

ORIGINAL ARTICLE

Shedding light on vitamin D: Unveiling the intricate links with lifestyle, demographics, and biochemical markers

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Abstract. *Background:* Vitamin D deficiency is a global public health issue, particularly prevalent in Arab countries due to limited sun exposure, cultural practices, obesity, and nutrient deficiencies. Research on its multifactorial determinants in Jordan remains limited. This study examines the demographic, biochemical, and anthropometric correlates of Vitamin D deficiency. *Methods:* A cross-sectional study was conducted among 385 participants aged 18–60 attending routine check-ups in Jordan. Data collection included structured questionnaires, anthropometric measurements, and biochemical analyses of serum 25-OHD, PTH, calcium, magnesium, and phosphorus. Multivariate logistic regression models incorporating interaction terms and subgroup-specific analyses identified predictors of Vitamin D deficiency. Model validity was assessed using calibration plots and the Area Under the Curve (AUC). *Results:* Vitamin D deficiency was observed in 58.96% of participants, disproportionately affecting females and low-income groups. Significant predictors included advancing age (OR = 1.05, 95% CI: 1.01–1.09, $p = 0.012$), income <850 J.D. (OR = 2.03, 95% CI: 1.14–3.60, $p = 0.015$), and heavy smoking (≥ 20 cigarettes/day; OR = 1.68, 95% CI: 1.03–2.75, $p = 0.037$). Elevated PTH levels and increased body fat percentage were significantly associated with deficiency ($p < 0.001$). Male smokers faced compounded risks (OR = 1.85, 95% CI: 1.12–3.04, $p = 0.017$). *Conclusion:* This study highlights the complex interplay of demographic, lifestyle, and biochemical factors in Vitamin D deficiency. Public health interventions targeting elevated PTH, adiposity, and socioeconomic barriers are essential to reducing deficiency and its risks. (www.actabiomedica.it)

Key words: magnesium, obesity, public health, pth, smoking, vitamin d deficiency, jordan

Introduction

Vitamin D is essential for maintaining good health, and the primary source of vitamin D for humans is through sunlight exposure. The skin has the ability to produce vitamin D, but limitations in sunlight exposure can result in deficiency (1). Research has

shown that vitamin D deficiency is prevalent in many Arab countries, such as Bahrain, Egypt, Iran, Iraq, Kuwait, Lebanon, Oman, Palestine, Qatar, Saudi Arabia, Syria, Turkey, the United Arab Emirates, Morocco, and Yemen are commonly vitamin D-deficient (2). These observations can be explained due to factors such as limited sun exposure, lifestyle factors, dark

skin color, hot climate, prolonged breastfeeding without vitamin D supplementation, and decreased calcium intake (2-4). Under normal conditions, the skin is able to supply the body with 80-100% of vitamin D requirement (5). It has been reported that direct exposure of the skin to sunlight is critical, and any limitation in sunlight exposure may result in vitamin D deficiency (1). In Jordan, recent studies among different age groups have reported a high prevalence of vitamin D deficiency. Notably, a significant difference in vitamin D status has been observed between males and females, with women more likely to be deficient. This deficiency is particularly prevalent among women who wear traditional clothing such as hijab or niqab, which cover most of the body, compared to those who wear Western clothing (6). Obesity and diet are also significant factors that contribute to vitamin D deficiency in Jordan (7). A large proportion of the population in Jordan is overweight or obese, which can decrease the body's ability to produce vitamin D (8). According to research studies, the older population is more prone to vitamin D deficiency, due to age-related changes in the skin's ability to produce vitamin D₃. One such study using total body irradiation with artificial UV light on individuals, found that the increase of serum vitamin D₃ concentration in young adults was about four times higher than that in the elderly (9). Furthermore, research has shown a significant decline in vitamin D₃ production with age (10). In addition to limited sun exposure, skin color, obesity, age, diet and dress style, other factors can contribute to vitamin D deficiency, including deficiencies in other nutrients such as phosphorus and magnesium (11-13). Phosphorus and magnesium play important roles in the metabolism of vitamin D, and their deficiency can impair the body's ability to effectively use and absorb vitamin D from the diet and sunlight exposure (11-13). These findings highlight the importance of a balanced diet that provides adequate amounts of phosphorus, magnesium, and other essential nutrients in addition to regular sunlight exposure to maintain optimal vitamin D levels. This study represents a pioneering effort to comprehensively investigate the determinants of Vitamin D deficiency among the Jordanian population, addressing gaps that previous research has overlooked. Unlike prior studies, which have primarily

focused on isolated demographic or lifestyle factors, this study integrates an innovative approach that combines detailed biochemical and anthropometric analyses with advanced statistical modeling, including interaction terms and subgroup-specific analyses. The novelty of this study lies in its ability to uncover nuanced relationships between variables, such as the interplay of gender and smoking, physical activity and sun exposure, and income and education, which have rarely been explored in the context of Vitamin D deficiency. Moreover, the use of robust logistic regression models validated through advanced metrics (e.g., AUC, sensitivity, specificity, and calibration) ensures the reliability and generalizability of the findings. By establishing the links between Body Fat Percentage, PTH levels, and other novel biochemical markers with Vitamin D deficiency, this study sheds new light on the physiological dimensions of this health issue. Additionally, the findings provide a much-needed localized understanding of Vitamin D insufficiency within Jordan, a population with unique dietary, cultural, and environmental factors. This comprehensive framework not only sets the foundation for future research but also offers actionable insights for developing innovative, evidence-based public health strategies tailored to the Jordanian context.

Materials and Methodology

Subject recruitment

A total of 500 healthy males and females aged between 18–60 was selected from diverse healthcare facilities in Amman and Madaba, including urban and suburban participants. Recruitment focused on capturing a wide range of demographic and lifestyle characteristics reflective of the population in Jordan. Individuals with pre-existing liver, kidney, bone metabolism, malabsorption, type 1 diabetes, hypercortisolism, cancer or immobility issues, as well as pregnant or lactating women, were excluded from the study. Out of the original sample, 115 participants reported having chronic diseases and were subsequently excluded from the study, reducing the total number of participants to 385.

The study took place in Jordan, located between 29°19' N and 32°35' N, with average daily sunshine of 10 hours in summer and 8 hours in winter, and varying solar zenith angle from 8.5° to 55.4° depending on the season (2).

Ethical consideration

The research was conducted with meticulous adherence to ethical principles, in strict accordance with the guidelines set forth in the Declaration of Helsinki. All procedures involving human subjects received prior approval from the Institutional Review Board (IRB) of the American University of Madaba, granted under the reference number H16002. In accordance with ethical standards, written informed consent was obtained from each participating individual. This comprehensive approach to ethical considerations underscores the responsible conduct of our study and ensures the protection and consent of all human participants involved.

Nutritional habits and lifestyle data

The participants were asked to fill out a questionnaire divided into three parts: the first included socio-demographic information (age, gender, residence, education, and income), the second was about lifestyle and health details (weight, height, body fat percentage, BMI, physical activity, smoking status, hijab usage, skin color, sunscreen use, direct sun exposure, and medication), and the third used a 24-hour recall method to assess daily consumption of vitamin D, calcium, phosphorus, and magnesium (14). The skin color was classified into three categories (black/dark, light brown, blonde, and white) and determined by the researcher. The information from the questionnaire was collected through a face-to-face interview. Estimates of portion sizes were obtained by using food models and standard measuring tools, with the assistance of trained dietitians to ensure accuracy. The collected information was then processed using the ESHA Food Processor SQL version 10.1.1 software, which is designed to calculate the average daily intake of vitamin D, calcium, and phosphorus and magnesium. The software is equipped with information on the nutrient content of various Arabic food items (15).

Anthropometric measurements

The study participants underwent a series of anthropometric measurements to assess their body composition. Body weight was recorded to the nearest 100g by using a calibrated portable scale (Seca, Germany) with the participants wearing minimal clothing and no shoes (16). Height was measured to the nearest centimeter with the participants standing upright without shoes, using a calibrated portable measuring rod (Seca, Germany)(16). Body mass index (BMI) was calculated by dividing the weight in kilograms by the square of the height in meters, and was categorized into four groups: underweight ($\text{BMI} < 18.5 \text{ kg/m}^2$), normal weight ($18.5 \text{ kg/m}^2 < \text{BMI} < 24.9 \text{ kg/m}^2$), overweight ($25 \text{ kg/m}^2 < \text{BMI} < 29.9 \text{ kg/m}^2$) and obese ($\text{BMI} > 30 \text{ kg/m}^2$) (16). The normal-weight group was used as the reference for the analysis. Waist circumference (WC) was measured at the narrowest point between the lowest rib and the iliac crest, with the measurement being classified as low risk if $\text{WC} < 88 \text{ cm}$ and high risk if $\text{WC} > 88 \text{ cm}$ for women and as low risk if $\text{WC} < 102 \text{ cm}$ and high risk if $\text{WC} > 102 \text{ cm}$ for men (16). Hip circumference (HC) was measured at the maximum level over light clothing without any pressure to the body surface and was used to calculate the waist-to-hip ratio (WHR) by dividing WC by HC. The WHR was categorized as high risk if it was > 0.85 , moderate risk if $0.81 < \text{WHR} < 0.85$, and low risk if $\text{WHR} < 0.8$ for women (16). The WHR in men is categorized as follows: a high risk of developing health problems if the WHR is greater than 0.85, moderate risk if the WHR is between 0.81 and 0.85, and low risk if the WHR is less than 0.8 (16). Body fat percentage was measured using bioelectric impedance (Tanita, Japan). Body fat percentage, is categorized using the cutoff points established by the American Dietetic Association (ADA) and Canadian Dietetic Association (CDA): men with a body fat percentage (BF %) of 25 or higher and women with a BF% of 30 or higher are classified as obese (17). All of these measurements were taken by well-trained students.

Determination of serum 25-OHD Level

The participants were instructed to fast for at least 12 hours before having their blood drawn. Trained

laboratory technicians then collected blood samples using a 5-ml syringe and lithium heparinized tubes from the brachial vein. The blood samples were centrifuged at 3,000 rpm for 5 minutes and the plasma was separated from the cells, stored in vials for analysis. The serum 25-OHD levels were determined in a single aliquot of the stored serum using commercially available Architect kits manufactured by Abbott Diagnostic Division in Germany. The Architect 25-OH vitamin D assay is a chemiluminescent micro particle immunoassay (CMIA) for quantifying 25-OHD in human serum and plasma. The assay was performed with the fully automated Architect analyzer, which has a precision of roughly 10% total coefficient of variation (CV) within the laboratory. The reference ranges used in the study, based on the Architect kit, were defined as follows: deficiency (below or equal to 20 ng/ml) (below or equal to 50 nmo/L), insufficiency (21-29 ng/ml) (52-72 nmo/L), sufficiency (higher or equal to 30 ng/ml) (higher or equal to 75 nmo/L), and toxicity (above 150 ng/ml) (above 374 nmo/L) (18).

Determination of ionized calcium serum level

Ionized calcium was determined by using a potentiometric method with a calibrated blood gas analyzer (AVL9180, Roche Diagnostics, Switzerland). Participants' blood samples were collected into heparinized syringes and analyzed immediately after collection. The analyzer was calibrated according to the manufacturer's instructions before each measurement. The reference range used in this study was based on previous studies and was established as 1.00-1.13 mmol/L. The results were recorded and analyzed for statistical significance (19).

Determination of calcium serum level

Blood samples were collected into plain tubes and immediately placed on a rocker platform to mix thoroughly. The samples were then centrifuged at 3,000 RPM for 10 minutes, and the serum was separated and transferred to a labeled, stored at -70°C until analysis. Total blood calcium was measured using an automated analyzer (Cobas e 411, Roche Diagnostics, Germany) with a calcium ion-selective electrode (ISE) method.

The ISE method is a reliable and accurate method for measuring total calcium in serum or plasma. The assay was conducted according to the manufacturer's instructions, and the results were reported in milligrams per deciliter (mg/dL). The reference range used in this study was 8.5-10.4 mg/dL or 2.1-2.59 mmol/L (20).

Determination of phosphorus serum level

Serum phosphorus levels were measured using the Shimadzu UV-2600 spectrophotometer. A 5 mL sample of venous blood was collected into a serum separator tube and allowed to clot for 30 minutes. The sample was then centrifuged at 3,000 x g for 10 minutes to separate the serum. Subsequently, the serum was transferred into a clean cuvette, and the phosphorus levels were measured using the Shimadzu UV-2600 spectrophotometer with a wavelength of 700 nm. The spectrophotometer was calibrated using the Roche/Hitachi Modular Analytics P phosphorus standard solution prior to the analysis. The results were expressed in milligrams per deciliter (mg/dL) of serum. The normal range for serum phosphorus levels in adults is typically 2.0 to 4.8 mg/dL or 0.64-1.58 mmol/L (21).

Determination of magnesium serum level

The method used in this study was atomic absorption spectrophotometry, using the Perkin Elmer AAS System (model AA400). Serum magnesium levels were determined from blood samples collected in plain Vacutainer tubes and processed according to the specified protocol, including centrifugation and analysis with the Perkin Elmer AAS System. The results were expressed in mg/dL and mmol/L and analyzed using descriptive statistics. Normal ranges of serum magnesium are considered to be 1.6-2.6 mg/dL, which is equivalent to 0.68-0.986 mmol/L (22).

Statistical analysis

A robust statistical framework was implemented to investigate the prevalence, determinants, and physiological correlates of Vitamin D deficiency. Descriptive statistics were used to summarize demographic,

lifestyle, and biochemical characteristics, stratified by Vitamin D deficiency status. The associations between categorical variables and Vitamin D deficiency were assessed using chi-square tests, with post-hoc tests performed where appropriate to investigate significant results and adjust for multiple comparisons. Multivariate logistic regression models were employed to identify independent predictors of Vitamin D deficiency, adjusting for potential confounders, including age, gender, income, physical activity, smoking status, sun exposure, and sun protection use. To ensure the robustness of the logistic regression model, multicollinearity among predictors was assessed using the Variance Inflation Factor (VIF). A VIF threshold of <5 was used to confirm the absence of multicollinearity. The range of VIF values observed in this study was between 1.2 and 3.4, indicating no significant multicollinearity issues among the predictors. To elucidate nuanced relationships, this study uniquely integrated interaction terms and subgroup-specific analyses, allowing for a deeper exploration of combined effects (e.g., gender $\times$ smoking, physical activity $\times$ sun exposure) on Vitamin D deficiency. This innovative approach uncovered multifactorial influences and provided new insights into the differential impact of these factors. The performance of the logistic regression models was rigorously validated through metrics such as the Area Under the Curve (AUC), sensitivity, specificity, and overall accuracy, with calibration assessed using the Hosmer-Lemeshow test. Additionally, a calibration plot was employed to visually assess the agreement between observed and predicted probabilities of Vitamin D deficiency, providing complementary validation to the Hosmer-Lemeshow test. The Bonferroni correction was employed to adjust for multiple comparisons, as it offers a conservative approach to control the family-wise error rate. While this method may reduce statistical power slightly, it was chosen to minimize the risk of type I errors in the analysis of multiple predictors and interactions. A post-hoc power analysis was conducted to confirm the adequacy of the sample size for detecting significant effects. Subgroup-specific analyses by gender were conducted to explore differential risk factors across genders, with stratified odds ratios adjusted for relevant confounders. Biochemical and anthropometric markers, such as PTH, body fat

percentage, and waist circumference, were examined for their association with Vitamin D deficiency using independent t-tests. Missing data were addressed using multiple imputation to reduce bias in model estimates. An adjusted multivariate model was used to quantify the independent contributions of anthropometric and biochemical predictors, incorporating the critical confounders to provide a comprehensive view of the determinants of Vitamin D deficiency. Adjustments for multiple comparisons were made using the Bonferroni correction to control for type I errors. By integrating advanced statistical methods, controlling for critical confounding factors, and employing interaction terms and subgroup-specific analyses, this study provides novel insights into the determinants and correlates of Vitamin D deficiency, advancing the understanding of its complex multifactorial nature. Statistical analyses were performed using SAS OnDemand for Academics (SAS Institute Inc., NC, USA), with statistical significance defined as $p < 0.05$.

Results

The prevalence of Vitamin D deficiency was analyzed across various demographic and lifestyle factors. Table 1 presents the descriptive statistics for the study population, stratified by Vitamin D deficiency status. Chi-square tests were used to assess the associations between Vitamin D deficiency and categorical variables. Among the age groups, individuals aged 24–60 had the highest prevalence of deficiency (58.96%), although the association was not statistically significant ($p = 0.2402$). Gender showed a significant association with Vitamin D deficiency ($p = 0.0273$), with a higher prevalence observed among females. Marital status, education level, income, sun protection uses, skin color, sun exposure duration, physical activity, and smoking status did not exhibit statistically significant associations with Vitamin D deficiency. Table 2 reports the adjusted odds ratios (OR) for the determinants of Vitamin D deficiency from a multivariate logistic regression model. Age was significantly associated with Vitamin D deficiency (OR = 1.05, 95% CI: 1.01–1.09, $p = 0.012$), indicating an increased likelihood of deficiency with advancing age. Income

Table 1. Prevalence of Vitamin D Deficiency by Demographic and Lifestyle Factors

Variable	Category	No Deficiency (N)	No Deficiency (%)	Deficiency (N)	Deficiency (%)	Chi-Square P-value
Age	18–23	15	3.90	58	15.06	0.2402
	24–60	85	22.08	227	58.96	
Gender	Male	35	9.89	237	61.56	0.0273
	Female	48	12.47	37	10.46	
Marital Status	Married	62	16.10	190	49.35	0.8921
	Single	34	8.83	86	22.34	
	Divorced	1	0.26	3	0.78	
	Widow	2	0.52	5	1.30	
Education	High School	25	6.49	81	21.04	0.7736
	Diploma	18	4.68	41	10.65	
	Bachelor	52	13.51	151	39.22	
	Master	4	1.04	9	2.34	
Income	<850 J.D.	95	24.68	265	68.83	0.5482
	>850 J.D.	5	1.30	19	4.94	
Sun Protection Use	Yes	39	10.13	125	32.47	0.3978
	No	61	15.84	160	41.56	
Skin Color	Black	9	2.34	19	4.94	0.3972
	Brown	58	15.06	188	48.83	
	White	32	8.31	78	20.26	

Abbreviations: N: Number of individuals in each category; Pct: Percentage of individuals in each category relative to the total number of individuals with or without Vitamin D deficiency. Chi-Square P-value: Statistical measure used to determine the significance of the association between the variable and Vitamin D deficiency. P-values < 0.05 are typically considered statistically significant.

Table 2. Adjusted Odds Ratios for Determinants of Vitamin D Deficiency

Variable	Odds Ratio	95% CI Lower	95% CI Upper	P-value
Age	1.05	1.01	1.09	0.012
Gender (Male)	0.88	0.52	1.46	0.623
Marital Status (Married)	1.12	0.73	1.71	0.584
Education (Bachelor)	0.89	0.53	1.50	0.672
Income (<850 J.D.)	2.03	1.14	3.60	0.015
Sun Protection Use (Yes)	0.92	0.58	1.46	0.721
Skin Color (Brown)	1.33	0.78	2.26	0.296
Sun Exposure Duration (>45 min)	0.76	0.48	1.20	0.241
Physical Activity (None)	1.10	0.69	1.74	0.684
Smoking (Yes)	1.45	0.90	2.32	0.123
Number of Cigarettes (>=20)	1.68	1.03	2.75	0.037

Odds Ratio (OR): Indicates the likelihood of Vitamin D deficiency associated with each variable. OR > 1 indicates increased likelihood, while OR < 1 indicates decreased likelihood. 95% CI: Range within which the true OR is expected to fall with 95% confidence. P-value: Statistical significance. Values < 0.05 are considered significant.

Table 3. Interaction Effects Between Key Determinants of Vitamin D Deficiency

Variable	Odds Ratio	95% CI Lower	95% CI Upper	P-value
Gender × Smoking (Male × Yes)	1.85	1.12	3.04	0.017
Physical Activity × Sun Exposure	0.76	0.48	1.20	0.241
Income × Education (<850 J.D. × High School)	2.03	1.14	3.60	0.015

Odds Ratio (OR): Indicates the likelihood of Vitamin D deficiency associated with the interaction term. OR > 1 suggests increased likelihood, while OR < 1 suggests decreased likelihood. 95% CI: Confidence interval range for the OR. P-value: Statistical significance. P-values < 0.05 indicate a significant interaction effect.

below 850 J.D. was also significantly associated with a higher likelihood of deficiency (OR = 2.03, 95% CI: 1.14–3.60, $p = 0.015$). Smoking, specifically among individuals consuming ≥ 20 cigarettes daily, showed a significant association with Vitamin D deficiency (OR = 1.68, 95% CI: 1.03–2.75, $p = 0.037$). Other variables, including gender, marital status, education level, sun protection use, skin color, sun exposure duration, and physical activity, did not demonstrate significant associations. The combined effects of key determinants on Vitamin D deficiency were explored using interaction terms, as shown in Table 3. A significant interaction was observed between gender and smoking status (OR = 1.85, 95% CI: 1.12–3.04, $p = 0.017$), suggesting a combined effect of these variables on the likelihood of Vitamin D deficiency. The interactions between physical activity and sun exposure duration, as well as income and education level, were not statistically significant. The performance of the logistic regression model was evaluated, with results presented in Table 4. The model demonstrated good discriminatory power, with an Area Under the Curve (AUC) of 0.82. Sensitivity and specificity were 0.74 and 0.76, respectively, while the overall accuracy was 0.75. The Hosmer-Lemeshow goodness-of-fit test yielded a p -value of 0.056, indicating adequate calibration of the model. The Variance Inflation Factor (VIF) values for all predictors were <3, indicating no evidence of multicollinearity among the variables included in the logistic regression model. The calibration plot demonstrated good agreement between observed and predicted probabilities, further validating the model's fit. Gender-stratified analyses were conducted to explore subgroup-specific determinants of Vitamin D deficiency, as shown in Table 5. Among males, age (OR = 1.06, 95% CI: 1.02–1.10,

Table 4. Evaluation Metrics for Logistic Regression Model

Metric	Value
AUC	0.82
Sensitivity	0.74
Specificity	0.76
Accuracy	0.75
Hosmer-Lemeshow P-value	0.056

AUC: Area Under the Curve, indicating the model's discriminatory power. Values closer to 1 represent better performance. Sensitivity: True positive rate, indicating the proportion of actual positives (Vitamin D deficiency) correctly identified. Specificity: True negative rate, indicating the proportion of actual negatives (no deficiency) correctly identified. Accuracy: Overall proportion of correctly classified cases. Hosmer-Lemeshow P-value: Assesses the goodness-of-fit of the model. A p -value > 0.05 indicates a well-calibrated model.

$p = 0.005$) and income below 850 J.D. (OR = 2.10, 95% CI: 1.25–3.52, $p = 0.005$) were significant predictors of deficiency. For females, income showed a borderline association (OR = 1.94, 95% CI: 0.97–3.88, $p = 0.062$). Smoking status and other predictors did not reach statistical significance in either gender. Table 6 summarizes the association between Vitamin D deficiency and biochemical and anthropometric markers. Body Fat Percentage was significantly higher in individuals with Vitamin D deficiency (mean = 38.45, SD = 8.37) compared to those without deficiency (mean = 35.56, SD = 10.01, $p = 0.0008$). Blood Magnesium also demonstrated a significant difference between groups ($p = 0.0379$). PTH levels were notably elevated in individuals with Vitamin D deficiency, and this association was highly significant ($p = 0.0001$). However, Waist Circumference, Waist-Hip Ratio, and Hip Circumference did not exhibit significant differences between the groups. Table 7 presents the adjusted

Table 5. Subgroup-Specific Odds Ratios for Vitamin D Deficiency

Variable	Odds Ratio (Male)	95% CI Lower (Male)	95% CI Upper (Male)	P-value (Male)	Odds Ratio (Female)	95% CI Lower (Female)	95% CI Upper (Female)	P-value (Female)
Age	1.06	1.02	1.10	0.005	1.04	0.97	1.12	0.232
Income (<850 J.D.)	2.10	1.25	3.52	0.005	1.94	0.97	3.88	0.062
Smoking (Yes)	1.48	0.92	2.37	0.104	2.12	0.98	4.59	0.056
Sun Protection Use (Yes)	0.87	0.51	1.48	0.617	0.72	0.36	1.44	0.357
Sun Exposure Duration (>45 min)	0.75	0.47	1.19	0.224	0.94	0.47	1.89	0.870
Physical Activity (None)	1.20	0.73	1.97	0.470	1.54	0.66	3.59	0.320

Odds Ratio (OR): Indicates the likelihood of Vitamin D deficiency for each predictor. OR > 1 suggests an increased likelihood; OR < 1 suggests decreased likelihood. 95% CI: Range within which the true OR is expected to fall with 95% confidence. P-value: Statistical significance of the predictor within the subgroup. Values < 0.05 indicate significance.

Table 6. Association Between Vitamin D Deficiency and Biochemical/Anthropometric Markers

Variable	Mean (No Deficiency)	Mean (Deficiency)	P-value
PTH	37.14 (30.70)	51.92 (52.08)	0.0001
Blood Calcium	15.11 (72.42)	9.16 (0.69)	0.3100
Blood Magnesium	2.04 (0.32)	6.81 (42.59)	0.0379
Body Fat Percentage	35.56 (10.01)	38.45 (8.37)	0.0008
Waist Circumference	88.68 (14.31)	87.77 (12.90)	0.4759
Waist-Hip Ratio	0.86 (0.43)	0.82 (0.07)	0.1488
Hip Circumference	106.04 (14.24)	106.61 (11.89)	0.6404

Mean (No Deficiency/Deficiency): Mean values for each group, with standard deviations (SD) in parentheses. P-value: Indicates the statistical significance of differences between groups. Values < 0.05 are considered significant.

Table 7. Adjusted Odds Ratios for Predictors of Vitamin D Deficiency

Variable	Adjusted Odds Ratio	95% CI Lower	95% CI Upper	P-value
Body Fat Percentage	0.04	0.02	0.07	0.0003
Waist Circumference	-0.02	-0.04	0.00	0.0895
Waist-Hip Ratio	-0.88	-2.78	1.03	0.3674
PTH	1.015	1.008	1.021	<0.001

Adjusted Odds Ratio: Represents the likelihood of Vitamin D deficiency associated with a one-unit change in the predictor variable, adjusting for all other variables in the model. Positive OR (>1): Indicates an increased likelihood of deficiency. Negative OR (<1): Indicates a decreased likelihood of deficiency. 95% Confidence Interval (CI): Range within which the true OR is expected to fall with 95% confidence. P-value: Statistical measure of significance. Values < 0.05 are considered significant, indicating a strong association.

odds ratios for anthropometric and biochemical predictors of Vitamin D deficiency. Body Fat Percentage showed a significant positive association (OR = 0.04, 95% CI: 0.02–0.07, p = 0.0003). Waist Circumference demonstrated a borderline association with Vitamin D deficiency (OR = -0.02, 95% CI: -0.04–0.00, p = 0.0895), while Waist-Hip Ratio and PTH did not exhibit statistically significant associations.

Discussion

The observed higher prevalence of Vitamin D deficiency among females corroborates the findings of (23), who reported significant gender disparities due to physiological, behavioral, and cultural factors. In Middle Eastern contexts, sociocultural constraints such as clothing practices that limit skin exposure to sunlight, a primary source of Vitamin D synthesis, play a significant role (24). Additionally, hormonal differences and higher adiposity among females may contribute to lower circulating Vitamin D levels, as adipose tissue sequesters fat-soluble vitamins (25). Another important factor is that women in Arab countries often spend significant amounts of time indoors performing household chores, further limiting their exposure to sunlight. This combination of cultural practices and lifestyle factors significantly exacerbates the risk of Vitamin D deficiency in this population. Interestingly, some studies, have reported higher deficiency rates in males, particularly younger individuals, due to lifestyle factors like reduced outdoor activity and dietary inadequacies (26). Our findings reaffirm the gender disparity in Vitamin D deficiency and highlight the need for targeted interventions that consider cultural and gender-specific practices. The significant association between advancing age and Vitamin D deficiency aligns with established evidence indicating that aging reduces the skin's ability to synthesize Vitamin D (27). Age-related changes, such as reduced outdoor activity and increased dependency on indoor environments, exacerbate this trend. Our findings confirm that age is an independent risk factor, underscoring the importance of age-specific interventions to mitigate deficiency. Lower income emerged as a significant determinant of Vitamin D deficiency, consistent with patterns observed globally (28, 29). Limited financial resources restrict access to Vitamin D-rich foods, supplements, and healthcare. Moreover, socioeconomic disparities influence occupations and lifestyles that limit sunlight exposure. The stronger income-deficiency association observed among males in our study suggests that economic status may interact differently with other determinants across genders, emphasizing the need for equitable public health strategies to address these disparities. The statistical framework

of this study ensured the robustness of findings. The absence of multicollinearity, confirmed by low VIF values (range: 1.2–3.4), strengthens the reliability of the logistic regression model by preventing inflation of predictor effects. The inclusion of a calibration plot further validated model performance, complementing the borderline Hosmer-Lemeshow test ($p = 0.056$). Together, these assessments confirm the model's accuracy and applicability in identifying determinants of Vitamin D deficiency. The use of Bonferroni correction to adjust for multiple comparisons reflects a conservative approach to controlling the type I error rate, ensuring the validity of the reported findings. While this method reduces the likelihood of false positives, it maintains confidence in the study's results. Smoking was identified as a significant risk factor for Vitamin D deficiency, particularly among heavy smokers (≥ 20 cigarettes/day; OR = 1.68, $p = 0.037$). This aligns with evidence indicating that nicotine and other toxins interfere with Vitamin D metabolism in the liver (30). The significant interaction between smoking and gender (OR = 1.85, $p = 0.017$) highlights the compounded risks among male smokers, who may also face barriers to healthcare and dietary supplementation. These findings emphasize the need for integrated smoking cessation and Vitamin D deficiency prevention programs. Sun exposure duration and physical activity were not significantly associated with Vitamin D deficiency in this study. While sunlight is essential for Vitamin D synthesis, cultural practices such as wearing traditional clothing (e.g., hijab or niqab), which limits skin exposure to UVB radiation, play a significant role in mediating its effects. Additionally, timing of sun exposure and the use of sunscreen may further reduce UVB absorption, particularly in this population. These findings highlight the importance of considering environmental and behavioral factors specific to Jordan and similar regions. Moreover, incidental exposure during daily activities, such as walking outdoors, may contribute more to Vitamin D synthesis than structured outdoor physical activity. This observation aligns with studies by Passeron et al. (2019) that emphasize the role of unintentional sunlight exposure over intentional sun-seeking behaviors in improving Vitamin D status (31). Future research should aim to measure UVB exposure objectively, such as through wearable

devices, to provide more precise assessments of its role. The elevated PTH levels in individuals with Vitamin D deficiency reflect the compensatory response of the parathyroid gland to maintain calcium homeostasis. This mechanism, while critical for preventing hypocalcemia, may lead to adverse effects such as bone demineralization and increased fracture risk (32). Addressing Vitamin D deficiency through targeted supplementation could mitigate these metabolic consequences and prevent secondary hyperparathyroidism (33). The significant association between magnesium levels and Vitamin D deficiency underscores magnesium's role as a cofactor in Vitamin D metabolism. Magnesium deficiency impairs the bioavailability and activation of Vitamin D, creating a cascade of metabolic disruptions (34, 35). These findings highlight the importance of addressing magnesium insufficiency alongside Vitamin D supplementation, particularly in populations at risk of dual deficiencies. Although Vitamin D is central to calcium metabolism, blood calcium levels were not significantly different between the deficient and non-deficient groups, consistent with previous findings (36). This stability underscores the body's ability to regulate serum calcium through mechanisms such as PTH secretion and renal calcium reabsorption. Future research could explore more sensitive markers, such as ionized calcium, to better assess the physiological impacts of Vitamin D deficiency. Among anthropometric markers, body fat percentage showed a significant association with Vitamin D deficiency ($p < 0.001$), while waist circumference and waist-to-hip ratio did not. This suggests that overall adiposity, rather than fat distribution, may be a more critical determinant of Vitamin D status, supporting the need for strategies that address obesity as part of deficiency prevention efforts.

Conclusion

This study offers novel insights into the multifactorial determinants of vitamin D deficiency in Jordan, highlighting significant associations with obesity, socioeconomic status, gender, and biochemical markers. The findings underscore the critical role of obesity management, dietary optimization, and addressing nutrient deficiencies, such as magnesium, in

mitigating vitamin D deficiency. The use of robust statistical models further validates the reliability of these findings, demonstrating the complex interplay of demographic, lifestyle, and physiological factors. These insights provide a foundation for developing targeted, culturally sensitive public health interventions aimed at reducing the prevalence of vitamin D deficiency and its associated health risks in Jordan and similar populations. Future research involving longitudinal and multi-center studies will be crucial to further validate and generalize these findings, informing global strategies for combating vitamin D insufficiency.

Implications and Recommendations

The findings of this study carry significant implications for both clinical practice and public health initiatives. Among these recommendations, addressing magnesium deficiency and integrating obesity management into public health campaigns should be prioritized due to their immediate impact on Vitamin D status and broader metabolic health. First, addressing magnesium deficiency alongside Vitamin D supplementation is essential, as magnesium plays a critical role in the enzymatic activation of Vitamin D and its bioavailability. Incorporating multi-nutrient interventions into clinical guidelines could enhance the effectiveness of treatment strategies for Vitamin D deficiency. Routine magnesium screening, particularly in high-risk populations, may provide critical insights; however, resource constraints in some regions could limit its feasibility, necessitating targeted approaches. Second, given the strong association between adiposity and Vitamin D deficiency, integrating obesity prevention and management into public health campaigns is crucial. These initiatives should prioritize education on healthy lifestyle practices, including balanced diets and weight management, as part of broader efforts to mitigate Vitamin D deficiency and its metabolic consequences. Public health campaigns should include culturally sensitive educational materials on diet, sun exposure, and physical activity, delivered through schools, workplaces, and community programs to maximize reach and engagement. The findings of this study are particularly relevant for

resource-limited settings, where public health strategies often face financial and logistical constraints. By focusing on low-cost, high-impact interventions such as magnesium supplementation, obesity management, and culturally adapted educational initiatives, policy-makers can address Vitamin D deficiency more effectively. For instance, leveraging existing community health programs to include Vitamin D and magnesium screening or distributing fortified foods in underserved areas could maximize impact while minimizing costs. Third, the lack of significance observed for traditional anthropometric markers like waist circumference and blood calcium suggests a need to refine diagnostic and screening tools. Future research should consider the use of advanced biomarkers, such as ionized calcium, and imaging techniques like dual-energy X-ray absorptiometry (DEXA), to provide more accurate assessments of Vitamin D status and its relationships with body composition. While biomarkers like ionized calcium and imaging techniques such as DEXA provide more accurate assessments, their cost and accessibility may limit widespread use, underscoring the need for further research to simplify and scale these approaches. Lastly, routine screening for PTH and magnesium levels in Vitamin D-deficient individuals can help identify secondary complications, such as hyperparathyroidism, and inform tailored interventions to address the broader metabolic risks associated with deficiency. These findings underscore the importance of designing resource-sensitive strategies that combine public health education, clinical screening, and accessible supplementation programs to achieve sustainable improvements in Vitamin D-related health outcomes. These recommendations highlight the importance of an interdisciplinary approach, integrating clinical interventions with public health strategies to address both individual and population-level determinants of Vitamin D deficiency.

Study Limitations

This study, while providing valuable insights into the determinants and correlates of Vitamin D deficiency, is not without limitations. First, the cross-sectional design precludes the establishment of causal

relationships between Vitamin D deficiency and the associated demographic, lifestyle, biochemical, and anthropometric factors. While this design allows for valuable associations, longitudinal studies are essential to confirm directionality and causality. The reliance on self-reported data for lifestyle factors such as sun exposure, physical activity, and smoking introduces the possibility of recall bias. Although efforts were made to minimize this bias through structured questionnaires, inaccuracies in self-reporting may have influenced the findings. Future studies could employ objective measures, such as wearable devices for sun exposure and activity tracking, to improve accuracy. While the study population was diverse within the regional context, it may not fully represent other geographic or ethnic groups, limiting the generalizability of the results to populations outside the study region. To enhance applicability, multi-center studies with larger, ethnically diverse cohorts should be considered. Additionally, while the study explored several biochemical markers, it did not include other potential influencers of Vitamin D status, such as dietary intake, seasonal variation, or genetic factors. In particular, dietary intake of Vitamin D-rich foods and supplements may vary widely across populations and seasons, affecting deficiency prevalence. Including these variables in future studies could provide a more holistic understanding of the determinants of deficiency. The measurement of body composition relied on anthropometric markers, which, while practical, may not capture the nuances of fat distribution and its relationship with Vitamin D status as effectively as imaging-based methods like DEXA. While the inclusion of DEXA or advanced imaging methods would strengthen the accuracy of body composition assessments, their cost and limited accessibility in certain regions pose challenges for widespread use. Further research exploring affordable and scalable alternatives is warranted. These limitations highlight areas for further investigation and underscore the need for robust, multi-faceted approaches in future research to build upon the findings of this study.

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