Review

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Outdoor Physical Activity as a Confounder for Vitamin D Status: A Scoping Review

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Abstract

This scoping review sought to assess the evidence base for physical activity (PA) as a potential confounder of vitamin D (vitD) status in health outcomes. Correlations between vitD and health/disease are well-documented. However, this does not always translate in vitD supplementation studies. We hypothesize that these observed relationships may be confounded by PA, especially outdoor PA, which contributes to both sun exposure and cardiorespiratory fitness. We conducted a scoping review utilizing Arksey and O'Malley's five-stage framework and aligned with the PRISMA guidelines. Literature was searched from CINAHL, Cochrane Library, PubMed, Scopus, and SportDISCUS. After removal of duplicates and irrelevant results (N=2270), 154 articles were included, mostly published from 2011-2023 (n=124), cross-sectional (n=97), and in adults (n=106). The literature shows a strong link between PA and improved vitD status, attributable to sun exposure. However, evidence conflict on PA's independent impact on vitD, with some studies suggesting protective effects in athletes irrespective of sunlight. This review highlights PA as a potential confounder in vitD-related health outcomes, particularly those associated with cardiorespiratory fitness. Yet, inconsistencies in study design, measurement methods, and reporting limit the ability to disentangle these relationships. Standardized reporting guidelines including measures of vitD status; details of sun exposure (time, location, UV protection, melanin concentration, etc.); PA type, duration, and setting; and sufficient details on other potential confounders within the population (adiposity, veiling, vegan diet, etc.) are urgently needed to clarify these relationships and enable effective public health strategies.

Keywords: physical activity; vitamin D; sunlight; research design; health outcomes; lifestyle and behavior; methods standardization; translational science

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Introduction

Research has established correlations between vitamin D (vitD) status and a number of health outcomes and disease states ranging from bone health to immune competence; however, these relationships have not always been consistent especially when comparing observational studies, Mendelian randomization studies, and randomized controlled trials (RCTs). A recent umbrella review found that meta-analyses were consistent for observational and Mendelian randomization studies for 17 of 28 (60.7%) health outcomes including all-cause mortality.[1] Only 13 (46.4%) also had consistent RCTs. Therefore, in the literature to date, the translation from observational studies to RCTs is quite inefficient, indicating a fundamental misunderstanding, confounding, or some other significant contributor that has yet to be identified.

Given that sun exposure is the primary driver of vitD status in humans (measured as serum 25-hydroxyvitamin, 25(OH)D, also known as calcidiol) and that physical activity (PA) is commonly a proxy for sun exposure in the vitD literature, conclusions about vitD-related health outcomes should consider these factors separately as well as any potential interaction. While outdoor PA will influence sun exposure and vitD status, all PA will support cardiorespiratory (CR) fitness. CR fitness strongly correlates with health span and many of the same health outcomes as vitD.[2-4] Therefore, PA in any

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setting is a potential confounder for vitD status in health outcomes research. Sun exposure also warrants consideration beyond its impact on vitD status when assessing health outcomes given the known non-vitD-related health benefits such as resetting circadian rhythms,[5-7] nitric oxide production,[8-10] and stimulation of endorphins and the subsequent feeling of well-being.[11-13] The magnitude of the potential confounding effects between vitD status, sun exposure, and PA on health outcomes will determine how the evidence should be interpreted as well as the appropriate public health interventions. For instance, if there is strong confounding between PA / CR fitness and vitD status for a given health outcome, then the appropriate public health intervention may be to encourage more PA with vitD supplementation and/or outdoor PA with sensible sun precautions rather than a vitD supplement alone. A recently published systematic review found that PA seems to be associated with increased vitD status but notes that stratifying PA by indoor or outdoor setting seems to have little relevance.[14] This same study acknowledges the importance of exploring this issue in greater detail; conducting more rigorous research exploring possible confounders such as race, season, and geographic latitude is necessary to further unpack this issue.

As little research exists examining the relationship between vitD and possible confounders such as PA and other elements of sun exposure explicitly, we conducted a scoping review of the literature, a type of systematic synthesis of the evidence base on a given topic that is similar to a systematic review. A scoping review aims to determine the scope of knowledge rather than answer a specific question, where a systematic review may be appropriate. Thus, scoping reviews map the available evidence including research conduct.

The primary objective of this scoping review is to assess the evidence base for sun exposure and PA as potential confounders of the relationship between vitD status and related health outcomes. To this end, we review any literature that specifically seeks to measure vitD, sun exposure, and PA (likely outdoor) and to establish how these factors are defined and measured. Additionally, we investigated if interactions between these factors were considered in the literature. Therefore, we hypothesis that PA may be an unmeasured third variable that affects both the cause and the supposed effect in the observed relationship between vitD and health outcomes that may act as an effect modifier (altering the relationship) or an intermediary (meaning the relationship is spurious).

Definition of Terms

The following terms are used throughout the review. As part of the research process, the researchers (PGC, LAF, AMB, SHV) defined these terms to guide the discussion below.

- **Confounding**: A situation where an observed relationship between two variables (e.g., vitD and health outcomes) is influenced by a third variable (confounder, e.g., PA) associated with both the exposure (vitD) and the outcome (health outcomes). This creates the appearance of a causal relationship between the two variables when, in fact, the third variable may partly or fully explain the association. For example, PA could independently influence both vitD status (through outdoor activity and sun exposure) and health outcomes (through improved cardiovascular fitness), making it a confounder in studies linking vitD to health outcomes.
- **Physical Activity (All)**: Any physical movement requiring energy expenditure. This term is used when research collects data on indoor and outdoor PA but does not stratify results based on type of PA.
- **Physical Activity (Indoor):** PA happening in enclosed spaces (e.g., gyms, athletic arenas, homes) where exposure to natural sunlight does not occur.
- **Physical Activity (Outdoor)**: Physical activities performed outside involving natural sunlight exposure
- **Physical Activity (Unspecified)**: Instances where PA is reported without details regarding its type or context (i.e., not clear if activity occurs indoors or outdoors).
- **Spurious Relationship**: A seeming causal association between two variables that is due to a third variable (confounder) influencing both. For example, the relationship between vitD status

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and improved health outcomes might appear causal but could be due to PA or sun exposure, not vitD itself.

- **Sun Exposure**: The exposure of the skin to ultraviolet (UV) radiation from sunlight. While sun exposure is necessary to photoproduce vitD, it varies in its effectiveness for vitD synthesis by time of day, season, geographic location, skin pigmentation, etc.

Methods

This scoping review is designed to follow the five-stage process as described by Arksey and O'Malley:[15] A full description of our methods and justification can be found in the study protocol.[16]

1. Identifying the Research Question
2. Identifying Relevant Studies
3. Study Selection
4. Charting the Data
5. Collecting, Summarizing, and Reporting the Data

and align with the Preferred Reporting Items for Scoping Reviews (PRISMA-ScR) Guidelines. These distinct steps are discussed in greater detail below and provide a roadmap for the scoping review protocol we present. The complete PRISMA-ScR checklist is presented in the appendix.

Step One: Identifying the Research Questions

Research Questions

Prior to conducting this scoping review, our research team published a detailed protocol to describe our process and rationale.[16] Following an initial review of the literature, we identified the following three questions to guide our study.

1. What correlations exist between sun exposure, PA, and vitD status?
2. How might sun exposure and regular PA improve health outcomes and/or disease conditions independently of vitD, as opposed to dependent upon vitD?
    a. What spurious relationships between vitD, sun exposure, and PA have been previously identified?
3. What is the potential for and magnitude of confounding via a spurious relationship?

Institutional Review Board (IRB) Statement

This project did not engage any human subjects or involve a process of informed consent. This manuscript exclusively reports the results of a scoping review. Consequently, this research was not subject to review by an Institutional Review Board.

Step Two: Identifying Relevant Studies

The questions guiding this scoping review aim to clarify what is known about the role of general PA and, specifically, outdoor PA in vitD status; and to assess potential confounding factors in these relationships that require further investigation in order to better understand implications on health outcomes. A detailed discussion of our strategy development has been previously published in the scoping review protocol and is not recreated here.[16] Of note, five research databases were included in this study: CINAHL, Cochrane, PubMed, Scopus, and SportDISCUS. This search was conducted in January 2023 and again in May 2026 and the entire search strategy, including the specific search strings for each database, was reviewed independently by a research library affiliated with the George Washington University Himmelfarb Health Sciences Library.

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Inclusion and Exclusion Criteria

Consistent with Arksey and O'Malley's process for conducting scoping reviews, we developed specific inclusion and exclusion criteria to ensure the relevance and appropriateness of the articles included in this study. Articles were eligible for inclusion if they were published in English, came from peer-reviewed sources, considered the role of photoproduced vitD (as opposed to dietary or supplemental sources alone), and included any identified form of PA. Articles were excluded if they were informal publications (e.g., blog posts, industry reports, or non-refereed sources), registers of clinical trials without available results (e.g., protocol papers or trials in progress), only measured dietary or supplemental vitD, or did not address PA.

In practice, while these criteria helped narrow the focus to studies relevant to our research questions, their implementation highlighted key challenges. For example, although the studies included had identified some form of PA, the specific context of PA (indoor vs. outdoor) was not uniformly reported. This inconsistency limited our ability to fully explore the relationship between outdoor PA, sun exposure, and vitD synthesis. These observations underscore the need for standardized reporting in future research to improve comparability and the robustness of evidence in this area. These criteria are also available in Table 1.

Table 1. Study Inclusion and Exclusion Criteria.

Inclusion Criteria	Exclusion Criteria
• Published in English	• Published in any language other than English
• From a Peer-Reviewed Source	• Informal Publications (e.g., blog posts, industry reports, non-referred publications) • Register of Clinical Trial without available results (e.g., protocol papers, trials in progress)
• Considers the role of photoproduced vitD (as opposed to dietary/supplemental vitD)	• Only measures dietary/supplemental vitD
• Has identified any form of PA	• Does not discuss PA

Stage Three: Study Selection

The third stage of the Arksey and O'Malley process entails the elimination of the studies irrelevant to the central research question. To determine relevance and inclusion, the research team conducted a three-phase process of review utilizing Covidence, an online tool to facilitate and organize review and analysis.

First, all titles and abstracts were screened to determine relevance given the questions guiding this study. In this first phase, two researchers reviewed each title and abstract to determine relevance. If there was not consensus among these two researchers, a senior researcher provided a final determination. Second, the researchers conducted a full-text review of each publication. In this phase, two researchers were required to review each publication to determine whether it aligns with our specific inclusion criteria following the population, intervention, comparison, and outcome (PICO) guidelines.[17] Finally, the third step included data extraction of relevant information for thematic analysis. Our full PRISMA diagram is available in Figure 1 and the extraction form guiding the final step of the scoping review is available in Table 1. The full PRISMA-ScR checklist is available in the appendix and the PRISMA diagram is available as Figure 1.

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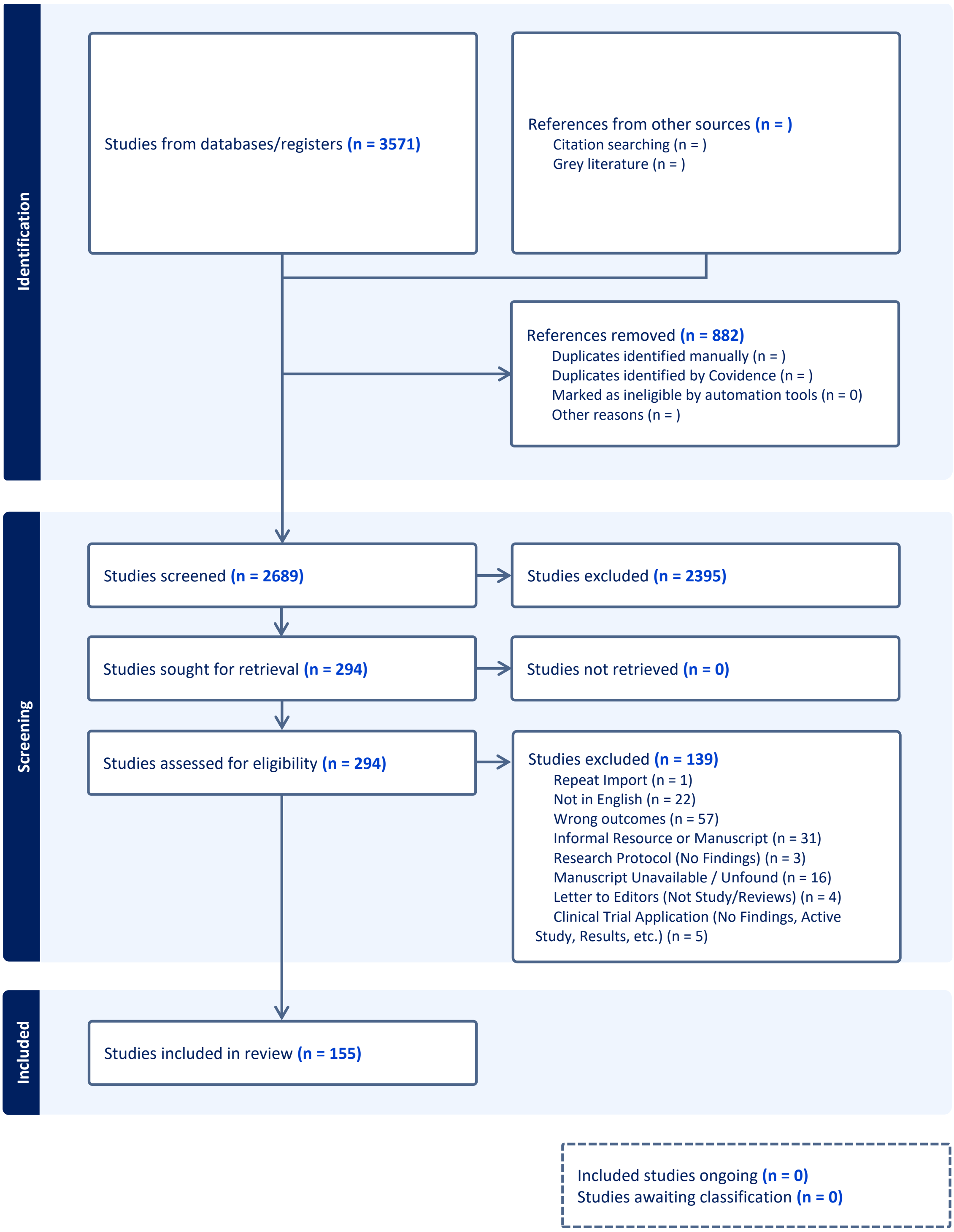

Figure 1. PRISMA Diagram.

Step Four: Charting the Data

As discussed above, the research team utilized the data extraction tool from Covidence. This form allowed the research team to manage the literature in a highly structured system to determine the relevance to our research questions. Table 2 provides an overview of the data extraction form the researchers employed to chart the data. This form allowed us to follow a uniform approach to reviewing the published body of knowledge.

Table 2. Covidence Data Extraction Form.

Data to Extract	Specific Material
General Data	Title
	Authors
	Publication year
	Publication source
	Country
	Other notes
Characteristics of Study	Research question(s)
	Aim of study/Objectives
	Methods
	Study design
	Do you have concerns about study design (e.g., not rigorous, variables not well defined, not controlling for PA, no control group, etc.)
	Is primary outcome related to vitD & PA?
	If VitD & PA is not primary, explain inclusion rationale
	Is sun exposure quantified?
	Describe how sun exposure is discussed
	Study start date
	Study end date
	Funding source
	Potential conflicts of interest
Participants	Population description
	Inclusion criteria
	Exclusion criteria
	Recruitment methods
	Total n
Results	Study conclusions
	Clearly identify any relationship between vitD & PA discussed in this source
	Clearly identify potential confounding between vitD & PA discussed in this source (e.g. the health benefits of PA leading to a spurious or false relationship between vitD and the same health benefits)
	Clearly identify any other interactions between vitD & PA discussed in this source (e.g. skin color/race, veiling/religion, geography, etc.)
	How does this source contribute to your understanding of the issue under study?

Step Five: Collecting, Summarizing, and Reporting the Data

The final stage of this scoping review included a comprehensive review of extracted data to identify salient commonalities in the literature, areas of disagreement, and to provide answers to the study's guiding research questions. Arksey & O'Malley[15] note that this fifth step includes a number of distinct processes: 1) collecting the data in a single location, 2) summarizing the totality of the data in terms of both quantitative and qualitative results, and 3) reporting the data in a structured way. For the first step, the extracted data was exported from Covidence into Microsoft Excel for data management and content analysis. Next, we conducted two layers of analysis – the quantitative descriptive characteristics of the study and the more qualitative assessment of the results from the included studies. Throughout this process the researchers (PGC, LAF, AMB, SHV) met regularly to

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discuss analysis, areas of uncertainty, and to provide review of each other's work. The final step, reporting the data, is discussed at length below.

Results

Characteristics of Included Studies

The supplemental material available online provides a comprehensive summary of the articles included in this scoping review (n=155) while Tables 3, 4, and S1 below provide summary characteristics. Most studies are cross-sectional representing a large range of populations across the globe. The largest single country producers of research into vitD and PA were Australia (n=22) and the United States (n=21). Other studies were conducted in various European countries (n=43), countries in the Middle East (n=25), across Asia (n=22), in Central and South American countries (n=15), across Africa (n=5), and Oceania (n=2). Many studies were conducted in regions with high UVB exposure, such as Brazil and the UK. This geographical variation plays a significant role in the relationship between assumed or measured sun exposure during PA and vitD synthesis, which could be highlighted as an important factor when discussing global health recommendations.

Table 3. Included Study Characteristics.

Study Characteristics	Manuscripts (N=154)
Publication Year	
1992	2
2001 – 2005	4
2006 – 2010	24
2011 – 2015	53
2016 – 2020	58
2021 – Present	14
Study Design	
Case Control	4
Case Report	1
Cohort	28
Cross Sectional	98
Non-Randomized Experimental	1
Systematic Reviews	9
Randomized Control Trial	7
Prevalence	1
Text/Opinion	2
Unspecified	4

Table 4. Included Study Location (Alphabetical).

Country	Number of Studies
Argentina	1
Australia	22
Austria	1
Bahrain	1
Belgium	1
Brazil	12
Canada	2
China	3
Cyprus	2
Denmark	2

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Egypt	3
Finland	2
France	1
Germany	3
Greece	5
India	5
Indonesia	2
Iran	6
Ireland	1
Israel	1
Italy	4
Japan	4
Malaysia	2
Mexico	2
Morocco	1
Multiple Countries	2
Netherlands	1
New Zealand	2
Pakistan	2
Philippines	1
Poland	5
Portugal	1
Qatar	2
Saudi Arabia	6
South Korea	5
Spain	2
Sudan	1
Sweden	2
Switzerland	3
Tunisia	1
Turkey	2
UAE	2
UK	5
USA	21

The majority of studies included in this review were conducted on adults (n=106; 68%), followed by studies exclusively conducted with children (n=31; 20%), and few considering the health of both adults and minors (n=18; 12%). As there are likely distinct patterns in vitD status depending on age and lifestyle, this is a significant source of variation. The sample size ranged from 1 at the smallest, a single case study of a patient to 6,370[18] at the largest, a cross-sectional study of data from the National Health and Nutrition Examination Survey (NHANES).[18] Tables 3 and S1 provide a detailed overview of study characteristics, including publication year and study design; the supplementary table provides greater detail, including the study population, inclusion/exclusion criteria, sample size, vitD measurement methodology, relationships, confounding, interactions, and conclusions.

It is particularly relevant to discuss the vitD measurement methodologies used in these studies, as the accuracy and reliability of these measurements directly impact the validity of the findings. Among the reviewed studies, a variety of methods were employed to assess serum 25(OH)D, with the most common being Liquid Chromatography-Tandem Mass Spectrometry (LC-MS/MS) and Chemiluminescence Immunoassay (CLIA). LC-MS/MS, considered the gold standard due to its high specificity and ability to distinguish between different forms of vitD, was used in several studies. CLIA, valued for its practicality in clinical settings, was also frequently utilized. However, it is notable

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that approximately one quarter of the studies did not specify the measurement technique used. In some cases, it is possible the authors thought that the techniques in use were not immediately relevant to the study design, i.e. a review; however, these various techniques are not directly comparable. This lack of detail could potentially affect the interpretability and comparability of results across studies, highlighting the need for more consistent reporting standards in future research. This is a trend throughout the vitD literature.

Known Relationships: Vitamin D and Outdoor Physical Activity

The Impact of Vitamin D on Physical Activity

One of the primary findings from this scoping review was to establish known relationships between serum vitD status and PA. There was substantial heterogeneity in the types of physical activities studied: primarily aerobic activities[19-22] such as running,[18,23,24] swimming,[18] dancing,[21] and field sports such as soccer, basketball, and lacrosse.[25-28] Most evident is the clear role that sun exposure has on maintaining sufficient vitD status (see Figure 2).[23,25,29-36]

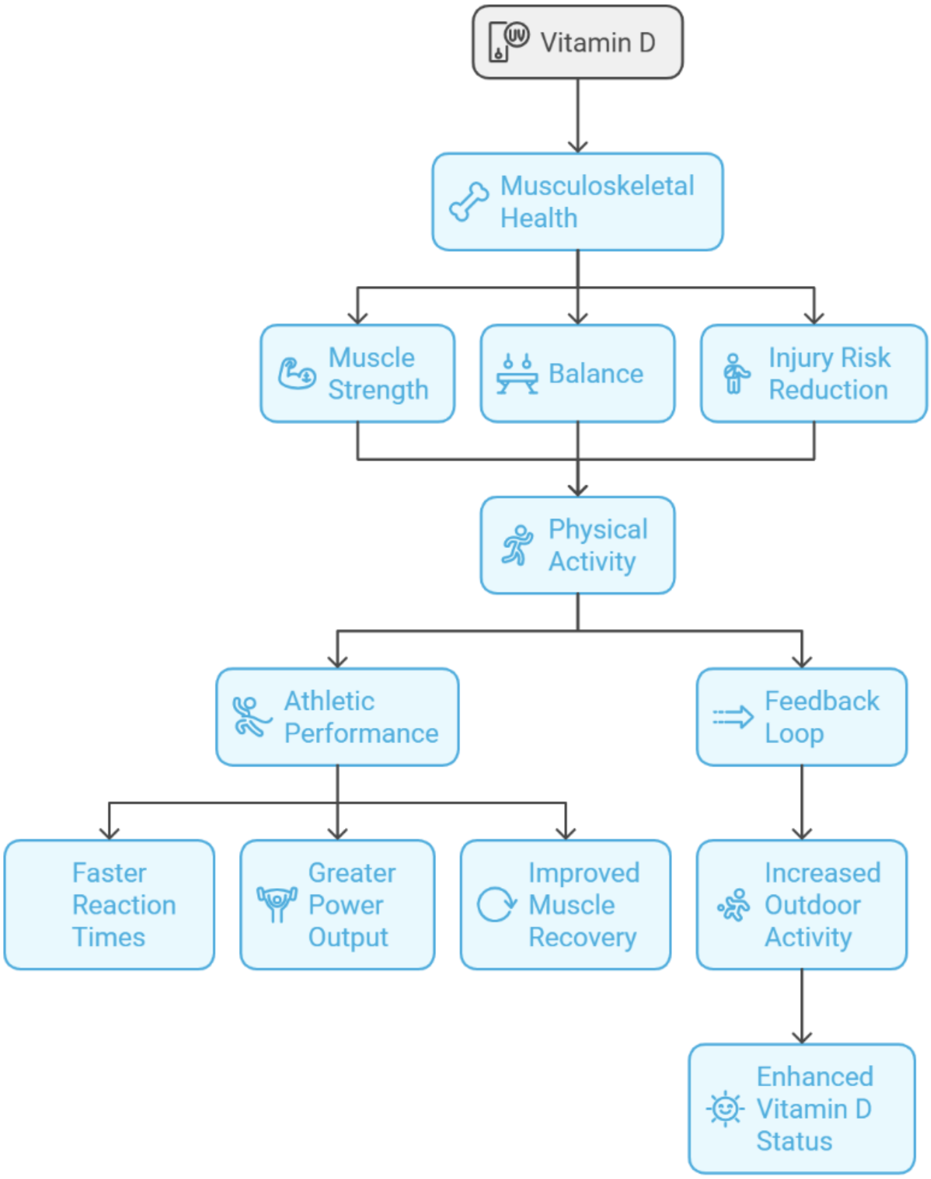

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Figure 2. The Impact of Vitamin D on Physical Activity. Vitamin D's role in physical function and activity stems largely from its effects on musculoskeletal health, including muscle strength, balance, and reduction in injury risk, which are all essential for maintaining an active lifestyle.

The Impact of Physical Activity on Vitamin D

Additionally, sixteen studies affirmed a protective factor between outdoor PA and sufficient serum vitD (see Figure 3).[17,37-51] This relationship is affirmed by studies specifically measuring vitD status among individuals who live sedentary lifestyles, all of which found that sedentary individuals experience vitD deficiency at higher rates than their active peers.[52-56] Interesting, there are a small number of studies that either found no statistically significant relationship between vitD status and outdoor PA[57-59] or, remarkably, found a negative relationship between vitD status and vigorous outdoor PA.[60,61] In other words, these studies found that vigorous outdoor PA was associated with lower serum vitD despite a potentially increased sun exposure. However, studies did not commonly report known factors that influence cutaneous vitD synthesis and/or vitD requirements, meaning that these factors could, potentially, explain some if not all of this variation.

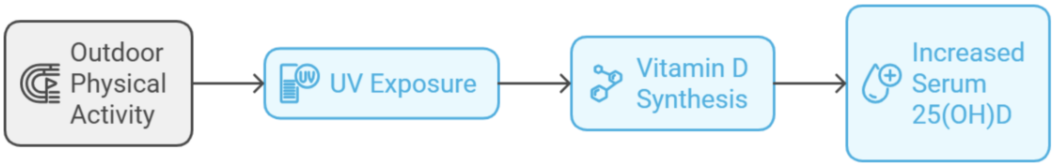

Figure 3. The Impact of Physical Activity on Vitamin D Physical activity, especially when conducted outdoors, directly influences vitamin D status by increasing exposure to sunlight, which catalyzes the synthesis of vitamin D in the skin. Regular outdoor activities such as running, walking, cycling, or team sports significantly increase opportunities for UV exposure, enhancing vitamin D production.

Several studies noted a seasonal impact on vitD status, particularly in athletes and outdoor workers, who showed higher vitD in sunnier months. Including seasonal influences can enhance the discussion on how timing of outdoor activity affects vitD status. This is an example of an important determinant of vitD photosynthesis that was not typically reported.

One significant question that remains unanswered regards the isolated role of PA in vitD status.[21,26,20,61-65] Research affirms that sun exposure increases vitD, but it remains unclear if regular PA serves as a mediator for the endogenous production of vitD or related health outcomes.[29,39,44,47,51,66-72] In other words, what exactly is the role of PA in vitD photoproduction and related health outcomes. Whether or not PA has a positive effect on vitD status regardless of sun exposure remains unclear.[21,67,72-81] That said, a number of studies suggest that PA generally, irrespective of indoor or outdoor context, is associated with higher serum vitD.[53,82-86,159] These differential findings suggest that there remains much we do not understand regarding vitD status, sun exposure, and PA and how these relate to health outcomes.

Known Health Outcomes Associated with Vitamin D

While an exploration of the health outcomes associated with vitD is beyond the scope of this study, particularly because research has long established the many health outcomes associated with vitD, we briefly note some associations that were affirmed by the literature included in this study. In particular, the literature included in this review identified that sufficient vitD status is associated with muscle strength and bone health,[20,24,26,27,62,63,87-91] positive mental health outcomes,[92] and reduced risk for a number of chronic health conditions including peripheral artery disease, cardiovascular disease, and cancers.[93-95] VitD deficiency is associated with a number of negative health outcomes, including obesity.[95-97] Some studies suggested that the observed relationship between vitD and physical activity

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could be spurious, meaning the improvements in health outcomes might be attributed more to physical activity and fitness rather than vitD alone.

Potential Confounding & Interaction

This scoping review helped us to identify a number of persistent confounding and interaction relationships across the published literature (see Figure 4). It remains to be seen what benefits of outdoor PA are from sun exposure and vitD status versus the overall health benefits of being highly physically active and well-conditioned (i.e., active and "in shape," good CR fitness).[17,18,32,37,68,98-103] While these terms are defined differently across publications, they typically refer to aerobic activity that increases participants' heart-rates and lasts approximately 75-150 minutes per week, depending upon intensity. Additionally, the types of PA (e.g., strength and conditioning, aerobic exercise, etc.) and their impact on vitD status remain unknown and poorly measured.[60,64,71,77,104,105] The role of various other factors impacting sun exposure such as season of data collection, geographic location, cultural norms (including dress and veiling), and sun protection use are poorly studied or controlled for in existing research.[25,106-113]

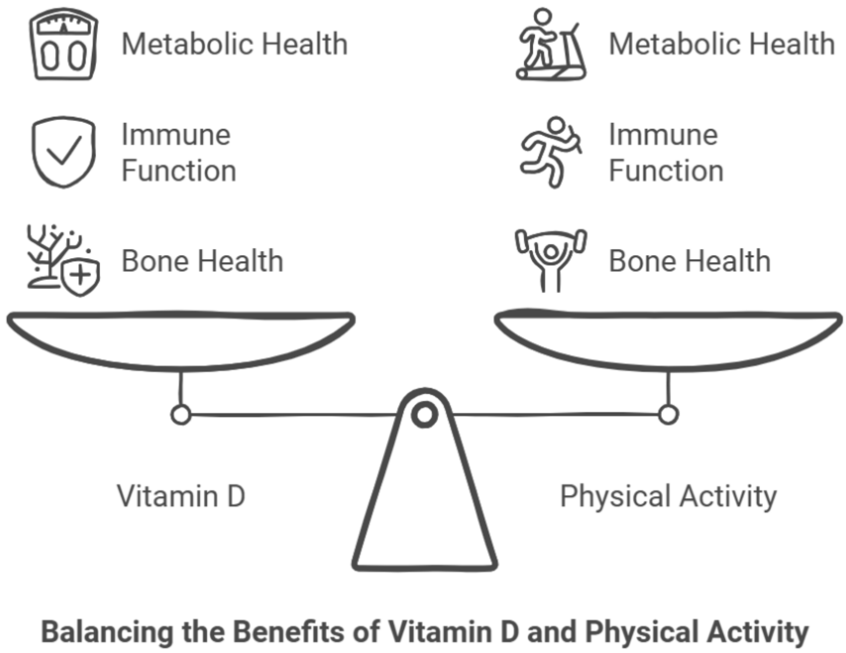

Figure 2. Potential Confounding and Interaction between Physical Activity, Vitamin D, and Health Outcomes The interaction between vitamin D and physical activity is complex and introduces potential confounding in studies investigating either factor's effect on health. The positive health outcomes often associated with vitamin D, including improved bone health, reduced inflammation, better immune response, and metabolic benefits, overlap with the well-established benefits of physical activity. Consequently, studies examining vitamin D's role in these outcomes must account for physical activity levels, particularly outdoor PA, to avoid confounding.

Reporting Challenges

Proxy Measures and Bioavailability

Another persistent challenge is the inconsistent use of sun exposure proxy measures, which are poorly measured and controlled across the literature.[56,78,88,101,103,110,114-123] In other words, researchers regularly reference sun exposure proxy measures to approximate sun exposure in place of more concrete measures. Research considers multiple mediating factors (e.g., sun exposure, PA, vitD supplementation, dietary intake) without controlling for these variables.[28,49,124-127] A significant

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number of studies included in this review look at the role of PA and sun exposure when measuring vitD status, but there remains significant work to better understand these factors in isolation or how they might interact. Finally, the role of obesity in impacting the bioavailability of vitD is often poorly described among study participants.[65,128]

Inadequate Sun Exposure Measurements

One significant issue impacting vitD studies are the few mechanisms that exist to accurately and objectively measure sun exposure in study participants feasibly.[38,41,73,83,88,97,99,110,113,124,129-145] Compounding the limitation regarding accurate measurements of sun exposure, most studies accept self-reported PA as a measure of participant activity levels.[52,76,99,118,124,137-141,143-154] Self-reported data is subject to many biases, errors in reporting, and can lead to correspondingly poor measurements. In addition to these limitations, there are few studies that effectively establish why self-reported PA occurs indoors or outdoors.[83,85,106,109,132,133,149,154-156] A small number of studies also identify the different vitD assays that exists and how various in lab protocol may skew how studies report vitD status.[22,66] A number of researchers identify how these overall inconsistencies in datasets make it hard to draw meaningful conclusions.[21,147,157,158]

Additionally, this review highlights the lack of consistency and valid tools for measuring sun exposure during outdoor PA, a significant challenge in determining the strength of individual studies as well as the knowledge-base as a whole. The inconsistency in how these measurements are captured and reported may further limit the generalizability of our findings. That said, identifying this inconsistency was one of the primary aims of this review. In other words, the work from this review affirms the challenges in determining the magnitude of the relationship between outdoor PA / sun exposure, vitD status, and related health outcomes and calls for on-going research to identify and detangle potential confounding that exists.

Overview of Included Studies

Several studies identified potential confounding factors, particularly related to outdoor PA, as sun exposure often influences vitD synthesis. Despite the variation in study designs and objectives, most studies found a positive association between outdoor PA and improved vitD status, though the confounding effect of PA on vitD-related health outcomes remains an area for further exploration. Studies also pointed out limitations in standardization across methodologies and measurement techniques, emphasizing the need for consistent protocols in future research. Overall, the findings underscore the complexity of disentangling the effects of PA and sun exposure on vitD status, with some studies advocating for both vitD supplementation and PA with sun precautions to address insufficiency in at-risk populations.

Discussion

The findings of this scoping review highlight a significant body of literature that acknowledges the relationship between sun exposure, PA, vitD status, and various health outcomes. While the initial aim of this study was to explore potential confounders within these relationships, inconsistencies in the definitions and measurements of PA were identified during the literature review, rendering this approach impractical. Consequently, the scope of the analysis was expanded to encompass both confounders and interactions observed in the data. Accordingly, both aspects will be discussed in this review, as the complexity of these interactions and the potential for confounding remain prominent challenges in this area of research. The reviewed studies generally affirm that outdoor PA positively influences serum 25(OH)D, vitD status, through increased sun exposure, which in turn may contribute to improved health outcomes such as enhanced bone health, muscle strength, and mental well-being in addition to the benefits from PA itself. Yet, a closer examination reveals substantial variability in the study designs, methodologies, and reported outcomes across the literature.

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A recurring theme in the studies included in this review is the influence of outdoor PA as a potential confounder in the relationship between vitD status and health outcomes. Given that outdoor PA not only enhances vitD status via sun exposure but also improves CR fitness and overall health and wellness, it is challenging to disentangle the independent effects of vitD from those of PA, plus those of sun exposure alone. This potential confounding effect may explain the discrepancies observed in RCTs that fail to replicate the positive associations between vitD status and health outcomes found in observational studies.

Additionally, several studies noted a protective factor associated with outdoor PA against vitD deficiency, particularly in athletic populations. However, conflicting evidence exists, with some studies reporting no significant relationship or even a negative association between vigorous outdoor PA and serum vitD status. These divergent findings underscore the need for more rigorous research to determine the precise nature of the relationship between vitD status, sun exposure, and outdoor PA, as well as the potential moderating effects of factors such as intensity and duration of PA, geographical location, and seasonal variations.

An important aspect that emerged from this review is the inconsistent and often inadequate measurement of key variables, particularly sun exposure and PA (see Figure 5).

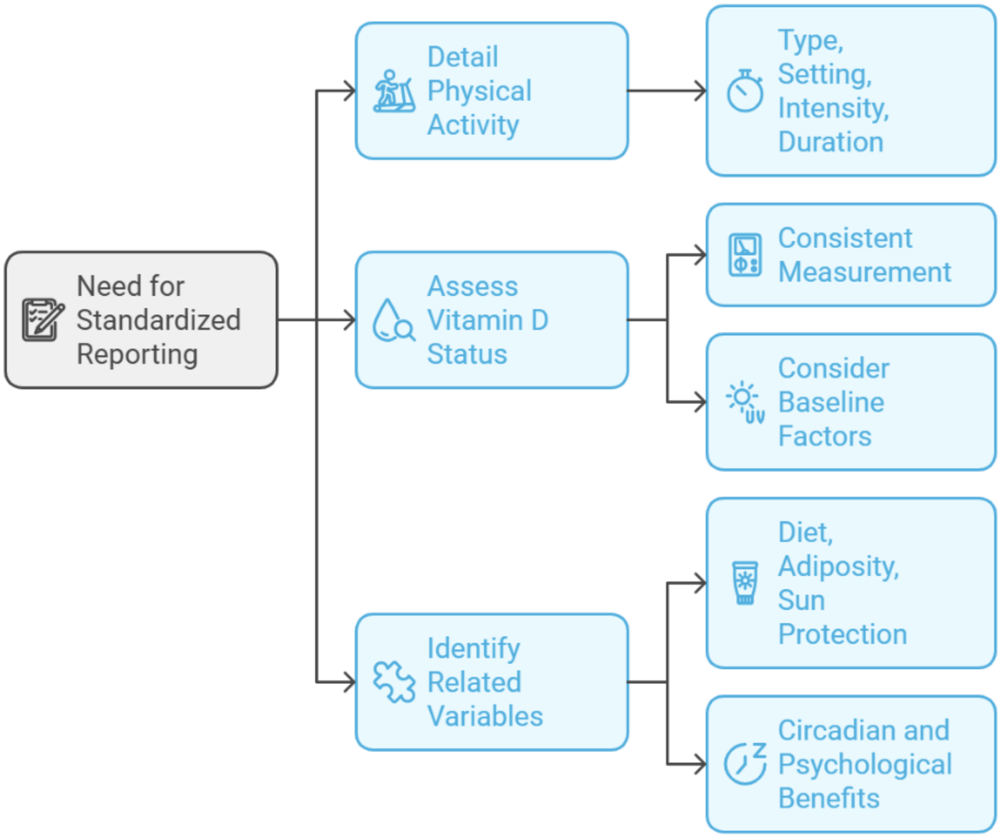

Figure 3. Guidance for Future Research on Vitamin D and Physical Activity Given the overlap between vitamin D and physical activity in contributing to health outcomes, future studies should prioritize standardized measures of both factors to clarify their individual and interactive effects.

Many studies relied on self-reported PA and proxy measures of sun exposure, both of which are subject to bias and error. The lack of standardized tools and protocols for measuring these variables complicates the interpretation of study results and limits the generalizability of findings. Future research should prioritize the development and implementation of objective, validated measures of sun exposure and PA to strengthen the evidence base.

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For instance, to ensure accurate assessment of vitD status in the context of PA, it is crucial to select appropriate measurement techniques for serum 25(OH)D concentrations. Liquid Chromatography-Tandem Mass Spectrometry (LC-MS/MS) is considered the gold standard for its specificity and ability to distinguish between 25(OH)D_2 and 25(OH)D_3, which is vital when considering different sources of vitD, such as sunlight and diet. However, the use of automated immunoassays, which are more common in clinical settings due to their convenience and cost-effectiveness, may introduce variability and limit the precision of such vitD measurements. These limitations are particularly relevant when investigating the potential confounding effect of PA on vitD status as it relates to health outcomes, as inconsistent measurements can obscure the true relationship between PA, sun exposure, vitD, and health outcomes. Therefore, employing standardized and highly accurate methods, such as LC-MS/MS, in research settings is essential for advancing our understanding of these complex interactions. However, this is typically not the case in the literature, broadly. Much of this is due to use of clinical data (either retro- or prospectively), at least in part due to insufficient funding.

The current literature also fails to adequately account for other confounding factors, such as dietary intake of vitD, use of sun protection, and variations in skin pigmentation. These factors can significantly influence vitD status and should be systematically controlled for and/or documented in future studies. Additionally, the role of obesity in altering the bioavailability of vitD remains underexplored, despite evidence suggesting that adiposity can sequester vitD and reduce its circulating concentrations.

Given these limitations, it is clear that further research is needed to better understand the interplay between PA / sun exposure, vitD status, and health outcomes. Large-scale, longitudinal studies that incorporate standardized measures of vitD, sun exposure, and PA, as well as detailed information on potential confounders and effect modifiers, are essential for advancing our knowledge in this area. Such research will not only clarify the independent and combined effects of PA and vitD on health but also inform public health recommendations aimed at optimizing vitD status and promoting overall well-being.

While there is strong mechanistic support for PA as a confounder in vitD-related health outcomes, the literature to date is fragmented and inconsistent. Standardized reporting guidelines, improved measurement tools, and a more nuanced understanding of confounding factors are critical for addressing the gaps in the current evidence base. Future research should aim to quantify the magnitude of the confounding effect of PA on vitD status and health outcomes, ultimately leading to more targeted and effective public health interventions.

Limitations

This scoping review was designed in consultation with a reference librarian and faculty members who are experts in scoping and systematic reviews; however, this study is not without limitations. There remains a possibility that the search strategy did not return all possible relevant literature given the numerous research databases that contain nutrition and PA data as well as the variety of terms used to identify and categorize PA. In other words, our search strategy may not have been sufficiently comprehensive to capture all possible literature. Additionally, our search protocol did not collect gray literature including doctoral theses, governmental reports (e.g., work from the Department of Agriculture and the Food and Drug Administration), which may limit some of the findings presented in this manuscript. Finally, our research team is entirely English-speaking with limited proficiencies in other languages. For this reason, our search was limited to articles published in English. Given this limitation, it is likely that we missed literature published in other languages.

Conclusions

This scoping review reveals conflicting information regarding the relationship between vitD status, sun exposure, and PA. While some research suggests that PA alone does not improve 25(OH)D concentrations, other studies show lower rates of vitD deficiency among athletes, even without sun

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exposure. Overall, the current science indicates that the relationship between vitD status and PA is largely driven by sun exposure, with limited research considering the potential confounding between the health benefits of PA and vitD separately or in combination. Mechanistic evidence supports PA as a significant confounder in the relationship between vitD and health outcomes, particularly those linked to CR fitness. However, the literature remains inconsistent in study design and data reporting, making it difficult to determine the extent of this confounding effect. Standardized reporting guidelines—incorporating detailed measures of vitD status, sun exposure, PA type and setting, and other potential confounders such as adiposity and diet—are essential to disentangle these complex relationships. Future research should focus on addressing these gaps with large-scale, well-designed studies that can quantify the confounding effects of PA on vitD status in related health outcomes. This may help explain the discrepancies between observational studies and RCTs and guide more effective public health interventions.

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Appendix

Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) Checklist

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
		TITLE	
Title	1	Identify the report as a scoping review.	1
		ABSTRACT	
Structured summary	2	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	1
		INTRODUCTION	
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	2-3
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	3
		METHODS	
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web	5-6

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		address); and if available, provide registration information, including the registration number.	
Eligibility criteria	6	Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale.	5
Information sources*	7	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	6
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.	7
Selection of sources of evidence†	9	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.	7
Data charting process‡	10	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators.	7-8
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.	7-8
Critical appraisal of individual sources of evidence§	12	If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate).	N/A
Synthesis of results	13	Describe the methods of handling and summarizing the data that were charted.	7-8
RESULTS			
Selection of sources of evidence	14	Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	6
Characteristics of sources of evidence	15	For each source of evidence, present characteristics for which data were charted and provide the citations.	7-9
Critical appraisal within sources of evidence	16	If done, present data on critical appraisal of included sources of evidence (see item 12).	N/A
Results of individual sources of evidence	17	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.	7-9
Synthesis of results	18	Summarize and/or present the charting results as they relate to the review questions and objectives.	9-11
DISCUSSION			
Summary of evidence	19	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions	11

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		and objectives, and consider the relevance to key groups.	
Limitations	20	Discuss the limitations of the scoping review process.	15
Conclusions	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	15-16
FUNDING			
Funding	22	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.	After References

JBI = Joanna Briggs Institute; PRISMA-ScR = Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews.

* Where *sources of evidence* (see second footnote) are compiled from, such as bibliographic databases, social media platforms, and Web sites.

† A more inclusive/heterogeneous term used to account for the different types of evidence or data sources (e.g., quantitative and/or qualitative research, expert opinion, and policy documents) that may be eligible in a scoping review as opposed to only studies. This is not to be confused with *information sources* (see first footnote).

‡ The frameworks by Arksey and O'Malley (6) and Levac and colleagues (7) and the JBI guidance (4, 5) refer to the process of data extraction in a scoping review as data charting.

§ The process of systematically examining research evidence to assess its validity, results, and relevance before using it to inform a decision. This term is used for items 12 and 19 instead of "risk of bias" (which is more applicable to systematic reviews of interventions) to include and acknowledge the various sources of evidence that may be used in a scoping review (e.g., quantitative and/or qualitative research, expert opinion, and policy document).

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