

Factors Influencing the Level of Vitamin D in Lead-exposed Workers in Java, Indonesia

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ABSTRACT

Background. Despite extensive research on vitamin D metabolism and lead toxicity, specific nutritional and occupational health guidelines to prevent vitamin D insufficiency among lead-exposed workers remain lacking. This gap is particularly relevant in tropical regions, where adequate sunlight is often assumed to ensure sufficient vitamin D status. While previous studies have examined the effects of lead on vitamin D and calcium metabolism, the combined influence of sunlight exposure, dietary calcium, and protein intake on vitamin D levels in occupationally exposed populations has not been well characterized.

Objective. This study investigates the crucial role of vitamin D in calcium absorption and bone health, particularly in lead-exposed workers.

Methods. This cross-sectional study, conducted in five lead-contaminated areas in Java, Indonesia, with 144 subjects meeting inclusion criteria, explores factors such as BMI, age, vitamin and food intake, and workplace exposure. Characteristics, including age, were obtained through interviews, while a Semi-Quantitative Food Frequency Questionnaire was used to assess food and vitamin intake (using the Nutrisurvey 2007 program), and ICP-MS to assess blood lead levels (BLL). Sun exposure was evaluated based on sunlight duration, and chi-square tests were conducted between observed factors and vitamin D levels.

Results. Median BLLs among participants were 6.8 µg/dL (1.1–58.8). Bivariate analysis revealed that sunlight exposure and protein intake were associated inversely with BLLs; however, multivariate analysis showed that vitamin D intake ($p = 0.009$) and calcium intake ($p = 0.051$) were found to be significant predictors.



eISSN 2094-9278 (Online)
Published: September 30, 2026
<https://doi.org/10.47895/amp.v60i18.10015>
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Conclusion. This research highlights the absence of a significant correlation between vitamin D levels and sunlight exposure or protein intake. Notably, it reveals a significant association between vitamin D and calcium intake with vitamin D levels, emphasizing the intricate interplay of factors influencing vitamin D status in lead-exposed workers and underscoring the importance of dietary considerations.

Keywords: age, blood lead level, body mass index, calcium intake, sunlight exposure, vitamin D, vitamin D intake

INTRODUCTION

Exposure to lead among workers can result in various health impacts, including a decrease in vitamin D levels in the body. However, vitamin D levels are not solely influenced by the level of lead exposure; other factors such as sunlight exposure, vitamin D intake, protein, and calcium also play a role in this regard.¹ The skin's exposure to Ultraviolet B light from the sun enables the synthesis of vitamin D₃ in humans, constituting the most natural form. Once ingested, vitamin D is integrated into chylomicrons, entering the venous blood via absorption into the lymphatic system. Vitamin D obtained from the skin or diet is initially inert and undergoes liver hydroxylation by vitamin D-25-hydroxylase (25-OHase), transforming into 25(OH)D. Subsequent kidney hydroxylation by 25(OH)D-1-OHase (CYP27B1) produces the biologically active form of vitamin D, 1,25(OH)₂D, stimulating intestinal calcium absorption. In the absence of vitamin D, only 10–15% of dietary calcium and approximately 60% of phosphorus are absorbed. Adequate vitamin D levels enhance calcium and phosphorus absorption by 30–40% and 80%, respectively.

Vitamin D deficiency (VDD), as defined by organizations such as The Endocrine Society, the National and International Osteoporosis Foundation, and the American Geriatrics Society, is characterized by a 25-hydroxyvitamin D (25 OH D) level below 30 ng/mL. The Endocrine Society advocates for maintaining a preferred range of 40 to 60 ng/mL, whereas the National Institutes of Health sets the deficiency threshold at less than 20 ng/mL. Additionally, some authorities categorize insufficiency as 12 to 19 ng/mL and deficiency as below 12 ng/mL.¹ Inadequate sunlight exposure is a primary cause of VDD. VDD diminishes the absorption of dietary calcium and phosphorus, resulting in elevated Parathyroid Hormone (PTH) levels. PTH-mediated osteoclastic activity forms areas of bone weakness, reducing bone mineral density and leading to osteopenia and osteoporosis. VDD also induces muscle weakness, affecting mobility in both children and the elderly.²

Various factors influence vitamin D levels, encompassing different aspects of individual health and lifestyle. In terms of BMI, there is an inverse association between serum 25(OH) D and a BMI exceeding 30 kg/m², indicating that obesity is linked to VDD. Obese individuals tend to have lower serum 25(OH)D levels compared to their non-obese counterparts, suggesting that obese individuals may require higher vitamin D intakes to achieve levels similar to those with normal weight.³ The presence of greater subcutaneous fat in obesity may sequester more vitamin D and alter its release into circulation. Additionally, individuals who have undergone gastric bypass surgery face an increased risk of VDD over time due to the bypassed upper small intestine, where vitamin D is absorbed. Furthermore, certain medications, such as anticonvulsants and those used to treat AIDS/HIV, enhance the catabolism of 25(OH)D and 1,25(OH)₂D, putting

patients at risk for VDD. Individuals with a history of chronic granuloma-forming disorders, including sarcoidosis, tuberculosis, chronic fungal infections, certain lymphomas, and primary hyperparathyroidism, are also at a heightened risk of VDD.² Aging poses another risk factor, with older adults facing a higher likelihood of vitamin D insufficiency due to reduced skin synthesis efficiency, increased indoor time, and potentially inadequate vitamin D intake. Limited sun exposure is a significant factor, affecting homebound individuals, women with religious attire covering their skin, and those with occupations limiting sun exposure. The role of sunscreen in reducing vitamin D synthesis is still unclear. While the health consequences of lower 25(OH) D levels in individuals with dark skin remain uncertain, adequate vitamin D intake from foods and/or supplements at recommended levels can ensure sufficient nutrient levels for these individuals.^{2,4-6}

In addition to the factors mentioned above, vitamin D levels can also be influenced by other mechanisms such as lead exposure in lead workers. Lead exposure can have negative impacts on health and may affect the metabolism of vitamin D in the body. Therefore, lead exposure can be considered as an additional factor that can affect an individual's vitamin D status.^{7,8}

The human body can be exposed to lead through food, water, soil, and air. In adults, lead exposure occurs due to occupational exposure.⁹ Each year, approximately 1.5 million workers in the United States are at risk of lead exposure.¹⁰ Occupations with a high risk of lead exposure include metal welding, battery manufacturing workers, mechanics, lead smelters, construction workers, police officers, artists, and pipefitters.⁹ Lead can enter the human body through inhalation, ingestion, dermal absorption, absorption from embedded foreign objects, and transplacental (endogenous) routes. Inhalation is the primary route of lead exposure.¹¹ The impacts of lead on health are diverse. Exposure to lead can disrupt homeostasis and ion transport, protein binding, oxidative stress, and inflammation in most cells. The effects of lead exposure may include neurological effects, the occurrence of metabolic syndrome, increased oxidative stress leading to cell structure damage, and inhibition of DNA transcription and vitamin D synthesis processes.¹²

Lead exposure can affect calciotropic hormones by inhibiting the synthesis of 1,25 dihydroxyvitamin D (calcitriol), which plays a role in 1- α -hydroxylation of 25-hydroxyvitamin D, leading to VDD.¹³ Moreover, lead that has previously accumulated in bones has a half-life of more than 10 years. In conditions of increased bone turnover, bones can become a source of endogenous lead exposure. Increased bone turnover and hyperparathyroidism can be caused by VDD, as described in Figure 1.⁷

VDD has been linked to various health issues, including cancers, autoimmune diseases, and metabolic disorders like type 1 and type 2 diabetes mellitus. Vitamin D is believed to have a significant impact on insulin resistance and the

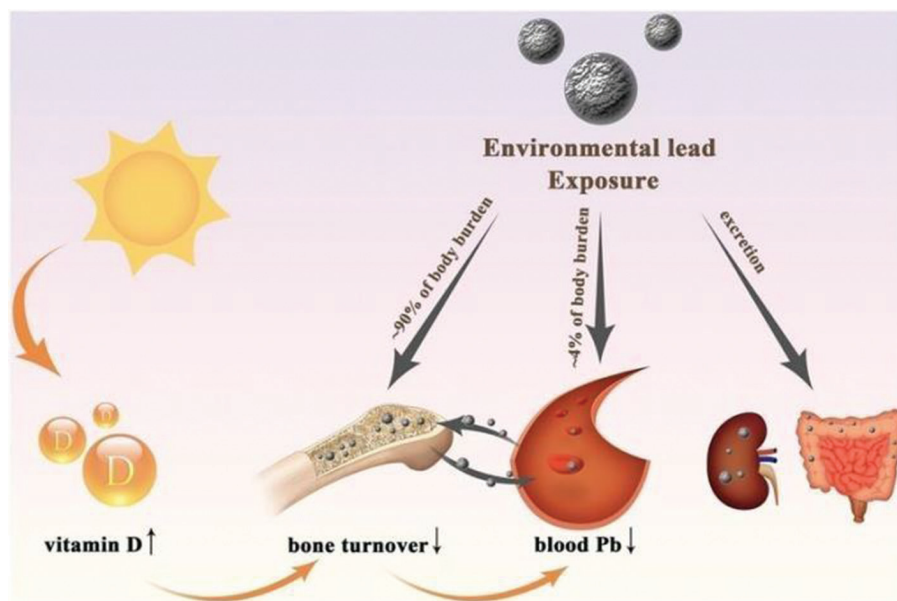


Figure 1. Interaction between vitamin D and lead exposure.⁷

development of type 2 diabetes by influencing insulin sensitivity in target cells (skeletal muscle, adipose tissue, and liver), β -cell function, or both.¹⁴ Moreover, a lack of vitamin D results in diminished bone mineralization, leading to a decline in bone mineral density and an elevated risk of osteoporosis. About 90% of the total lead content in the adult body is stored within the bones. As a result, the lead found in the blood may derive from lead that had previously accumulated in bones with a half-life exceeding 10 years. Groleau et al. found that low intake of vitamin D and calcium is a known risk factor for increasing lead levels in bones. Lead, which is toxic to the kidneys, can inhibit the enzyme 1α -hydroxylase in the renal tubules, which plays a crucial role in the formation of calcitriol and the absorption of calcium in the small intestine.¹⁵ For workers with lead exposure, adequate vitamin D intake can support the recovery of cells that may have experienced negative impacts due to lead exposure.

The previous study by Batra et al indicated that a high Blood Lead Level (BLL) significantly alters vitamin D and calcium metabolism ($P < 0.001$).¹⁶ Another study by Rahman et al., investigating the association of BLL with vitamin D Binding Protein (DBP), total, and free 25(OH) D in healthy adolescents (n 1347; age range 11–16 years) cross-sectionally selected from all Governorates of Kuwait, revealed a positive association between DBP and BPbL ($\beta = 0.81$; 95% CI 0.14, 0.22; $P < 0.001$).¹⁷ Another similar study by Himani et al. showed that BLL was significantly higher in Low Lead Exposure with Bone Weakness (LEBW) compared to No Low Lead Exposure with Bone Weakness (NLEC) ($p < 0.0001$).¹⁸

Despite extensive research on vitamin D metabolism and lead toxicity, there remains a lack of specific nutritional

recommendations or occupational health guidelines to prevent vitamin D insufficiency or deficiency among workers exposed to lead. This represents a significant public health and occupational nutrition gap, especially in tropical regions where sunlight is assumed to ensure sufficient vitamin D synthesis. Although earlier studies have explored the effects of lead exposure on vitamin D and calcium metabolism, no prior research has examined the combined contributions of calcium intake, protein intake, and sunlight exposure on serum vitamin D levels in occupationally exposed adult populations living in tropical countries.^{19–21} The current study aims to find the association between sunlight exposure, vitamin D, protein, and calcium intake with vitamin D levels among lead exposure workers. The findings from this study may have broader implications for public health, particularly for individuals working in environments with lead exposure, to prevent inadequate vitamin D levels in their bodies. The insights gained could contribute to the development of policies and guidelines aimed at protecting workers and fostering healthier workplace environments.

MATERIALS AND METHODS

Subjects and Sample Size

This cross-sectional study was conducted from May to August 2023 in five locations representing varying degrees of environmental contamination. Four sites exhibited elevated soil lead levels, whereas one site demonstrated undetectable or minimal concentrations. These areas were selected based on the status of used battery recycling activities in those locations, soil lead concentration measurements, the number of populations at risk, and government support at both the national and local levels. Sample size calculation used the

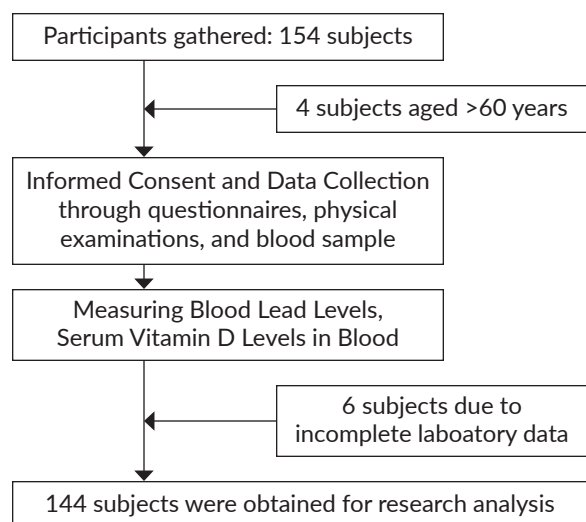


Figure 2. Flow of research subject recruitment.

formula for cross-sectional studies, resulting in a minimum sample size of 144 samples from the five areas. Male with the age of 18-60 and working with lead exposure and sign the informed consent were the inclusion criteria.

Figure 2 illustrates the flow of research subject recruitment. There were 154 male adults identified; four subjects did not meet the age criteria, six individuals were found to have incomplete laboratory results and only 144 met the inclusion criteria.

Ethical Considerations

The study protocol was reviewed and approved by the Health Research Ethics Committee - Faculty of Medicine Universitas Indonesia and Dr. Cipto Mangunkusumo National Hospital (HREC FMUI-CMH) No. KET-335/UN2.F1/E.TIK/PPM.00.02/2023, and all participants provided their informed consent prior to their involvement.

Data Collection

Data were collected using a purposive sampling approach, beginning with the identification of individuals potentially exposed to lead through records obtained from subdistrict public health centers and village offices. Prospective participants were provided with a comprehensive explanation of the study objectives and procedures, after which they were screened according to predefined inclusion and exclusion criteria. Individuals who met the eligibility requirements gave written informed consent prior to enrollment. Sociodemographic characteristics were gathered through structured interviews utilizing a standardized questionnaire, which captured information on age, educational attainment, duration of employment, sunlight exposure, and occupational position. Anthropometric data were obtained using calibrated instruments following standardized procedures. Body weight was measured to the nearest 0.1 kg using a digital scale, while

height was assessed to the nearest 0.1 cm with a stadiometer. Waist circumference was measured at the midpoint between the lower border of the last palpable rib and the iliac crest using a non-stretchable measuring tape, recorded to the nearest 0.1 cm. Nutrient intake including protein, calcium, and vitamin D was assessed using a semi-quantitative Food Frequency Questionnaire (FFQ) adapted from validated tools previously used in Indonesian populations. The FFQ comprised approximately 120 commonly consumed food items in the study area. Participants reported their usual frequency of consumption (daily, weekly, or monthly) and portion sizes, assisted by visual aids such as household measures and calibrated utensils to improve accuracy. Trained data collectors conducted interviews to document participants' intake of major food groups, portion sizes, and consumption frequency over the preceding month (FFQ) or the previous 24 hours (dietary recall). Nutrient intakes of vitamin D, protein, and calcium were subsequently calculated using the Nutrisurvey 2007 program, and the database was updated according to the Indonesian Food Composition Table 2019.

Sample Collection

Venous blood samples were collected in trace-element-free EDTA tubes for the determination of blood lead levels. Analyses were performed at a certified laboratory using Inductively Coupled Plasma Mass Spectrometry (ICP-MS), with a limit of detection (LOD) of 0.02–0.05 µg/dL. Results were expressed in micrograms per deciliter (µg/dL). Vitamin D status was evaluated through serum 25-hydroxyvitamin D [25(OH)D] concentrations, analyzed using chemiluminescence immunoassay (CLIA; LOD: 4–6 ng/mL). Total serum protein was assessed using the Biuret method (LOD: 0.1 g/dL). Serum calcium was quantified using a colorimetric Arsenazo III assay (LOD: 0.1 mg/dL). For selected samples, liquid chromatography–tandem mass spectrometry (LC-MS/MS) was employed as a reference method, with an LOD of 1–2 ng/mL.

Statistical Analysis

Descriptive statistics were used to summarize participants' sociodemographic and anthropometric characteristics. Categorical variables were presented as frequencies and percentages, while continuous variables were assessed for normality using the Kolmogorov–Smirnov test and expressed as mean ± standard deviation (SD) or median (Q1–Q3), as appropriate. The relationships between sunlight exposure, nutrient intakes (vitamin D, protein, calcium) and vitamin D levels were analyzed using independent *t*-tests or Mann–Whitney *U* tests, as well as Pearson or Spearman correlation analyses, depending on data distribution. Variables with a *p*-value <0.25 in the bivariate analysis were subsequently included in a multiple linear regression model. Regression results were expressed as β coefficients with corresponding 95% confidence intervals (CIs), and a *p*-value <0.05 was considered statistically significant.

RESULTS

General Characteristics of Study Population

Of the total 144 subjects recruited in this study from five study areas. Table 1 shows the median age of the participants is 39 years, and the median BMI is 21.6. The BMI categories reveal that the majority of participants fall into the normal-underweight group, comprising 87 participants or 60.4%. Regarding work-related factors, the participants have an average work duration of 8 years, with an average working time of 5 years. Around 43,1% of participants report adequate exposure, while 56,9% report inadequate sunlight exposure. The median levels of vitamin D, protein intake, and calcium intake are 22, 54.2, and 379.7, respectively.

Correlation Between Variables

Table 2 describes sunlight exposure, vitamin D, calcium, and protein intake with vitamin D level indicates that there is no statistically significant correlation between sunlight exposure and protein intake with vitamin D levels, as shown by *p*-values of 0.330 and 0.113. However, there is a statistically significant correlation between vitamin D and calcium intake with vitamin D levels, as indicated by *p*-values of 0.024 and 0.011, respectively.

Factors Influencing Vitamin D Levels

Table 3 presents the results of a multivariate analysis between selected predictor variables including vitamin D,

protein, calcium intake, and vitamin D levels. After adjusting for multiple nutritional and anthropometric factors, vitamin D intake (95% CI 1.43-12.46, *p* = 0.009) and calcium intake (95% CI 0.07-1.00, *p* = 0.051) were found to be significant predictors.

DISCUSSION

The present study demonstrates a significant association between both dietary calcium intake (*p* = 0.011) and vitamin D (*p* = 0.024) intake with serum vitamin D levels among lead-exposed workers. In contrast, sunlight exposure (*p* = 0.330) and protein intake (*p*-value of 0.157) did not show significant relationships with vitamin D status. These findings provide important nuance to the understanding of vitamin D regulation in populations with chronic low-to-moderate lead exposure, particularly in tropical settings where sunlight is assumed to be abundant.

The significant association observed between calcium intake and vitamin D levels is biologically plausible and consistent with previous scientific evidence. Vitamin D plays a central role in maintaining calcium balance by stimulating the active transcellular absorption of calcium in the intestine via binding of its active metabolite, 1,25-dihydroxyvitamin D, to the vitamin D receptor (VDR). When circulating 25(OH)D concentrations fall below approximately 20 nmol/L, calcium absorption efficiency declines markedly, resulting in compensatory elevations in parathyroid hormone

Table 1. Characteristics of Participants (n = 144)

	Median (Q1-Q3)	(%)
Age (years)	39 (20-59)	
>40		63 (44.7)
<40		78 (55.3)
BMI (kg/m²)	21.6 (15.2-34.2)	
Obesity		32 (22.2)
Overweight		25 (17.4)
Normal-Underweight		87 (60.4)
Working time (months)	5 (1-43)	
Work duration (hours)	8 (2-18)	
Sufficient sunlight exposure (without clothing coverage)		
Low (<15 mins)		82 (56.9)
Normal (≥15 mins)		62 (43.1)
Vitamin D intake (mcg)	1.2 (0-24.7)	
Protein Intake (gram)	54.2 (17-168.8)	
Calcium Intake (mg)	379.7 (50.5-1425.6)	
Vitamin D Level (ng/mL)	22 (4-52)	
≥30		21 (14.6)
20-29		72 (50.0)
<20		51 (35.4)
BLL (μg/dL)	6.8 (1.1-58.8)	
>30		9 (6.4)
10-30		36 (25.5)
<10		96 (68.1)

Table 2. Relationship between Sunlight Exposure, Vitamin D, Protein, and Calcium Intake with Vitamin D Level

	Level of Vitamin D		<i>p</i>
	Low	Normal	
Sunlight Exposure			
Low	68 (82.9%)	14 (17.1%)	0.330
Normal	55 (88.7%)	7 (11.3%)	
Vitamin D Intake (mcg)			0.024
≤1.2	68 (91.9%)	6 (8.1%)	0.113
>1.2	55 (78.6%)	15 (21.4%)	
Protein Intake (gram)			0.113
<54.5	59 (80.8%)	14 (19.2%)	0.011
≥54.5	64 (90.1%)	7 (9.9%)	
Calcium Intake (mg)			0.011
<381.4	57 (78.1%)	16 (21.9%)	0.051
≥381.4	66 (93.0%)	5 (7.0%)	

Table 3. Multivariate Logistic Regression Model of Factors Influencing Vitamin D Levels

	OR	95% CI	<i>p</i> -value
Vitamin D intake (mcg)	4.23	1.43-12.46	0.009
Protein intake (gram)	0.67	0.19-2.35	0.532
Calcium intake (mg)	0.27	0.07-1.00	0.051

and increased bone turnover.¹⁵ Individuals with chronically low calcium intake rely more heavily on adequate vitamin D concentrations to maintain normocalcemia. Thus, in populations with marginal vitamin D status, such as the workers in this study (median 25(OH)D: 22 ng/mL), dietary calcium may become a critical determinant of measured vitamin D concentrations because low calcium availability can accelerate the conversion of 25(OH)D to 1,25(OH)₂D, reducing circulating 25(OH)D stores.

The multivariate logistic regression presented in Table 3 offers a clearer picture of which factors independently contribute to vitamin D status among lead-exposed workers. After adjustment for nutritional and anthropometric variables, vitamin D intake emerged as a strong and statistically significant predictor of adequate vitamin D levels (OR 4.23; 95 percent CI 1.43–12.46; $p = 0.009$). This finding reinforces the central role of dietary intake in maintaining serum 25(OH)D, even in tropical settings where sunlight is abundant and often assumed to be sufficient for endogenous production. The magnitude of the association suggests that workers with higher dietary vitamin D intake were more than four times as likely to achieve normal vitamin D status, underscoring the vulnerability of populations whose habitual diets contain very limited vitamin D sources.

Our findings also align with evidence from nutritional epidemiology linking calcium and vitamin D intake to lead toxicokinetics. Previous work by Cheng et al. demonstrated that low calcium and vitamin D intake is associated with higher bone and blood lead levels in older men, partly due to increased bone resorption and the mobilization of skeletal lead stores.⁸ Similarly, experimental and occupational studies have shown that lead interferes with renal 1- α -hydroxylase activity, impairing the activation of vitamin D.^{16,22} Adequate calcium intake may mitigate some of these effects by stabilizing bone turnover and reducing endogenous lead release.

Calcium intake also demonstrated a borderline-significant association with vitamin D levels (OR 0.27; 95 percent CI 0.07–1.00; $p = 0.051$). Although the confidence interval approached unity, the overall trend supports the well-established physiological interdependence between calcium balance and vitamin D metabolism. In individuals with low baseline vitamin D intake, insufficient calcium may accelerate the consumption of circulating 25(OH)D through compensatory activation of 1- α -hydroxylase in the kidneys. In the context of chronic low-level lead exposure, this relationship becomes even more relevant, given that lead interferes with calcitriol formation and disrupts the hormonal feedback loops involved in calcium homeostasis.¹³ The multivariate findings therefore strengthen the biological plausibility that calcium intake contributes meaningfully to vitamin D sufficiency in this occupational population.

It was observed that there is no statistically significant association between exposure to sunlight and vitamin D levels (p -value = 0.544). This contrasts with the findings of a prior study conducted by Husna et al., which involved an

analytical cross-sectional examination of older women in two villages from Wonorejo and Kraton Districts, Pasuruan Regency.²³ In that research, a notable positive correlation was identified between the score reflecting sun exposure and serum 25(OH)D levels, although no correlation was established between vitamin D intake and serum 25(OH)D levels. Several factors may account for this discrepancy. First, the present study relied on a simplified categorization of sun exposure duration without detailed assessment of clothing, body surface area exposed, or timing of exposure, all of which influence cutaneous vitamin D synthesis. Second, the study population consisted of workers who spend a substantial portion of their time outdoors but may still receive insufficient ultraviolet B (UVB) exposure due to clothing or work conditions. Third, skin pigmentation likely plays a role. Meaning that workers with darker skin may require longer or more intense UVB exposure to achieve comparable vitamin D synthesis. These contextual factors may overshadow the effect of measured sun exposure duration, explaining the non-significant relationship observed.

Nevertheless, this current study aligns with the investigations conducted by Lee et al., who explored the impact of sunlight exposure on the concentration of serum 25-hydroxyvitamin D in women facing VDD.⁴ In that particular study, the alteration in serum 25OHD concentration demonstrated a significant negative correlation with the sun exposure score obtained through a questionnaire.

Similarly, protein intake showed no measurable association with vitamin D status. Although protein influences overall nutritional status and may affect the binding or transport of vitamin D metabolites, the evidence linking habitual protein intake with 25(OH)D concentrations remains inconsistent.²⁴ Dewansingh et al. reported mixed findings in older adults, suggesting that protein intake may not be a strong determinant of vitamin D status unless accompanied by deficiencies in other nutrients such as calcium.³

The absence of a significant correlation between blood lead levels and vitamin D status in this study contrasts with earlier findings that reported inverse associations.^{16,18} This discrepancy may be explained by the relatively low BLL observed in our study; only 6.4% of participants exceeded 30 $\mu\text{g/dL}$. Prior literature suggests that meaningful suppression of vitamin D metabolism occurs more consistently at higher levels of exposure, typically above 30–50 $\mu\text{g/dL}$.²² Furthermore, meta-analytic evidence indicates substantial heterogeneity in lead and vitamin D associations across studies, influenced by calcium intake, age, and baseline nutritional status.^{25,26} Given the low vitamin D intake among most participants (median 1.2 $\mu\text{g/day}$), dietary insufficiency may overshadow the metabolic effects of lead, thereby diminishing the observable correlation.

The lack of statistically significant findings in this study can be attributed to various factors. Primarily, the study cohort consists of informal workers, and the definition of

sun exposure employed revolves around exposure to sunlight for durations less than or more than 15 minutes, lacking specific guidelines regarding clothing. Consequently, it is plausible that only the skin on the legs and hands, exposed due to the clothing worn, is impacted. Additionally, the study participants include individuals with dark skin. A previous study expounded on the notion that dark skin, characterized by higher melanin levels in the epidermal layer, diminishes the skin's capacity to generate vitamin D from sunlight.⁶ Hence, sunlight exposure may not exert a significant influence on vitamin D levels when compared to vitamin D intake.

A notable strength of this study is the inclusion of a relatively large sample of workers exposed to varying levels of environmental lead contamination across multiple regions in Java. The study also employed rigorous laboratory methods, including ICP-MS for blood lead analysis and CLIA for serum 25(OH)D assessment, which reduced measurement error and strengthened the validity of the biochemical outcomes. A limitation of this study is that sun exposure was assessed using a simplified categorical measure that did not account for clothing, body surface area exposed, or the timing of UVB exposure, factors known to influence cutaneous vitamin D synthesis. Also, the dietary assessment relied on self-reported FFQ data, which is vulnerable to recall bias and may underestimate intake, particularly for nutrients such as vitamin D that are present in limited food sources.

CONCLUSION

This study highlights the central role of dietary vitamin D and calcium intake in shaping vitamin D status among workers chronically exposed to lead in environmentally contaminated areas. While sunlight exposure and protein intake did not demonstrate significant associations, both vitamin D and calcium intake emerged as key determinants of serum 25(OH)D levels, even in a tropical setting where endogenous synthesis is presumed adequate. These findings contribute valuable insights into the intricate interplay between various factors influencing vitamin D levels in lead-exposed workers, such as calcium and vitamin D intake, shedding light on the importance of dietary considerations in maintaining optimal vitamin D status.

Data Availability Statement

The data used to support the findings of this research are available upon reasonable request from the corresponding author.

Statement of Authorship

All authors certified fulfillment of ICMJE authorship criteria.

Author Disclosure

All authors declared no conflicts of interest.

Funding Source

None.

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