1	+	+	+	+	!	!
Park et al., 2009 (36)	1	+	!	+	+	!	!
von Hurst et al., 2010 (32)	1	+	+	+	+	+	+
Wahlquist et al., 2024 (9)	1	+	+	!	+	+	!
Yao et al., 2018 (38)	1	+	+	+	+	+	+

+ Low risk

- Some concerns

! High risk

D1 Randomisation process

D2 Deviations from the intended interventions

D3 Missing outcome data

D4 Measurement of the outcome

D5 Selection of the reported result

Figure 1 PRISMA flow chart

Figure 2. Forest plots of the effects of vitamin D supplementation on bone turnover markers. A. osteocalcin (OC); B. C-terminal telopeptide of type I collagen (CTX); C. bone-specific alkaline phosphatase (BALP). Effect sizes are expressed as standardized mean differences (SMDs) with 95% confidence intervals (CIs). Squares represent individual study estimates (size proportional to study weight), horizontal lines represent 95% CIs, and diamonds represent pooled estimates derived from a random-effects meta-analysis using the DerSimonian-Laird estimator. Between-study heterogeneity is summarized by the I^2 statistic. The vertical dashed line indicates no effect (SMD = 0).