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PUBLIC HEALTH NUTRITION (KE CHARLTON, SECTION EDITOR)

The Effect of Sunlight Exposure on Vitamin D Status in Countries of Low and High Latitudes: A Systematic Literature Review

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Abstract

Purpose of the Review To conduct a systematic review of studies to investigate the association between climate and vitamin D in humans.

Recent Findings There is growing interest in the association between the environment and vitamin D, but robust methods to understand this relationship are lacking. Studies focus mainly on seasonality and latitude. Research quantifying sunlight exposure necessary for adequate vitamin D synthesis in people with darker skin color and those people living at low latitudes are scarce, as are studies in urban populations that may have limited opportunity for sunlight exposure.

Summary There are gaps regarding values and timing of exposure to UV radiation required for adequate vitamin D synthesis considering skin color, geography, climate, and local irradiation. Nature-based solutions (NbS) that can mitigate climate change will become increasingly important for preventing hypovitaminosis D. For example, tree-shaded spaces might encourage more participation in outside activities and thereby favor vitamin D synthesis by the skin.

Keywords Vitamin D · Climate · Seasonality · Hypovitaminosis D · Environmental health · UVB radiation

Introduction

Vitamin D is essential for human health and is directly related to the environment. For most individuals, ultraviolet B (UVB) radiation from sunlight is the main source of this vitamin. Climatic and geographical elements provide different solar radiation intensities that can lead to different vitamin D production intensities [1]. It is estimated that 50% of the world population has low vitamin D status [2]. The high prevalence of vitamin D deficiency is considered a global public health issue by several authors [3–5], as it is a risk factor for total mortality in the general population [2]. Its detection, prevention, and treatment can constitute cost-effective therapies that would improve people's health and quality of life, especially in the aging process [6, 7].

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Regular sunlight exposure is considered a preventive measure against vitamin D deficiency. Such deficiency, related to inadequate exposure to UVB radiation, may result from the common lifestyles of many urban populations, who spend long periods of time indoors. Inadequate dietary intake, being overweight, having a dark skin pigmentation, advanced age, sunscreen use, and covered clothing style can also predispose to hypovitaminosis D [8], all of which are influenced by UV radiation according to time of year and latitude.

Alterations or deficiencies in the activation and control mechanism of vitamin D absorption result in organic disorders, which can progress to important pathologies such as rickets and osteomalacia and, in adults, when associated with osteoporosis, lead to an increased risk of fractures [6, 9, 10]. The non-skeletal benefits remain under study, but there is emerging epidemiological evidence that links low vitamin D status with mental health disorders, and increase risk of diabetes, cardiovascular disease, Alzheimer's disease/dementia, myopia, muscle degeneration, multiple sclerosis, some types of cancer, and depression [3, 11].

In order to allow better detection of population at risk, it is necessary to understand how climate affects vitamin D production, considering both heterogeneity within the same population and differences between populations.

At higher latitudes, from 42° N to 42° S, solar irradiation in the coldest months of the year may be insufficient or simply ineffective for vitamin D synthesis to be maintained at adequate status in the human body [2, 5]. This leads to frequent cases of rickets in children [11] and bone fractures in adults and older adults [6]. To address these problems, many countries located in high latitudes have developed public health strategies aimed at vitamin D supplementation, fortification of frequently consumed foods, or dietary recommendations to promote consumption of foods naturally rich in vitamin D.

There is a lack of literature that can provide scientific support for recommendations on values and time of exposure to UVB radiation required for adequate vitamin D synthesis in the skin that consider skin pigmentation, different geographic locations, and climate aspects, including local irradiation levels without posing a risk for skin cancer.

In an attempt to contribute to dealing with questions regarding hypovitaminosis D as a global phenomenon, a systematic review was conducted to assess how climate-related environmental aspects affect vitamin D status in humans, in order to identify potential public health strategies for the prevention of suboptimal vitamin status that take climate into consideration.

Methods

The objective was to identify what is being studied regarding vitamin D synthesis and its connection with different climate elements.

A Boolean search was performed on the Scopus and Web of Science databases to find publications with no initial cutoff date until June 2021. Prior to the search itself, a pre-search was performed, and tests of indexed keywords were carried out until the following search string was defined: "*Vitamin D*" AND *Climate* AND *Human*. The keyword "Human" was added to avoid publications that referred to animal species. In tests prior to the search, by using the keyword "Climate," it was possible to achieve results referring to "climate changes," "climate variations," "seasonality," "UV radiation levels," "solar irradiation," "cloudiness," and " latitude," the latter as indicative of the azimuth angle, having been defined as sufficient to encompass the search of environmental nature.

After conducting the research with no time range, 495 publications were found, including scientific articles, research published in conference annals, responses to editor's comments, and other scientific publication types.

Data was collected from both Scopus and Web of Science platforms, which include Pubmed and other databases from different areas of science.

Articles found with the words selected were exported to Start software, a free tool developed by the Federal University of São Carlos, Brazil, to support systematic reviews (Fig. 1).

The following inclusion criteria were defined: original study articles where the variables "Vitamin D and Climate" and/or "Vitamin D and Environment" and/or "Vitamin D and Seasonality" were included. Exclusion criteria were literature reviews, papers published in conference annals, responses to editor's comments, and other scientific publication types. Once the data were exported to Start and the fields for extracting those of interest were created, titles and abstracts were reviewed by the three authors. Fourteen articles, published in the last 5 years, were deemed to be eligible for data extraction.

Housing locations and year of publication of the cohorts analyzed in each study were identified. Then, a timeline was made with articles per year of publication (Fig. 2). The locations studied were grouped per country and arranged on a global horizontal irradiation (GHI) map, according to the number of publications (Fig. 3).

Among them, those published in the period 2017–2021 (last 5 years) were selected (Table 1), to focus on the most recent scientific findings and in a period when discussions on climate change have become a major focus of concern for scientists, governments, and even the population.

In order to guarantee fidelity to the information provided by each study, the data related to the vitamin D status adopted by the authors of the publications included in the review were respected, in nmol/L or in ng/mL (1 ng/mL = 2.5 nmol/L).

Results

In the initial search, publications on vitamin D and climate appeared as early as the 1970s, but were sporadic. From 2001 on, a series of papers has been produced associating vitamin D levels in humans with environmental and climate variables, showing a growth trend, with some oscillations. The years 2009, 2011, 2013, 2019, and 2020 stand out with more than 10 publications/year. In Fig. 2, the year 2021 only shows productions up to the month of June, when the search was carried out on the databases.

The first decade of the twenty-first century also records increased climate-related issue concern expressed by scientists, including physicians. Those concerns were motivated by increase in temperature, especially the strong heat wave that hit Europe in 2003, with over 22,000 deaths in France, Italy, England, and Portugal [12]. Since then, there has been much research indicating climate change as one of the major environmental health challenges of the century and climate elements as one of the determinants of human health.

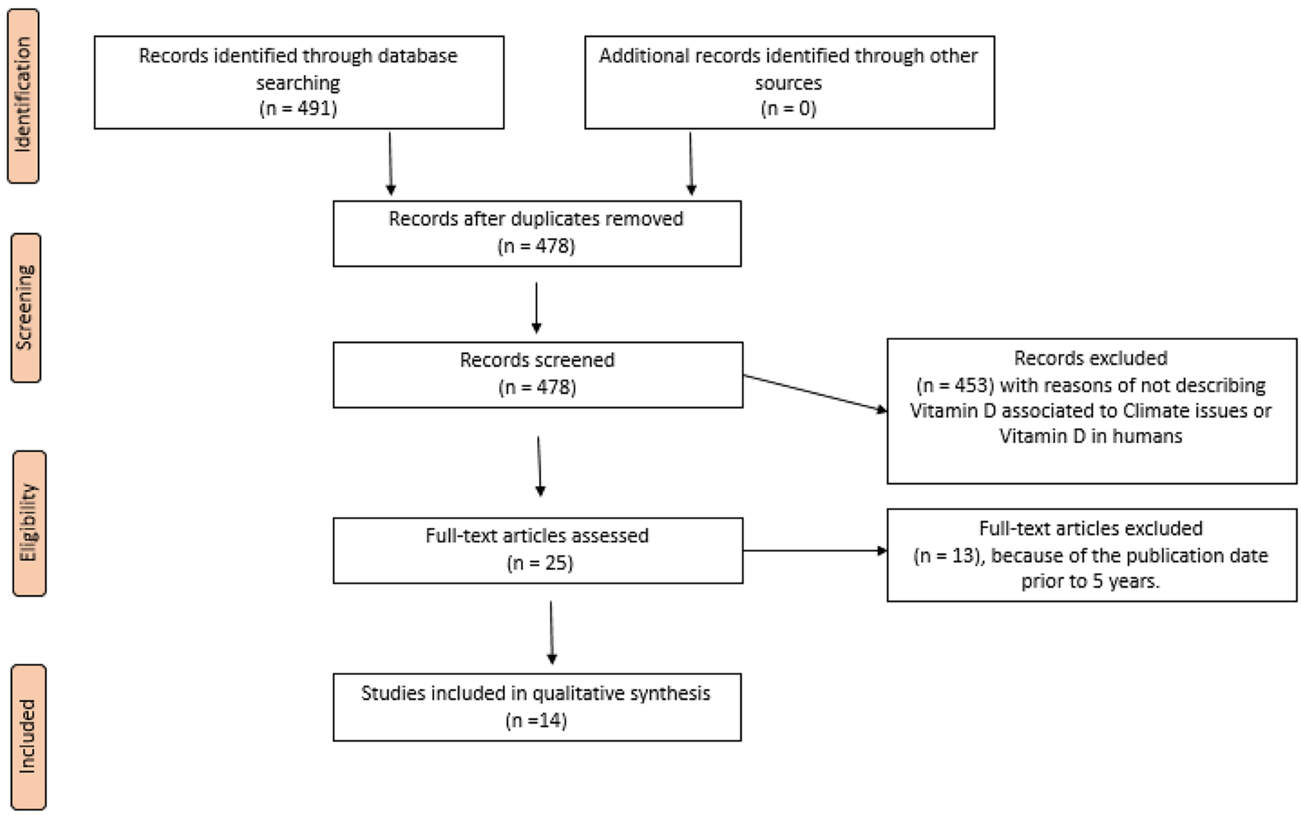

Fig. 1 PRISMA flow diagram. Presentation of the procedure of literature searching and selection with numbers of articles at each stage

Location of Research Mainly at High Latitudes

Most publications have studied populations residing in mid-high latitudes and in the northern hemisphere.

Figure 3 shows the distribution of research on vitamin D in association with climate elements, published between 2001 and 2021, arranged on a GHI map. It was grouped per country, and the spheres on the map indicate the number of publications related to the populations of that location.

According to FAO (2004) [26], hypovitaminosis D is a worldwide issue, especially in developing countries at high latitudes and in countries where sunlight skin exposure is discouraged. This review showed that research on the subject has been developed in different locations, especially in mid-high latitudes such as the UK and the USA, but also in countries located in mid-low latitudes (Fig. 3). Among the 14 publications selected, five studied the influence of the environment on mid-low latitudes: Afghanistan (31° N) [15], Australia (20° S) [16], Brazil (23° S) [19], Cyprus (35° S) N) [23], and the

Fig. 2 Selected publications on vitamin D in association with climate elements 2001 to 2021

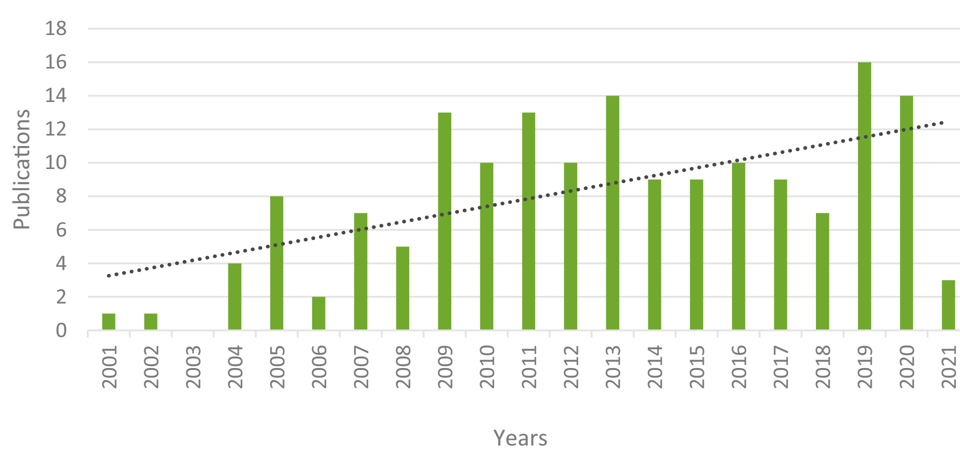

Table 1 Publications that related vitamin D levels and climate variables between 2017 and June 2021

Reference	Region	Study objective	Population	Methods	Vit D status *	Atmospheric variables	Results
Kraus et al. [13]	Germany (52° N)	Investigate the impact of two extreme summers on vitamin D [25(OH)D]	13,406 (> 40 years) individual first record of in- and outpatients University Hospital Halle	Clinical records and climate data time series analysis (2014–2019)	2014–2017 = 28% severe deficiency (< 25 nmol/L 25(OH)D); 60% deficient (< 50 nmol/L 25(OH) D); 81% insufficient (< 75 nmol/L 25(OH)D) 2018–2019 = 19%; severe deficiency 48% deficient 71% insufficient	Sunshine hours per month, UV data, and seasonality	The two record summer years of 2018 and 2019, while not differing from each other, had significantly higher 25(OH)D concentrations than the previous four years (2014–2017), which did not differ from each other
Griffin et al. [14•]	Ireland (53° N)	Investigate the vitamin D status and serum 25(OH) D concentrations of adults living in an urban area versus adults living in a rural area	17,590 total individuals (> 18 year): *n* 4824 urban; *n* 12,766 rural	Cross-sectional retrospective analysis of clinical records of individual that had vitamin D [25(OH)D] blood measured for any reason	15.9% = deficiency (< 25 nmol/L) 35.6% = insufficiency (25–50 nmol/L) 48.5% = sufficiency (> 50 nmol/L)	Sunshine hours for the prior previous days (including day of sampling) and season	Serum 25 (OH)D concentrations higher in urban compared to rural dwellers in all seasons. Vitamin D deficiency more common in rural than urban dwellers in spring, autumn and winter but not in summer. Female < male vitamin D in general. Serum 25(OH) D concentrations increased sequentially from the 18 – 39 years age group to the 60 – 69-year-age group in urban and rural dwellers and decreased as age increased to ≥ 90 years. The odds of vitamin D deficiency increased with age, lower daily sunshine hours, male gender, rural, and season (winter and spring greater than summer and autumn)
Fallowfield et al. [15]	UK (54° N), Afghanistan (31° N)	Investigate the effect of hot-dry deployments on vitamin D status of young, male, military volunteers	98 (18–42 years) medically fit participants	Volunteers measured and samples drawn pre-deployment, mid-deployment and post-deployment	Location 54° N: 48% < 50 nmol/L; 9% < 25 nmol/L. Location 31° N: 33% > 185 nmol/L. No volunteers were suboptimal	Summer months in latitude 31° N	Sunlight exposure is most probably the largest single cause of the observed increase in 25(OH)D. The significant increase in concentrations was maintained at the post-deployment measure point
Lara Alvarez et al. [16]	Australia (20° S)	Investigate the relationship between season and low trauma hip fracture admission	1349 adults (24–108 years)	Retrospective analysis of clinical records of those admitted for hip fracture during a 7-year period	34.8% < 50 nmol/L (deficiency) 28.5% in summer 42.5% in winter	Seasonality	Higher number of fractures in winter months compared to other three seasons

Table 1 (continued)

Reference	Region	Study objective	Population	Methods	Vit D status *	Atmospheric variables	Results
Ferrari et al. [17••]	Italy (45° N)	Investigate the association between solar ultraviolet doses and vitamin D Lab clinical routine data	30,400 individuals > 18 years 90–95% control routine 5–10% from hospitalized patients	Retrospective analysis of clinical data records (2006–2018) correlated to climate data sets	November to March (cold months) = 71% < 30 nmL^{-1} (insufficient), 41% < 20 nmL^{-1} (deficient) May to December (warmer months) = 62% < 30 nmL^{-1} (insufficient), 32% < 20 nmL^{-1} (deficient) Colder (Feb–March) = 90% insufficient Warmer (September) 34 to 62% insufficient	Cloud-free UV index (UVIEF), cloud-free erythemal UV dose (UVDEC), cloud-free vitamin D UV dose (UVDVC), cloud-free DNA damage (UVDDC), local solar noon ozone column	Direct relationship between serum 25(OH)D concentrations and UVB radiation that reached the Earth. Reported changes in the Arctic stratospheric ozone layer were likely consequence of natural year-to-year variability and did not seem to influence the vitamin D status. Deficient/insufficient 25(OH)D levels exceeded 70% in cold season and > 60% in warm seasons, when sufficient UVDVC reached the Earth's surface. Thus, effective UV availability alone could not explain the population's vitamin D status, which was likely to be influenced by other factors related to the people's lifestyle and their personal characteristics
Corrêa et al. [18]	South America ten different locations between 10.5° S and 62.1° S	Investigate the association between changes in TOC—total ozone content—levels and the variability of UVR in South America, and the exposure time needed to developing erythema and synthesizing vitamin D under clear sky conditions	________	Climate modeling twenty-first century, using representative concentration pathways (RCPs)	________	Total ozone content (TOC), representative concentration pathways (RCPs), latitudes, UVR (DOSE-E), EVR (DOSE-D), tropospheric ultraviolet radiation model (TUV), historical data by seasons. Considered no aerosols and cloud conditions	Projections did not indicate D-UVR deficiency risks for the population at any season during the twenty-first century at any of the low and middle latitude regions. The high south latitude regions might experience a reduction of 22.3% by the end of this century
Bittar et al. [19]	Brazil (23° S)	Investigate whether sun exposure measured by a questionnaire could predict serum 25OHD concentrations in healthy Caucasian individuals in a tropical area	200 healthy Caucasian individuals Divided by groups 20–40 years and 60–80 years in summer and winter	A cross-sectional study correlating total sun exposure score (TSES) questionnaire answers and vitamin D blood tests	17.60 ± 7.3 ng/mL mean in all individuals 66.5% < 20 ng/mL Young = 18.27 + −7.13 ng/mL Summer = 21.51 + −6.08 ng/mL Winter = 14.95 + −6.58 ng/Ml (older = 16.93 + −7.45 ng/mL)	Sun exposure, total sun exposure score (TSES), seasonality categorized samples (summer and winter)	Mean serum 25OHD concentration was 17.60 ± 7.3 ng/mL with no difference between age groups. TSES weakly correlated with serum 25OHD levels ($r = 0.264$; $p < 0.001$). Vitamin D concentrations were significantly higher in the summer than in the winter only for the young participants

Table 1 (continued)

Reference	Region	Study objective	Population	Methods	Vit D status *	Atmospheric variables	Results
Sahin et al. [20]	Turkey (36° N–42° N)	Investigate the seasonal 25-OHD level and its association with intact parathyroid hormone (iPH) in Turkish children of all pediatric ages	90,042 (2 months–18 years)	Retrospective record review (2010–2016) of laboratory database on children	40–45% deficiency at early ages; 80–90% deficiency after 10 years Women = 22.3 mg/mL (mean) Male = 25.3 mg/mL (mean)	Seasonality and latitude	On the analysis of seasonal, gender, and age effects on vitamin D levels, children had low 25-OHD levels between February and May, and the population size with low 25-OHD levels was small during summer. The prevalence of 25-OHD deficiency became more predominant as the children grew to the age of 18. High prevalence of hypovitaminosis D in Turkish children, most of whom reside in a sunny subtropical climate
Majeed et al. [21]	UK (50° N–60° N)	Investigate the impact of the Atlantic multidecadal oscillation (AMO) on UK rickets incidence rates	~ 2.5 million (0–15 years)	Retrospective hospital admission for rickets analysis (1963–2011) correlation with AMO data sets	________	AMO data, sea surface temperature, sea pressure, sunshine data of summer months (June to August)	The study found statistically significance to AMO with increased cloudiness in summers in the mid-90 s, explaining the rise of rickets from that time after decades of decreasing trend. This suggests that the recent decline in sunshine duration is clinically important with respect to vitamin D production
Nowak et al. [22•]	Poland (52° N)	Investigate the seasonal variation of vitamin D in elderly hospitalized patients	242 individuals (72–85 years)	Analysis of vitamin D levels in the year 2013 categorized by season the blood sample was collected at admission	All year mean: 79.8% < 50 nmol/L (deficiency); 19% < 50.0–75.0 nmol/L (suboptimal); 1.2% > 75.0–125.0 nmol/L (adequate)	Seasonality	No significant differences in median vitamin D concentrations across all four seasons. Vitamin D deficiency observed in all geriatric patients irrespective of season
Byitler et al. [23]	Cyprus (35° N)	Investigate the frequency of Vitamin D deficiency and insufficiency and the impact of seasonal variation on the 25(OH)D levels	565 healthy children (0–18 years)	Retrospective database from routine consultation and correlation with atmospheric temperature	22.5% deficiency; 29% insufficiency; 48% sufficient	Average atmospheric temperature	Positive correlation of vitamin D levels with atmospheric temperature and a negative correlation with age. 25(OH)D deficiency and insufficiency were most frequent during winter and spring and less frequent during summer

Table 1 (continued)

Reference	Region	Study objective	Population	Methods	Vit D status *	Atmospheric variables	Results
Akinlawon et al. [24]	USA (42,4° N)	To identify risk factors for vitamin D deficiency/insufficiency among Puerto Ricans living in Massachusetts	822 adults (45–75 years)	Association between risk factors including the comparison of spring and autumn blood draw with multivariable general linear models	43% insufficient 13% deficient	Seasonality and time spent in warmer climate during the last 12 previous months	Individuals with vitamin D deficiency/insufficiency tended to be younger, to have higher BMI, and to consume less vitamin D from dietary sources. They were also more likely to have their blood drawn during the spring season, to have a dark or medium skin tone, to be current smokers, and were less likely to be taking vitamin D from supplements. Exposure to a southern climate during the past months was significantly associated with increased 25(OH)D
Oshiro [25]	Hawaii USA (19,8° N)	Investigate the major sources of Vitamin D (sun exposure and vitamin D intakes from food and supplements) and evaluate their collective role on rates of Vitamin D deficiency/insufficiency among older adults at age 60 clinic visit	223 (> 60 y)	Cross-Sectional Analysis of the relationship between serum 25(OH)D and sources of vitamin D	Total 5.4% deficiency < 20 ng/mL 37.7% insufficiency < 30 ng/mL Asian 7% deficiency 43.4% insufficiency White 0% deficiency 28% insufficient	Latitude Time spent outdoors Sun exposure by comparing sun-exposed and unexposed skin tone	The study results showed deficiency/insufficiency rates were much lower than in the general US population (77%), although more than 1/3 of participants (38%) still had vitamin D deficiency/insufficiency despite access to a tropical, sunny climate. Sun exposure and supplementation were the main predictors of serum 25(OH)D in this ethnically diverse sample of adults in their 60 s who were mostly residents of Hawaii

Table 1 (continued)

Reference	Region	Study objective	Population	Methods	Vit D status *	Atmospheric variables	Results
Webb et al. [8]	UK (50° N–60° N)	To quantity sun exposure required to meet vitamin D targets year-round and determine whether this can be safely achieved in a simply defined manner in the UK as alternative to increasing vitamin D oral intake	Adult white Caucasian metadata from intervention studies with volunteers wearing shorts and T-shirts	Data sets modeling	________	Sunlight data, sunlight exposure models, UVR data, solar zenith angles, and seasonality categorized data sets	The study exemplified a sun exposure regime that meets vitamin D requirements for white Caucasians. White-skinned people in the UK (and similar latitudes) are able to meet vitamin D requirements (defined as remaining at or above 25 nmol/L 25(OH)D throughout winter) by spending 9 min outdoors at lunchtime from March to September or for 9 to 13 min, dependent on south-north geographical location, June–August, in season-appropriate clothing. Where sun exposure is impractical, dietary sources should be assessed

*Some publications used measurements of circulating serum 25(OH)D in nmol/L, while others used ng/mL; the option was to leave it as described in each study instead of using one of the two methods as standard, because some interlocutor may be interested in observing the original method of each piece of research

USA/Hawaii (19.8° N) [25], and in four of them, significant percentages of their populations had hypovitaminosis D [16, 19, 23, 25], ranging from 34 to 66%.

Methods Used in Research

Among the publications analyzed, seven related climate elements to serum 25-hydroxyvitamin D [25(OH)D] concentrations using retrospective analyzes of medical records [13, 14•, 15, 17••, 20, 21, 23]. Five were observational [15, 19, 22•, 24, 25] and carried out by health researchers.

Three [8, 18 and 21] did not make direct association of data on vitamin D status with climate elements. Those came from environmental sciences, mainly from the area of meteorology, and focused mainly on climate parameters and their possible influence on vitamin D production in skin.

Little Ethnic Diversity in Research

Only two publications presented clear ethnic diversity and skin pigmentation as elements of analysis. The piece of research [24], carried out in MA, USA, with a cohort of Puerto Ricans, considered the ethnic diversity in its sample. The results indicated that 43% had insufficient Vitamin D (13% deficient) status, and that having a dark or medium skin tone was positively associated with vitamin D deficiency/insufficiency.

The other, also in the USA, in the state of Hawaii [25], considered different ethnicities, with analysis of white and Asian individuals. It showed that no white individual had vitamin D deficiency and 28% had insufficiency, while 7% of Asians had vitamin D deficiency and 43.4% insufficiency.

Among the other publications, two emphasize that they studied white populations [17••, 19], and others were developed in countries with mostly white native populations such as Germany and the UK [8, 13, 15, 21].

Age Diversity

There was age diversity among the individuals studied in the publications, but most studied adults, three of them [15, 19 and 25] analyzed specific groups of adults. Oshiro [25] included individuals aged over 60 years. Fallowfield. et al. [15], in their study carried out with military volunteers, analyzed young adults aged 18 to 42 years. Piece [1] analyzed two age groups, from 20 to 40 years old, and from 60 to 80 years old. Only the group of younger participants had higher levels of vitamin D in the summer. Piece [24], with Puerto Ricans who lived in Massachusetts aged from 45 to 75 years, found lower vitamin D levels in the youngest portion. The piece by Norwak et al. [22•], which worked with

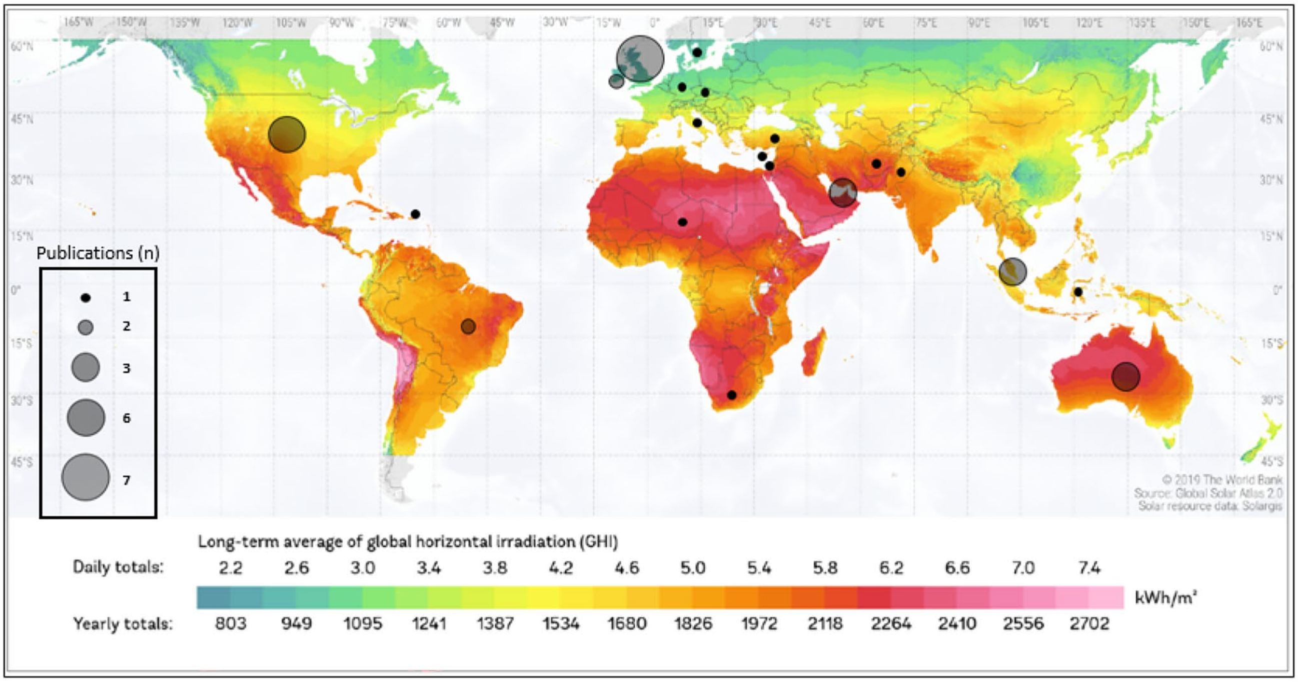

Fig. 3 Location of research on vitamin D in association with climate elements on GHI map—2001 to 2021. Fonte: Adapted by the authors from Global Solar 2.0 and The World Bank (2019)

institutionalized older people aged 72 to 85 years, did not find any connection between serum 25-hydroxyvitamin D [25(OH)D] concentrations and seasonal variations.

Research by Sahin et al. [20], Majeed et al. [21], and Byitler et al. [23] focused on children. Sahin et al. studied children in Turkey (36° N–42° N) aged 2 months to 18 years. Vitamin D status in children was lower during the late winter months and early spring months, and decreased as children got older, marking the beginning of school age [20]. Byitler et al. [23], in turn, studied children that lived in Cyprus (35° N) and found similar results to Sahin et al. [20].

Majeed et al. [21] connected vitamin D status with climate variables, through the prevalence of rickets in the UK child population, using a 1963–2011 historical series of children hospitalized in the country. The authors found a connection between the outcome and climate oscillations.

Meteorological and Climate Variables

There was a great diversity of methods used in the publications, although most of the objectives were to investigate the association between climate-related events or weather and climate environmental conditions and circulating 25(OH)D status.

Climate variables used in research were sunlight exposure; sunshine radiance; seasonality; summer months; cloudiness; latitude; atmospheric temperature; time spent in warmer climates; time spent outdoors; solar zenith angles; sunlight exposure models; total ozone content (TOC); solar spot noon ozone column; Atlantic multidecadal oscillation (AMO); sea surface temperature; sea pressure; cloud-free UV index (UVIEF); cloud-free erythema UV dose (UVDEC); cloud-free vitamin D UV dose (UVDVC); and cloud-free DNA damage (UVDDC). Sunlight exposure and seasonality were the most frequent variables used.

More robust research on climate elements has associated climatic events such as TOC [18] and AMO [21] with outcomes such as hypovitaminosis D and rickets, respectively. Ferrari et al. [17••] investigated the association between solar ultraviolet doses and vitamin D Lab clinical routine data, using satellite data for their modeling. Their results show that in hot months, there was sufficient solar irradiation for adequate vitamin D synthesis in the population, even so more than 60% of the population presented vitamin D insufficiency/deficiency in that period. They concluded that effective UV availability alone could not explain the population's vitamin D status, which would likely be influenced by other factors related to people's lifestyle and personal characteristics.

Majeed et al. [21] found that climate variations, in addition to the trivial variations of the seasons, can interfere with vitamin D synthesis, with a positive association between AMO impact on the UK rickets rates. It was possible to reach the conclusion that a long cycle variation, which lasts between 60 and 70 years, had impacts on rickets hospitalizations due to a decrease in sunshine hours during the negative phase of AMO.

Publications [15] and [24] considered time spent in warmer climates as one of its variables and found positive associations of this element with increased vitamin D levels.

Fallowfield et al. [15] studied the effect of hot-dry deployments on vitamin D status of young, male, military volunteers. The study compared the vitamin D status of volunteers in the UK (54° N) prior to departure for service in Afghanistan (31° N), then during service while residing in Afghanistan, and after returning to the UK. According to their measurements, almost half of the volunteers left the UK with vitamin D < 50 nmol/L, considered a sub-optimal level for bone health, while the optimal level would be from 50 nmol/L; in the service location (31° N), none of the volunteers had suboptimal levels of vitamin D, and more than a third of the military volunteers had levels greater than 185 nmol/L, which are levels almost three times higher than the level considered adequate. The study concluded that sunlight exposure is most probably the largest single cause of the observed increase in 25(OH)D, and about 14% of volunteers continued presenting high vitamin D status after service and back to latitude 54° N.

A study by Oladimeji et al. [24], among Puerto Ricans living in Massachusetts, found that time spent in lower latitudes in the southern hemisphere during the last few months was an important risk factor for vitamin D sufficiency.

Among the publications, two aimed to quantify the sunlight exposure necessary to synthesize adequate vitamin D levels. Webb et al. [8] sought to quantify sunlight exposure needed to meet year-round vitamin D targets and determine whether this can be achieved safely in the UK as an alternative to increasing vitamin D oral intake. They concluded that a sunlight exposure regimen that meets the white-skinned people's vitamin D needs in the UK (and similar latitudes) is able to meet the vitamin D needs during winter if the person spends either 9 min outdoors at lunchtime, from March to September, or 9 to 13 min, depending on the south-north geographic location. However, the authors reiterate that where sunlight exposure is impractical, food sources should be evaluated. Corrêa et al. [18], in turn, estimated the exposure time required to develop erythema and synthesize vitamin D under clear-sky conditions in South America. Ten locations were sampled between 10.5° S and 62.1° S; none of the projections indicated risk of vitamin D deficiency due to low solar irradiation levels in the twenty-first century with the exception of the spring season of the location at 62.1° S, in the South Pole, which by the end of the century should present a 22.3% decrease in chances of reaching satisfactory solar irradiation levels for vitamin D synthesis.

Populational Hypovitaminosis D Is Found even in Low or Mid-Low Latitudes

Studies carried out in resident populations of mid-low latitudes, such as Afghanistan (31° N) [15], Italy (45° N) [17••], Turkey (36° N–42° N) [20], Cyprus (35° N) [23], and USA-Massachusetts (42.4° N) [24], and low latitudes such as Australia (20° S) [16], Brazil (23° S) [19], and USA-Hawaii (19.8° N) [25], found significant proportions of their cohorts with hypovitaminosis D, although the climate in the studied places is warmer and sunnier than those of mid-high latitudes, and reiterate that lifestyle habits are important determinants of the levels of circulating 25(OH)D.

Main Findings

This review yielded 14 publications related to the association between climate conditions and vitamin D status across a broad range of populations residing at different latitudes. Despite a recommendation by WHO/FAO [26] in 2004 that further studies were needed to identify whether dietary vitamin D supplements were as effective as exposure to UV radiation, published research on the association between vitamin D levels and atmospheric and environmental factors remain limited. This review focused on the last 5 years, during which time climate change has become a matter of concern for scientists of the health sector as well. Nevertheless, the impact of climate change on radiation levels and on the population's vitamin D status is only mentioned in one of the publications. Among those published on journals more related to health and nutrition, the greatest concern regarding climatic factors is UV radiation in different seasons and at different latitudes. Those publications are largely epidemiological and associate vitamin D status in populations of different ages that live in places with different time of radiation. Publications more focused on climate factors and its current complex dynamics, indicating possible effects on vitamin D status, are published on environmental journals. This indicates that there is still a small integration between health scientists and environmental scientists.

The findings from this review have demonstrated that vitamin D deficiency is present across all latitudes, at all ages, thus making it a global issue. Interventions have mainly focused on providing vitamin D as oral supplements or in fortified food.

Studies have shown a high prevalence of vitamin D deficiency and insufficiency in locations where there is sufficient radiation throughout the year for its synthesis, as demonstrated in research conducted in Australia [16], Brazil [19], Cyprus [23], and Hawaii [25]. However, few publications recommend more sunlight exposure, such as that by Beyitler et al. [23], who conclude their study by recommending that once their country, Cyprus, has sufficient sunlight exposure, children should spend more time outdoors to benefit from vitamin D synthesis through sunlight. In turn, the only research into the recommended time of sunlight exposure for adequate vitamin D synthesis was performed in the UK and in a Caucasian population [8].

Another important finding is that the prevalence of deficiency/insufficiency is lower in newborn children and increases progressively until adolescence [20, 23]. This may suggest that the habit of staying indoors for a long time develops from an early age due to school and study activities and expands with productive age among some professions due to work responsibilities, lifestyles, physical activity, and diet. With aging, the risks of vitamin D deficiency increase with season [14•], cloud cover and due to a greater difficulty in receiving adequate exposure to sunlight, combined with lower dermal absorption.

Public Health and Nature-Based Solutions

Nature-based solutions (NbS) are policy options for ameliorating the problem of global anthropogenic climate change, suggested over the past decade, and incorporated by different actors. NbS use ecosystems and the services they provide to address societal challenges such as climate change, food security, or natural disaster (Cohen-Shacham et al. [27], p.2), simultaneously providing human well-being and biodiversity benefits. Chausson et al. [28] state that NbS involve working with and enhancing nature to help address those global environmental problems. As example, largest access to green areas contributes to reduce air temperature extremes, thus inviting for outdoor activities and contributing to an active life and normal weight, associated to better vitamin D status.

None of the cited papers investigated the number of hours and best time of the day for sunlight exposure in countries of lower latitudes and for darker-skinned populations that require higher radiation levels for vitamin D synthesis [24, 25]. Such data would support important recommendations, especially for lower-income populations and countries where vitamin supplementation represents an additional financial burden.

Besides, research that used measurements of radiation intake at individual level was not found either.

The increasing production of research into the subject in recent years may mean a greater interest of the academic community in the face of environmental issues, because either of the growing hypovitaminosis D pandemic, which can be the result of lifestyle habits that discourage external activities, or of the potential risk of climate change or variations, characterized by temperature extremes, which would lead people to remain in artificially conditioned environments.

In view of the findings, it is concluded that climate and weather interfere with human health and that modern lifestyles, work conditions, and warm temperatures have fostered habits of staying indoors most time of the day, reducing sunlight exposure. Even when there are favorable conditions for adequate vitamin D synthesis, recommendations for adequate sunlight exposure have been scarce. Of all the 14 cited papers, only one recommends that children should spend more time outdoors [23].

Understanding the influences of the environment on human health can provide us with tools to improve urban conditions in order to favor well-being and optimize available resources to remedy and/or prevent diseases, including those associated to hypovitaminosis D.

In countries located in low and mid-low latitudes, policies based on safe sunlight exposure can bring great benefits, such as those cited by Byitler et al. [23]. Chausson et al. [28] point out that nature-based solutions (NbS) have social impacts and economic costs/benefits that are more prevalent in low-income countries than in high-income ones. Research by Cohen Shacham [29] argues that SDG 3: Health and well-being [30] can benefit from the NbS method.

Conclusion

Currently, the NbS have gained priority in policies to combat climate change, and nutritional and public health spheres should turn to these solutions and expand interdisciplinarity.

Based on this review, it is possible to state that there is a growing interest in the association between environment and vitamin D status and research is still looking for increasingly robust methods and ways to understand this association. Research quantifying sunlight exposure necessary for adequate vitamin D synthesis in people with darker skin color and those people living in low latitudes are scarce, as are studies in urban populations that may have limited opportunity for sunlight exposure. Furthermore, there is also a lack of research that consider the habits of everyday urban life as a limiting factor for sunlight exposure, considering the types of housing, work environments, urban design, the presence of green areas and external spaces for coexistence and leisure, safety, and suitable routes for walking and/or riding bicycles. The use of nature-based solutions that can mitigate climate change will become increasingly important for preventing hypovitaminosis D. For example, tree-shaded spaces might encourage more participation in outside activities and thereby favor vitamin D synthesis by the skin.

Study Strengths

Connection between climate variables and vitamin D status is still little explored in its potential in the literature studied.

This systematic review analysed studies which used different methods, thus there was an integration of diverse investigation methods. Referenced studies performed blood samples collection and analysis of diverse ages in different countries at diverse latitudes, thus this systematic review allows understanding the Vitamin D status of population in a world context.

Results highlight that climate has a potential for use in nature-based solutions regarding vitamin D deficiency and insufficiency. It elucidates relevant issues regarding vitamin D status, which are of worldwide importance, especially in a climate change context and for a post-pandemic urban adaptation.

Study Limitations

There might be studies not indexed on the Scopus and Web of Science bases that were not included. Local studies in other languages rather than English were not included.

Declarations

Conflict of Interest The authors declare no competing interests.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

References

Papers of particular interest, published recently, have been highlighted as:
• Of importance
•• Of major importance

1. Moan J, Porojnicu AC, Dahlback A, Setlow RB. Addressing the health benefits and risks, involving vitamin D or skin cancer, of increased sun exposure. Proc Natl Acad Sci. 2018;105(2):668–73.
2. Nair R, Maseeh A. Vitamin D: the "sunshine" vitamin. J Pharmacol Pharmacother. 2012;3(2):118.
3. Hoel DG, Berwick M, de Gruijl FR, Holick MF. The risks and benefits of sun exposure. Dermato-endocrinology. 2016;8(1):e1248325.
4. Holick MF, Chen TC. Vitamin D deficiency: a worldwide problem with health consequences. Am J Clin Nutr. 2008;87(4):1080S-1086S.
5. Lee DH, Park KS, Cho MC. Laboratory confirmation of the effect of occupational sun exposure on serum 25-hydroxyvitamin D concentration. Medicine. 2018;97(27):e11419. https://doi.org/10.1210/jcem-67-2-373
6. Barral D, Barros AC, Correia de Araújo RP. Vitamina D: uma abordagem molecular. Pesqui Bras em Odontopediatria Clín Integr. 2007;7(3):309–15. Portuguese. https://www.redalyc.org/articulo.oa?id=63770319
7. Bjørklund G. Vitamin D deficiency: A global health problem. Ann Environ Sci Toxicol. 2016;1(1):023–4. https://doi.org/10.17352/aest.000004.
8. Webb AR, Kazantzidis A, Kift RC, Farrar MD, Wilkinson J, Rhodes LE. Meeting vitamin D requirements in white caucasians at UK latitudes: Providing a choice. Nutrients. 2018 Apr 17;10(4):497. https://doi.org/10.3390/nu10040497. PMID: 29673142; PMCID: PMC5946282.
9. Bandeira F, Griz L, Dreyer P, Eufrazino C, Bandeira C, Freese E. Vitamin D deficiency: a global perspective. Arq Bras Endocrinol Metabol. 2006;1988(50):640–6.
10. Saraiva GL, Cendoroglo MS, Ramos LR, Araújo LMQ, Vieira JGH, Maeda SS, Lazaretti-Castro M. Prevalência da deficiência, insuficiência de vitamina D e hiperparatiroidismo secundário em idosos institucionalizados e moradores na comunidade da cidade de São Paulo, Brasil. Arq Bras Endocrinol Metabol. 2007;51:437–42.
11. Public Health England. National diet and nutrition survey years 1-9 of the rolling programme (2008/2009 – 2016/2017): Time trendand income analyses. London, UK. 2019. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/772434/NDNS_UK_Y1-9_report.pdf. Accessed Nov 2022.
12. Patz, J. A. Cambio climático. In: Salud ambiental de lo global a lo local. Washington, D.C.: Organización Panamericana de la Salud. 2010; p.257–90.
13. Kraus FB, Medenwald D, Ludwig-Kraus B. Do extreme summers increase blood vitamin D (25-hydroxyvitamin D) levels? PLoS One. 2020;15(11):e0242230.
14.• Griffin TP, Wall D, Blake L, Griffin DG, Robinson S, Bell M, ... O'Shea PM. Higher risk of vitamin D insufficiency/deficiency for rural than urban dwellers. J Steroid Biochem Mol Biol. 2020;197:105547. https://doi.org/10.1016/j.jsbmb.2019.105547. **Vitamin D levels were lower among rural dwellers contrary to expected, in autum, winter and spring, due to low sunshine hours in high latitude.**
15. Fallowfield J L, Delves SK, Hill NE, Lanham-New SA, Shaw AM, Brown PE, ... Allsopp AJ. Serum 25-hydroxyvitamin D fluctuations in military personnel during 6-month summer operational deployments in Afghanistan. Br J Nutr. 2019;121(4):384–392.
16. Lara Alvarez SE, Bell K, Ward N, Cooke C, Inder WJ. Seasonality of hip fracture and vitamin D deficiency persists in a sub-tropical climate. Intern Med J. 2019;49(8):1029–32.
17.•• Ferrari D, Lombardi G, Strollo M, Pontillo M, Motta A, Locatelli M. Association between solar ultraviolet doses and vitamin D clinical routine data in European mid-latitude population between 2006 and 2018. Photochem Photobiol Sci. 2019;18(11):2696–706. **In winter, 60-90% of the population showed deficient/insufficient vitamin D status; in summer 30-50% in spite of plenty UV-radiation.**
18. Correa MP, Yamamoto ALC, Moraes GR, Godin-Beekmann S, Mahé E. Changes in the total ozone content over the period 2006 to 2100 and the effects on the erythemal and vitamin D effective UV doses for South America and Antarctica. Photochem Photobiol Sci. 2019;18(12):2931–41.
19. Bittar FB, Castro CH, Szejnfeld VL. Screening for vitamin D deficiency in a tropical area: results of a sun exposure questionnaire. BMC Endocr Disord. 2018;18(1):1–6.
20. Sahin ON, Serdar M, Serteser M, Unsal I, Ozpinar A. Vitamin D levels and parathyroid hormone variations of children living in a subtropical climate: a data mining study. Ital J Pediatr. 2018;44(1):1–7.
21. Majeed H, Moore GWK. Impact of multidecadal climate variability on United Kingdom rickets rates. Sci Rep. 2017;7(1):1–6.
22.• Nowak J, Hudzik B, Jagielski P, Kulik-Kupka K, Danikiewicz A, Zubelewicz-Szkodzińska B. Lack of seasonal variations in vitamin D concentrations among hospitalized elderly patients. Int J Environ Res Public Health. 2021;18(4):1676. **Vitamin D deficiency**

was observed in all geriatric patients (over 60 years) irrespective of season in South of Poland.
23. Beyitler İ, Uncu M, Bahceciler N, Şanlıdağ B, Dalkan C, Kavukcu S. Impact of Mediterranean climate and seasonal variation on vitamin D levels in children. Cyprus J Med Sci. 2018;1:15–8.
24. Akinlawon OJ, Lai CQ, Noel SE, Flanagan KD, Tucker KL. Risk factors associated with vitamin D status among older Puerto Rican adults. J Nutr. 2021;151(4):999–1007. https://doi.org/10.1093/jn/nxaa426.
25. Oshiro CE, Hillier TA, Edmonds G, Peterson M, Hill PL, Hampson S. Vitamin D deficiency and insufficiency in Hawaii: levels and sources of serum vitamin D in older adults. American Journal of Human Biology. 2021;e23636. https://doi.org/10.1002/ajhb.23636.
26. FAO/WHO expert consultation on human vitamin and mineral requirements. Vitamin and mineral requirements in human nutrition. Report of a Joint FAO/WHO Expert Consultation, Bangkok, Thailand. 2001;231. https://www.fao.org/3/y2809e/y2809e.pdf. Accessed Nov 2022.
27. Cohen-Shacham E, Walters G, Janzen C, Maginnis S, editors. Nature-based solutions to address global societal challenges. Gland, Switzerland: IUCN. xiii + 97pp. ISBN: 978-2-8317-1812-5. 2016. https://doi.org/10.2305/IUCN.CH.2016.13.en.
28. Chausson A, Turner B, Seddon D, Chabaneix N, Girardin CA, Kapos V, ... Seddon N. Mapping the effectiveness of nature-based solutions for climate change adaptation. Glob Chang Biol. 2020;26(11):6134–6155.
29. Cohen-Shacham E, Andrade A, Dalton J, Dudley N, Jones M, Kumar C, ... Walters G (2019) Core principles for successfully implementing and upscaling nature-based solutions. Environ Sci Policy. 2019;98:20–29.
30. World health statistics 2017: Monitoring health for the SDGs, sustainable development goals. Geneva: World Health Organization; 2017.Licence: CC BY-NC-SA 3.0 IGO. http://apps.who.int/iris/bitstream/handle/10665/255336/9789241565486-eng.pdf. Accessed Nov 2022.