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# Impact of Dust Events on UV Index and Vitamin D Synthesis in Bahrain and Its Correlation with Population Serum 25-Hydroxyvitamin D Levels

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**Abstract:** Vitamin D plays an important role in maintaining human health. Its deficiency has been associated with an increased risk of several chronic diseases. Sun exposure, particularly UV-B radiation, accounts for greater than 90% of vitamin D production in humans. The aim of this study was to examine the relationship between dust and UV index and its effect on vitamin D concentrations. Data on the UV index and the number of dusty days measured at ≤1000 m, ≤3000 m, and ≤5000 m altitudes in the period January 2017 to June 2022 were collected. Dust particles ($PM_{2.5}$ and $PM_{10}$) and vitamin D values were also gathered. No correlation was observed between UV index and $PM_{2.5}$ ($r = -0.013$, $p = 0.947$) and between UV index and $PM_{10}$ ($r = 0.251$, $p = 0.165$) due to numerous factors, such as unavailable data on UV-B and particle concentrations at a maximum of 1000 m rather than 20 to 30 km. A positive correlation was observed between the number of dusty days at all altitudes and $PM_{10}$ ($p < 0.001$), whereas no correlation was found between the number of dusty days at all altitudes and $PM_{2.5}$. A positive correlation was found between vitamin D-deficient patients and $PM_{2.5}$ (r = 0.529, $p = 0.005$) and between vitamin D-deficient patients and $PM_{10}$ (r = 0.399, $p = 0.024$). The PM $_{2.5}$ and $PM_{10}$ concentrations exceeded both the WHO guidelines and the Environmental Protection Agency's recommended levels during most months of the study period. The average range of the $PM_{2.5}/PM_{10}$ ratio was low (0.24–0.35), indicating dust pollution. The results indicate a strong relationship between $PM_{10}$ dust particles and the number of vitamin D-deficient patients, indicating high levels of dust air pollution, which might have an influence on the high levels of vitamin D deficiency in Bahrain. This study hypothesized that dust events may reduce UV-B levels, leading to vitamin D deficiency (VDD). However, the results of the study supported this hypothesis only partially due to several limitations, including the unavailability of data on UV-B, dusty days, and dust particles ($PM_{2.5}$ and $PM_{10}$) at higher altitudes (20–30 Km).

**Keywords:** dust; $PM_{2.5}$; $PM_{10}$; UV index; vitamin D deficiency

## 1. Introduction

Vitamin D is a crucial element for mineral metabolism and bones, helping to prevent the development of osteoporosis and rickets [1]. It has been estimated that 50% of the world's population suffers from vitamin D deficiency (VDD) [2]. The rate of VDD in the United Arab Emirates (UAE), one of the Gulf Cooperation Council (GCC) countries, is estimated to be 50–90% [3,4]. This is mainly due to environmental factors and lifestyles that limit people from sun exposure, which is needed for vitamin D synthesis [5]. The primary mechanism through which the body synthesizes vitamin D involves exposure to ultraviolet B (UV-B) rays from sunlight, whereas food sources come second [1,6]. There are few naturally occurring food sources that contain vitamin D, for example, fatty fish, fish liver oil, egg yolk, red meat, and fortified foods such as cereals and milk [7,8]. Getting the required daily intake of vitamin D from dietary sources is not always possible in many countries [9], and foods that are naturally rich in vitamin D are rarely/never consumed in others [10]. The half-life of circulating vitamin D is several weeks; therefore, a single measurement of vitamin D represents the multiple sources of vitamin D from the skin and gut, storage in adipose/other tissues, and use integrated over the previous weeks/months [11]. It has also been shown that vitamin D concentrations in the blood significantly increase in adults (based on age) 24–48 h following a 30 min bout of outdoor sun exposure of both dorsal and ventral sides at close to solar noon [12].

Without vitamin D, only 10–15% of dietary calcium and about 60% of phosphorus are absorbed. As a result, vitamin D sufficiency enhances calcium absorption by 30–40% and phosphorus absorption by 80%, leading to the development of stronger bones [5,6,13]. Moreover, studies have shown that people with low sun exposure produce low quantities of serum 25-hydroxyvitamin D (serum 25(OH)D), which is required to produce vitamin D in the body [1,14].

In addition to sun exposure, vitamin D can be absorbed from food sources such as eggs, fatty fish, cod liver oil, and fortified milk. There are two types of vitamin D: D2 and D3 [1]. Vitamin D2 is a synthetic form and is derived from plants and many fortified foods, whereas vitamin D3 can be obtained from animal sources and can be synthesized by the skin after sun exposure [1]. A low level of serum 25(OH)D is defined as VDD [15]. A range of disorders have been associated with low vitamin D levels. The most common bone diseases are osteoporosis and rickets [6,13]. Low vitamin D in the body can also weaken the immune system and result in increased risks of heart disease, bowel diseases, fractures, muscle weakness and falls, breast cancer, colon cancer, and prostate cancer [1,15]. There are many consequences of VDD, and links between VDD and a variety of diseases, such as infections, COVID-19, type 2 diabetes (T2D), hypertension, and cardiovascular, gastrointestinal, neurodegenerative, and autoimmune diseases, have been identified [16]. On the other hand, vitamin D insufficiency (VDI) results from impaired calcium absorption. It is associated with osteopenia, osteoporosis, and osteomalacia. VDI Is considered a risk factor for cancer, hypertension, cardiovascular disease, infection, type 1 diabetes, and autoimmune disease [17–19]. Table 1 shows the classification of vitamin D in relation to the levels of serum 25(OH)D obtained from King Hamad University Hospital (KHUH). The desirable concentration of serum 25(OH)D required by the body is 20–80/L. If the concentration is below 10 ng/L, it is considered vitamin D deficient [1,20,21].

**Table 1.** Serum 25(OH)D and its interpretations obtained from King Hamad University Hospital (KHUH).

| Classification | Serum 25(OH)D |
|---|---|
| Vitamin D deficiency | <10 ng/mL |
| Vitamin D insufficiency | 10–20 ng/mL |
| Adequate vitamin D threshold concentration | 20–80 ng/mL |

Despite ample sunlight and UV-B radiation, certain groups in the Gulf Cooperation Council (GCC) countries suffer from notable VDD, with no difference between expatriates and Bahrainis, considering both genders [14], and a high percentage of children, especially girls [22].

It is well known that the Sahara Desert, the Arabian Peninsula, and some parts of South Asia are major global sources of dust [23]. Based on synoptic weather reports, North Africa, the Middle East, Southwest Asia, and Northeast Asia are the regions with the highest dust frequencies [24]. In recent years, arid and semi-arid regions of the Sahara Desert, the Arabian Peninsula, and some parts of South Asia have experienced significantly increased dust storms [25–27]. This increased dust emission affects human health, air quality, agricultural production, and food security and severely damages economic and social infrastructure. Data analysis in the study conducted by Gobbi et al. (2000) [28] on Saharan dust showed that dust events can reach and persist in the 10 km altitude region. Increased dust emission can be attributed to land-use changes and human-induced climate changes, resulting in droughts and the destruction of vegetation and wetlands [29–34]. Global warming is the main cause of increased temperatures, longer fire seasons, droughts, rising sea levels, and intense storms. Recent drier conditions have resulted in an increased amount of dehydrated soil, which is swept up into the air, blowing dust around the globe; therefore, dehydrated soil is considered a new source of dust, resulting in new destinations for storms [23].

Very few studies have demonstrated a clear relationship between dusty weather and VDD. However, some studies have revealed that air pollutants are negatively associated with VDD [35–37]. A four-year study conducted in Kuwait obtained data from four weather stations across the country and concluded that atmospheric pollutants absorb UV rays, thus decreasing UV-B intensity on the earth's surface, resulting in a reduction in vitamin D synthesis in the body and a very high prevalence of VDD in Kuwait [36]. In addition, another study was conducted in two different regions: polluted and unpolluted. In the areas where pollutants were very low, no association was found between air pollution and VDD; on the other hand, many people were found to have VDD in the polluted area, justifying a link between air pollution and VDD [37]. The results of the current study are consistent with those of previous studies where positive correlations were found between the number of vitamin D tests conducted, VDD patients, and $PM_{2.5}$ and $PM_{10}$. Studies on the relationship between particulate matter and its effect on vitamin D, in general, are very rare; however, a few studies have proven the effects of particulate matter on serum 25(OH)D status in pregnant women. Two studies conducted in Shanghai (China) examined the effects of particulate matter on serum 25(OH)D levels in pregnant women in whom a direct significant incident of VDD was found after weekly exposure to $PM_{2.5}$. A 10 $\mu g/m^3$ increase in $PM_{2.5}$ exposure resulted in a 1.346 nmol/L drop in serum 25(OH)D [38,39].

In Section 2, the types of data collected, including daily dust measures at three different altitudes ($\leq$1000 m, $\leq$3000 m, and $\leq$5000 m), $PM_{2.5}$ and $PM_{10}$ dust particles at $\leq$1000 m, and serum 25(OH)D levels, are explained. Section 3 presents all collected data and the statistical analysis conducted. In Section 4, the results are discussed in alignment with the literature review and relevant previous studies. In Section 5, the conclusions of the study are provided, including the main and most important findings and the recommendations.

The objectives of this study are to analyze the trends of ground-level solar UV irradiance measurements over the period from January 2017 to June 2022, UV-B availability all year round, and the effect of dust events on UV-B irradiance, and to compare these UV-B data with representative population serum 25-hydroxyvitamin D (25(OH)D) data from Bahrain. We hypothesize that the dust events affect the trends of VDD or VDI. To the best of our knowledge, this is the first study in the region to investigate the possible relationship between increased dust emissions and increased VDD in residents of the Kingdom of Bahrain.

## 2. Methodology

### *2.1. Study Area*

This study was conducted in the Kingdom of Bahrain (Figure 1) [40], which is located in the Arabian Gulf, 25 Km from the eastern coast of Saudi Arabia (Arabian Peninsula) [41]. The climate in Bahrain is hot and dry from March to November, with short, mild winters and rare rainfall from December to February [42]. It is divided into five physiographic zones: the central plateau and jabals (small mountains), the interior basin, the multiple escarpments, the main back slope, and the coastal lowlands [42]. A few habitats were identified in these zones by El-Oqlah and Abbas (1992) [43], including conglomerates, sand dunes, sabkhas (saline soils), and mangroves.

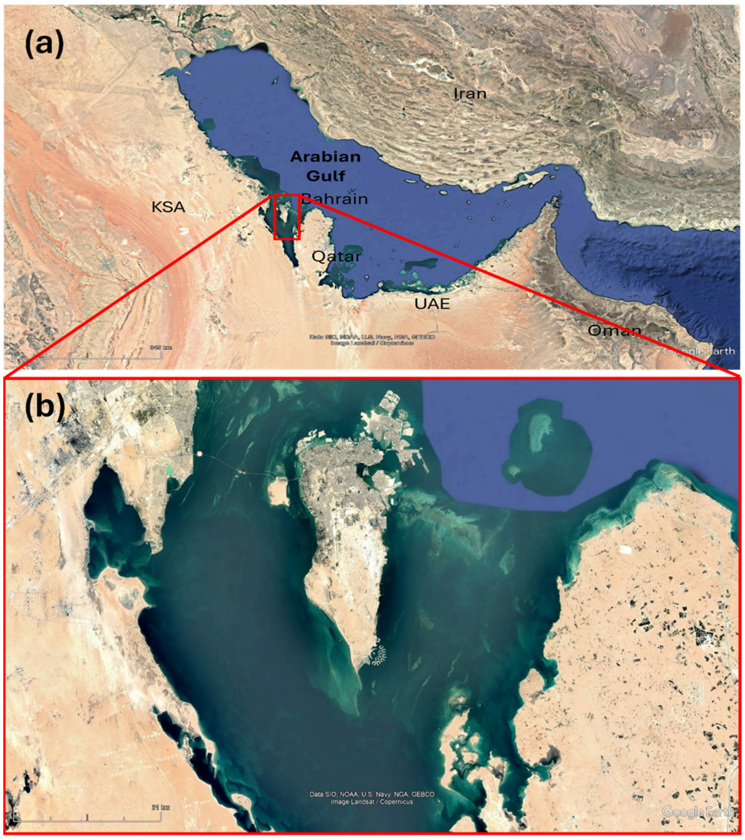


**Figure 1.** (**a**) Location of Bahrain within the Arabian Gulf, highlighted by the red triangle, with (**b**) showing a zoomed-in view [40].

### 2.2. Monitoring Period

This study is a cross-sectional exploratory study for the period from January 2017 to June 2022. The data were used to examine the associations between UV-B, vitamin D levels in patients, altitude levels, and dust events.

### 2.3. Sampling Procedure

Hourly measurements of the UV index (W/m$^2$), number of dusty days, temperature, and relative humidity (%) were obtained from the Meteorological Directorate. With regards to the environmental factors, the highest temperatures are seen in July and August and fluctuate yearly between 33 °C and 38 °C; on the other hand, the coolest months in Bahrain are from January to March, during which the temperature drops to an average of 17 °C. The months with the lowest relative humidity are May and June, and the highest humidity occurs from December to February. It could be interpreted that humidity levels in Bahrain are higher in the cooler months than in the hotter months; however, it was evident that the relative humidity in Bahrain is high throughout the year.

Daily UV index readings, which are recorded for aviation purposes in Bahrain, were obtained and the average for each month calculated. The sum for each month at each altitude was calculated annually from 2017 to June 2022, and only readings taken at $\leq$5000 m on dusty days were used in the study to provide the closest predicted results. According to the UV index readings obtained, Bahrain has a very high UV index throughout the year. UV-B values need to be accurately measured, even though UV-B only makes up around 5% of the UV index [44]. Due to the unavailability of UV-B measurements, UV index data were used in the current study. In addition, the numbers of dusty days measured at three levels above the ground (≤1000 m, ≤3000 m, and ≤5000 m) by professionally trained observers using naked-eye observations were also obtained. Visual observation data for dusty days have been used in several similar studies [45–47], thus justifying the use of this method.

In addition, data for dust particles ($PM_{2.5}$ and $PM_{10}$) at ≤1000 m were also obtained from the Supreme Council of Environment using Met One Instruments Powered by Acoem (BAM 1020) continuous air quality particulate monitors (Washington, DC, USA). It should be noted that the Environmental Protection Agency (US EPA, 2024) recommends that standard levels of $PM_{2.5}$ and $PM_{10}$ should not exceed 35 $\mu g/m^3$ and 150 $\mu g/m^3$, respectively, over 24 h, and the levels should not be exceeded more than once per year, on average, over 3 years [48]. The World Health Organization (WHO) established guidelines on air pollution levels in 2005 (25 $\mu g/m^3$ 24 h mean for $PM_{2.5}$ and 50 $\mu g/m^3$ 24 h mean for $PM_{10}$) [49]. These were updated in 2021 to be lower than the previous guidelines, working toward the incremental milestones of cleaner air worldwide. The 2021 guidelines are widely used as references for outdoor air quality management. The 2021 WHO guidelines state that $PM_{2.5}$ should not exceed 5 $\mu g/m^3$ and the average 24 h exposure should not exceed 15 $\mu g/m^3$ on more than 3–4 days per year, whereas 24 h mean $PM_{10}$ concentrations of 45 $\mu g/m^3$ are recommended [50].

Patients' vitamin D records were obtained from KHUH. All data from January 2017 to June 2022 were gathered and used. The study sample was based on patients with medical records at KHUH for the period January 2017 to June 2022. The samples were divided into two categories: the first one included all individuals who have medical records at KHUH, and the second category included individuals with any chronic diseases, including digestive, renal, or liver diseases, parathyroid gland dysfunction, and those who use any medications that affect bone metabolism and vitamin D status as well as obesity status. In addition, serum 25(OH)D data from all adult/older study populations and all child/adolescent study populations were used in the present work. Following approval from the Scientific Research and Development Directorate in KHUH (Ethic code reference number 22-556) on 22 November 2022, the study was performed in alignment with the Declaration of Helsinki and the ICH Guidelines for Good Clinical Practice.

Demographic information for the patients included personal number, number of vitamin D tests, the date of tests, and the age, which showed a wide range. The dataset included patients born between 1910 and 2009. Testing patients for vitamin D levels occurred from 7 years of age to 112 years of age. Out of the 33,262 patients, 16,239 (48.82%) were classified as vitamin D-deficient. In addition, a random sample of 1694 (10%) patients was selected from the 16,239 to represent patients with chronic diseases associated with VDD. The sample size of 1694 patients with chronic diseases associated with VDD was calculated using the following formula:

$$N = z^2\ (p\ (1 - p)/d^2$$

where N = desired sample size, z = standard normal deviation (set at 1.96, 95% confidence level), D = degree of accuracy desired (0.05), and p = expected prevalence of vitamin D deficiency in adolescents attending health centers (50%) [51].

### *2.4. Data Analysis*

The data were analyzed using Statistical Package for Social Science (SPSS version 28). Pearson's correlation was used to investigate the relationship between UV index, number of vitamin D tests, vitamin D-deficient patients, $PM_{2.5}$, and $PM_{10}$. The relationship between these parameters and the number of dusty days at ≤1000 m, ≤3000 m, and ≤5000 m were also investigated using Pearson's correlation to help draw a conclusion as to whether dust particles prevent UV rays from reaching the earth's atmosphere, leading to VDD.

Regression analyses of the key variables mentioned above were also conducted to evaluate the associations between them and the desired outcome of population serum 25(OH)D.

## 3. Results

The numbers of dusty days at three different altitudes ($\leq$1000 m, $\leq$3000 m, and $\leq$5000 m) for the years 2017 to 2022 were compared, and it was found that as the altitude increased, the number of dusty days also increased. The year with the highest number of dusty days was 2018, which had a total of four dusty days at $\leq$1000 m, a total of 30 days at $\leq$3000 m, and a total of 57 days at $\leq$5000 m. The data for 2022 were recorded only up to June; however, it was still predicted to be one of the dustiest years since it had a total of 5 days at $\leq$1000 m, 13 days at $\leq$3000 m, and 30 days at $\leq$5000 m, being relatively high only halfway through the year compared to the previous full years. Since no dust records were available for higher altitudes, dusty day readings at $\leq$5000 m were used throughout the study.

Table 2 shows the breakdown of the total number of dusty days at $\leq$5000 m from January 2017 to June 2022. The highest numbers of dusty days were in May 2017 (6), April 2018 (10), January 2019 (8), March 2020 (7), June 2021 (10), and May 2022 (11). These results suggest that January to June were the dustiest months in the studied years, while July to December were the months with the lowest number of dusty days, apart from July and August 2018.

**Table 2.** Total number of dusty days at $\leq$5000 m from January 2017 to June 2022.

| | **Year** | | | | | |
|---|---|---|---|---|---|---|
| **Month** | **2017** | **2018** | **2019** | **2020** | **2021** | **2022** |
| Jan | 0 | 5 | 8 | 5 | 1 | 4 |
| Feb | 4 | 5 | 0 | 3 | 0 | 2 |
| Mar | 2 | 5 | 5 | 7 | 4 | 4 |
| Apr | 3 | 10 | 2 | 6 | 0 | 6 |
| May | 6 | 6 | 6 | 2 | 0 | 11 |
| Jun | 3 | 9 | 1 | 0 | 10 | 3 |
| Jul | 0 | 9 | 1 | 0 | 1 | - |
| Aug | 0 | 6 | 2 | 0 | 1 | - |
| Sep | 0 | 0 | 0 | 1 | 2 | - |
| Oct | 0 | 2 | 0 | 0 | 0 | - |
| Nov | 2 | 0 | 0 | 0 | 0 | - |
| Dec | 3 | 0 | 0 | 1 | 0 | - |
| Total Number of Dusty Days | 23 | 57 | 25 | 25 | 19 | 30 |

Table 3 shows the average 24 h concentrations of $PM_{2.5}$ and $PM_{10}$ dust particles at $\leq$1000 m from August 2018 to June 2022; unfortunately, many readings were not available. The $PM_{10}$ value for August 2018 was the highest (181.7 $\mu g/m^3$) compared to the rest of the months. In 2019, $PM_{2.5}$ was highest in October (55.4 $\mu g/m^3$), and $PM_{10}$ was highest in May (161.9 $\mu g/m^3$). In 2021, $PM_{2.5}$ and $PM_{10}$ levels were both highest in August, at 80.3 and 295.7 $\mu g/m^3$, respectively. In 2022, $PM_{2.5}$ and $PM_{10}$ levels were both highest in May, at 97.0 and 285.5 $\mu g/m^3$, respectively. In addition, a trend of higher $PM_{10}$ than $PM_{2.5}$ can also be observed.

The standard recommended level of PM $_{2.5}$ (35 $\mu g/m^3$) over 24 h set in the NAAQS Table of the US EPA (2024) was exceeded in May–October 2019; April, May, June, August, October, and November 2021; and January–June 2022, whereas the standard recommended level of $PM_{10}$ (150 $\mu g/m^3$) over 24 h set by the US EPA was exceeded in September 2018; May 2019; March, April–August, and October 2021; and March–June 2022, indicating an increase in air pollution. However, the 2021 WHO guidelines (WHO, 2021) [50] for $PM_{2.5}$ not to exceed 5 $\mu g/m^3$, average 24 h $PM_{2.5}$ exposures not to exceed 15 $\mu g/m^3$ on more than 3–4 days per year, and the mean 24 h $PM_{10}$ exposure of 45 $\mu g/m^3$ were exceeded throughout the years.

**Table 3.** Monthly average $PM_{2.5}$ and $PM_{10}$ ($\mu g/m^3$) values derived from data recorded over 24 h at ≤1000 m from 2018 to June 2022, excluding 2020.

| | $PM_{2.5}$ | $PM_{10}$ | $PM_{2.5}$ | $PM_{10}$ | $PM_{2.5}$ | $PM_{10}$ | $PM_{2.5}$ | $PM_{10}$ |
|---|---|---|---|---|---|---|---|---|
| **Month** | **2018** | **2018** | **2019** | **2019** | **2021** | **2021** | **2022** | **2022** |
| Jan | - | - | 32.4 | 149.1 | - | - | 42.3 | 97.2 |
| Feb | - | - | 19.6 | 83.8 | 23.5 | 80.5 | 63.5 | 144.7 |
| Mar | - | - | 22.4 | 99.3 | 26.6 | 155.1 | 44.7 | 219.2 |
| Apr | - | - | 26.2 | 114.2 | 44.8 | 128.3 | 83.8 | 219.9 |
| May | - | - | 48.1 | 161.9 | 48.6 | 165.5 | 97.0 | 285.5 |
| Jun | - | - | 44.8 | 146.6 | 44.6 | 289.3 | 70.5 | 190.1 |
| Jul | - | - | 38.3 | 96.1 | 19.5 | 159.6 | - | - |
| Aug | - | 181.7 | 47.2 | 115.6 | 80.3 | 295.7 | - | - |
| Sep | - | 153.4 | 50.6 | 108.4 | - | - | - | - |
| Oct | - | 141.9 | 55.4 | 134.7 | 41.9 | 268.1 | - | - |
| Nov | - | 80.6 | 24.4 | 102.7 | 41.8 | 84.5 | - | - |
| Dec | - | 92.6 | - | - | 31.5 | 77.9 | - | - |

Table 4 shows the average $PM_{2.5}/PM_{10}$ ratio at ≤ 1000 m from 2019 to June 2022, excluding 2020. The average range of the $PM_{2.5}/PM_{10}$ ratio was 0.24–0.35. The highest ratios were observed in September 2019 (0.47), November 2021 (0.50), and January and February 2022 (0.44), whereas the lowest ratios were observed in January 2019 (0.22), July 2021 (0.12), and March 2022 (0.20).

**Table 4.** Average $PM_{2.5}/PM_{10}$ ratios at ≤ 1000 m from 2019 to June 2022, excluding 2020.

| | $PM_{2.5}/PM_{10}$ **Ratio** | $PM_{2.5}/PM_{10}$ **Ratio** | $PM_{2.5}/PM_{10}$ **Ratio** |
|---|---|---|---|
| **Month** | **2019** | **2021** | **2022** |
| Jan | 0.22 | - | 0.44 |
| Feb | 0.23 | 0.29 | 0.44 |
| Mar | 0.23 | 0.17 | 0.20 |
| Apr | 0.23 | 0.35 | 0.38 |
| May | 0.30 | 0.30 | 0.34 |
| Jun | 0.31 | 0.15 | 0.37 |
| Jul | 0.40 | 0.12 | - |
| Aug | 0.41 | 0.27 | - |
| Sep | 0.47 | - | - |
| Oct | 0.41 | 0.16 | - |
| Nov | 0.24 | 0.50 | - |
| Dec | - | 0.40 | - |
| Average $PM_{2.5}/PM_{10}$ ratio | 0.32 | 0.24 | 0.35 |
| n | | | |

Furthermore, patient data were gathered and compared with factors such as dusty days, non-dusty days, the number of tests conducted, and the number of VDD patients per specific year. It was found that the number of tests increased yearly. In 2017, a total of 2910 vitamin D tests were conducted. The number of tests per month ranged from the lowest (128 tests) in September to the highest (304) in May. In 2018, 3076 tests were conducted, with the lowest number of tests conducted in August (181) and the highest conducted in May (313). In 2019, the total number of tests increased to 5012, with the lowest number of tests conducted in January (352) and the highest in September (522). However, the total number of tests in 2020 decreased to 4406; this could be due to the COVID-19 pandemic restrictions in Bahrain. Notably, a significant increase in the number of tests was observed in 2021, with a total of 7237 tests conducted; the number of tests ranged from a low of 387 in February to a high of 816 in November. A total of 8414 tests were conducted from January to June 2022; the number of tests per month was observed to increase considerably, with the lowest number of tests in January (906) and the highest in May (1631).

A rapid increase in the number of patients with VDD was observed across the years 2017 to June 2022. The year with the highest number of VDD patients was 2021, which had more than 600 patients compared to 2019. In 2017, a total of 691 vitamin D-deficient patients were identified; the number of VDD patients per month ranged from 24 in September to 83 in May within the same year. In 2018, there were 826 identified VDD patients, with the lowest observed number in February (61) and the highest in December (94). In 2019, the total number of VDD patients increased to 1,186, with the lowest number in March (67) and the highest in November (135). In 2020, there were 1012 VDD patients, with the lowest in May (25) and the highest in November (126). A significant increase in the number of VDD patients was observed in 2021, with a total of 1834 patients identified; the number of VDD patients ranged from a low of 95 in February to a high of 227 in September. In 2022, a total of 1555 vitamin D-deficient patients were identified up to June; the number of VDD patients per month increased notably, with the lowest number in January (148) and the highest in March (272). The observed pattern may indicate a growing prevalence of VDD and outlines the importance of continued screening and intervention efforts.

Table 5 compares the total number of dusty days and the percentage of VDD patients. The total number of dusty days from 2017 to 2018 increased from 23 to 57, while the percentage of VDD patients increased from 23.7% to 26.8%. Furthermore, there was a decrease in the number of total dusty days from 2018 to 2019, and the same trend was observed in the percentage of VDD patients. The total number of dusty days remained the same in 2019 and 2020, and the percentage of VDD patients decreased slightly from 23.7% to 23%. However, there was a decrease in the total number of dusty days from 2020 to 2021, but the opposite trend was observed in the percentage of VDD patients, which increased from 23% to 25.3%. Except for 2021, the overall results show a direct relationship between the number of dusty days and the yearly average percentage of VDD patients.

**Table 5.** Comparison between total number of dusty days per year and percentage of vitamin D-deficient patients in the years 2017 to June 2022.

| Year | Total Number of Dusty Days | Percentage of Vitamin D-Deficient Patients |
|---|---|---|
| **2017** | 23 | 23.7 |
| **2018** | 57 | 26.8 |
| **2019** | 25 | 23.7 |
| **2020** | 25 | 23 |
| **2021** | 19 | 25.3 |
| **2022** | 30 | 18.5 |

Figures 2 and 3 summarize the total number of dusty days, non-dusty days, vitamin D tests, and vitamin D-deficient patients from 2017 to June 2022, where the number of tests conducted and the number of VDD patients kept increasing; however, the same trend was not observed with the number of dusty days. The year with the highest number of dusty days was 2018, and the year with the lowest was 2021. The percentage of vitamin D-deficient patients and the total number of tests conducted also varied, with proportions of approximately 23.7% in 2017, 26.8% in 2018, 23.7% in 2019, 25.3% in 2021, and 18.5% in 2022 (until June). The data exhibited a seasonal pattern for both dusty days, vitamin D tests, and VDD patients, with higher numbers typically occurring between January and June.

Another factor that might cause VDD is chronic diseases. To investigate whether chronic diseases are a major contributor to the deficiency in vitamin D, a sample of 1694 patients was selected from the total of 16,239 to represent patients with chronic diseases associated with VDD. Only 199 patients from the 1694 (11.7%) were found to have chronic diseases that directly affected vitamin D synthesis in their bodies, resulting in a deficiency in vitamin D. This implies that only 1.22% of the total 16,239 patients have VDD due to chronic diseases.

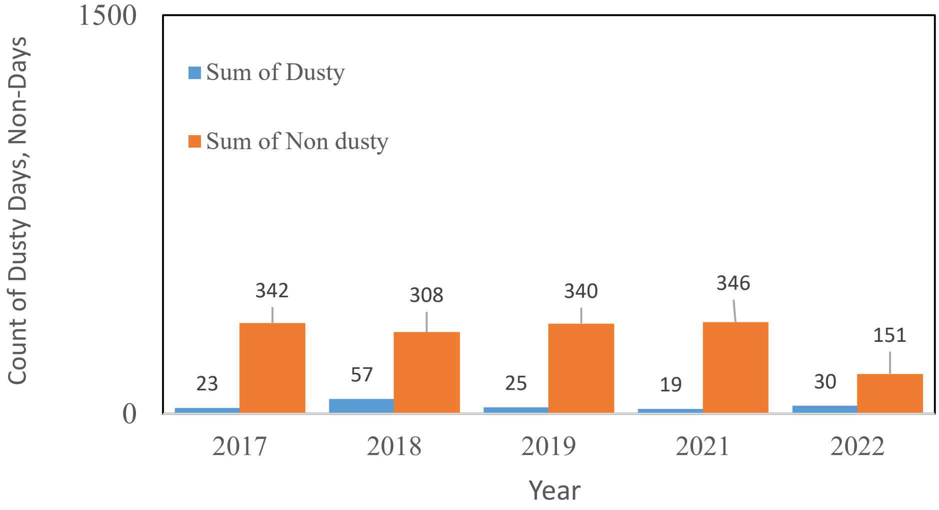


**Figure 2.** Summary of the number of dusty days and non-dusty days from January 2017 to June 2022.

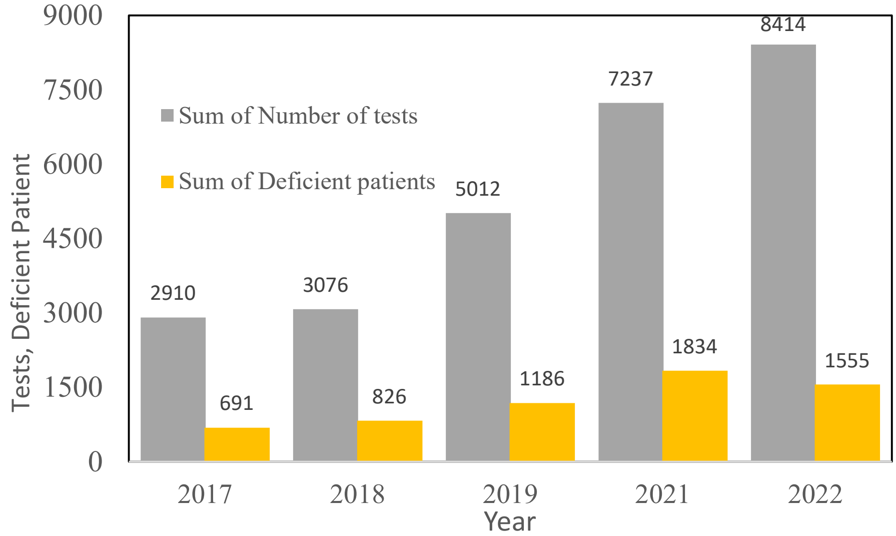


**Figure 3.** Summary of the number of vitamin D tests and vitamin D-deficient patients from January 2017 to June 2022.

Table 6 shows the chronic diseases that cause VDD in the randomly selected patients. The most common one was chronic kidney disease (CKD), followed by bariatric surgery.

**Table 6.** Patients with chronic diseases associated with VDD.

| | Frequency | Percent |
|---|---|---|
| Bariatric | 35 | 2.1 |
| Celiac disease | 2 | 0.1 |
| Cirrhosis | 11 | 0.6 |
| Chronic kidney disease | 118 | 7.0 |
| Chronic kidney disease with psoriasis | 3 | 0.1 |
| Hypoparathyroidism | 3 | 0.2 |
| Inflammatory bowel disease | 11 | 0.6 |
| Liver malignancy | 3 | 0.2 |
| Malnutrition (anorexia nervosa) | 1 | 0.1 |
| On Medication | 4 | 0.2 |
| Nephrotic syndrome | 1 | 0.1 |
| Psoriasis | 7 | 0.4 |
| Total | 1693 | 100.0 |

All correlations were analyzed based on monthly readings. Table 7 and Figures S1–S6 (Supplementary File) show a negative correlation between the number of dusty days at ≤5000 m and months, indicating that later months in the year have fewer dusty days in comparison to early months in the year (March–June). Significant positive correlations were observed between the number of dusty days at ≤1000 m and the number of dusty days at ≤5000 m ($r = 0.534$, $p < 0.001$) and between the number of dusty days at ≤3000 m and the number of dusty days at ≤5000 m ($r = 0.874$, $p < 0.001$); these indicate that when dust levels increase at one altitude, an associated increase occurs at the other altitude. No correlations were found between the number of dusty days at ≤5000 m and vitamin D-deficient patients ($r = 0.023$, $p = 0.866$), and the number of dusty days at ≤5000 m and the number of vitamin D tests conducted ($r = 0.149$, $p = 0.283$). Finally, no correlation was found between the UV index and the number of dusty days at ≤5000 m ($r = 0.038$, $p = 0.784$), indicating that the number of dusty days at this altitude has no influence on the UV index.

**Table 7.** Pearson's correlation analysis between dust at ≤5000 m and the study variables, including months, number of vitamin D tests, number of vitamin D-deficient patients, UV index, dusty days at ≤1000 m, and dusty days at ≤3000 m per month.

| | | **Dust at ≤5000 m** |
|---|---|---|
| Month | Pearson's Correlation | −0.381 ** |
| | Sig. (2-tailed) | 0.004 |
| | N | 54 |
| Number of vitamin D tests | Pearson's Correlation | 0.149 |
| | Sig. (2-tailed) | 0.283 |
| | N | 54 |
| Number of vitamin D-deficient patients | Pearson's correlation | 0.023 |
| | Sig. (2-tailed) | 0.866 |
| | N | 54 |
| UV index | Pearson's correlation | 0.038 |
| | Sig. (2-tailed) | 0.784 |
| | N | 54 |
| Dusty days at ≤1000 m | Pearson's correlation | 0.534 ** |
| | Sig. (2-tailed) | 0.000 |
| | N | 54 |
| Dusty days at ≤3000 m | Pearson's correlation | 0.874 ** |
| | Sig. (2-tailed) | 0.000 |
| | N | 54 |

** *p* value is significant at <0.01.

All correlations were analyzed based on monthly readings. Table 8 shows the comparison of Pearson's correlation values between each altitude and the UV index. No correlations were found between the UV index and the number of dusty days at ≤1000 m, ≤3000 m, or ≤5000 m.

**Table 8.** Comparison of Pearson's correlation values between UV index and dust levels at ≤1000 m, ≤3000 m, and ≤5000 m per month.

| | | **Dusty Days at ≤1000 m** | **Dusty Days at ≤3000 m** | **Dusty Days at ≤5000 m** |
|---|---|---|---|---|
| UV index | Pearson's correlation | −0.135 | 0.023 | 0.038 |
| | Sig. (2-tailed) | 0.332 | 0.867 | 0.784 |
| | N | 54 | 54 | 54 |

All correlations were analyzed based on monthly readings. Table 9 shows a positive correlation between dust particles at all altitudes and $PM_{10}$ ($p < 0.001$). Positive correlations were found between the number of vitamin D tests and $PM_{2.5}$ (r = 0.604, *p* = 0.001) and $PM_{10}$ (r = 0.430, *p* = 0.014), which means that there is a moderate relationship between these dust particles and the number of vitamin D tests conducted. Similarly, positive correlations were also found between the vitamin D-deficient patients and PM2.5 (r = 0.529, *p* = 0.005) and between the vitamin D-deficient patients and $PM_{10}$ (r = 0.399, *p* = 0.024). This again indicates that there is a relationship between dust particles and vitamin D-deficient patients. In addition, there was no correlation between the UV index and $PM_{2.5}$ (r = −0.013, *p* = 0.947) or $PM_{10}$ (r = 0.251, *p* = 0.165). This suggests that the dust particles might not have an impact on the UV index.

**Table 9.** Comparison of Pearson's correlation values between UV index and the dust particles $PM_{2.5}$ and $PM_{10}$.

| | | **UV Index** | $\mathbf{PM_{2.5}}$ | $\mathbf{PM_{10}}$ |
|---|---|---|---|---|
| Month | Pearson's correlation | 0.124 | 0.062 | −0.091 |
| | Sig. (2-tailed) | 0.373 | 0.760 | 0.621 |
| | N | 54 | 27 | 32 |
| Number of vitamin D tests | Pearson's correlation | −0.207 | 0.604 ** | 0.430 * |
| | Sig. (2-tailed) | 0.134 | 0.001 | 0.014 |
| | N | 54 | 27 | 32 |
| Number of vitamin D-deficient patients | Pearson's correlation | −0.159 | 0.529 ** | 0.399 * |
| | Sig. (2-tailed) | 0.252 | 0.005 | 0.024 |
| | N | 54 | 27 | 32 |
| UV index | Pearson's correlation | 1 | −0.013 | 0.251 |
| | Sig. (2-tailed) | | 0.947 | 0.165 |
| | N | 54 | 27 | 32 |
| Dusty days at ≤**1000** m | Pearson's correlation | −0.135 | 0.365 | 0.463 ** |
| | Sig. (2-tailed) | 0.332 | 0.061 | 0.008 |
| | N | 54 | 27 | 32 |
| Dusty days at ≤**3000** m | Pearson's correlation | 0.023 | 0.328 | 0.602 ** |
| | Sig. (2-tailed) | 0.867 | 0.095 | 0.000 |
| | N | 54 | 27 | 32 |
| Dusty days at ≤**5000** m | Pearson's correlation | 0.038 | 0.362 | 0.546 ** |
| | Sig. (2-tailed) | 0.784 | 0.064 | 0.001 |
| | N | 54 | 27 | 32 |

* *p* value is significant at <0.05. ** *p* value is significant at <0.01.

Linear regression was conducted based on monthly readings. The linear regression model was fitted using the number of vitamin D-deficient patients against the other variables. The model was as follows:

$$\text{the number of vitamin D-deficient patients} = 215.98 + 0.428\text{ month-}145.61\text{UV-B} + 3.4\text{ dusty days at} \leq 1000\text{ m} + 11.109\text{ dusty days at} \leq 3000\text{ m} - 10.745\text{ dusty days at} \leq 5000\text{ m} + 1.171\, PM_{2.5} + 0.289\, PM_{10}$$

This informs us that the effects of $PM_{2.5}$ and $PM_{10}$ on the number of vitamin D-deficient patients are very small compared to the other variables, and the UV index has a negative effect. The number of dusty days at ≤3000 m has the highest effect on the number of vitamin D deficiencies diagnosed per month. The only significant coefficient was the UV index, with *p*-value= 0.013. The global test shows that the model was a good fit (*p*-value = 0.023); this means that at least one of the coefficients was not zero. Residual analysis also showed that less than 5% of the residuals are within three standard deviations of zero (Figure 4). The limitation of this is that the number of observations suitable for regression was only 27 since several variables had missing values.

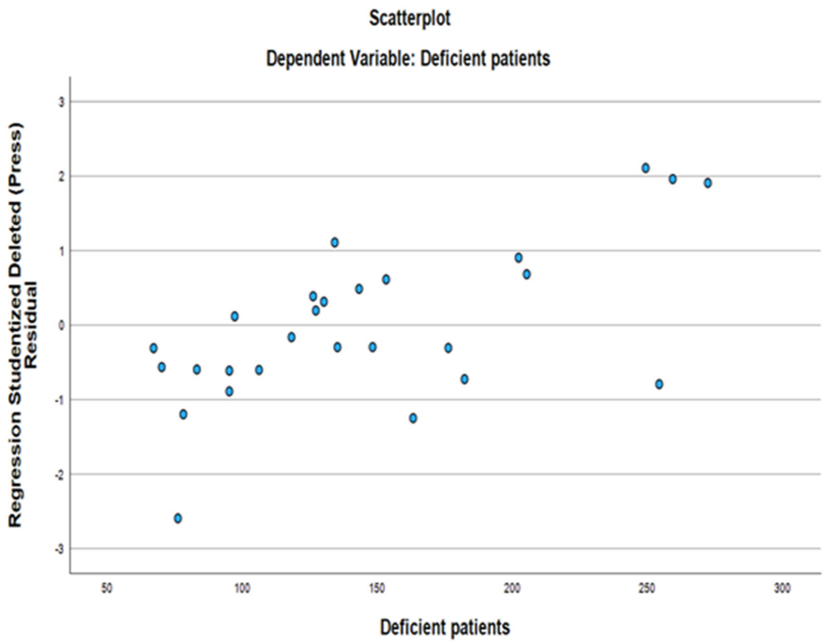


**Figure 4.** Residual plots versus number of vitamin D-deficient patients per month using linear regression.

## 4. Discussion

Although no correlations were found in the statistical analysis of dusty days and UV index, Table 4 shows a direct relationship between the total number of dusty days and the percentage of vitamin D-deficient patients; increases or decreases in dusty days corresponded to changes in the percentage of vitamin D-deficient patients each year. However, an exception occurred in 2021, where a decrease in dusty days coincided with a 2% increase in vitamin D deficiency. This anomaly may be attributed to COVID-19 outbreaks and social distancing measures in Bahrain, with cases peaking at 20,829 in 2021 [52]. Lockdowns likely led to reduced sun exposure, contributing to the increase in vitamin D-deficient patients, while improved air quality during the epidemic led to fewer dusty days [53,54]. It is also important to consider the average time required for vitamin D levels to change in the human body. The level of vitamin D does not instantly change with changes in environmental factors or oral supplements; rather, it gradually increases or decreases in the body. According to the hospitals and health centers in Bahrain, a vitamin D-deficient patient is called for follow-up every 3–6 months, depending on the severity of the deficiency.

Discrepancies in the results of the UV index could be explained by the unavailability of UV-B data and dust readings recorded at higher altitudes. According to Glover (2014) [55], the ozone layer absorbs a significant quantity of UV-B rays. The ozone layer deteriorates the most in the lower stratosphere, at around 20–30 km above sea level; as a result, UV-B levels are significantly higher at altitudes of more than 20–30 km. Several studies conducted in the Alps, Africa, Switzerland, Iran, and the Middle East showed that as height increases, UV radiation also increases [56,57].

Another justification was the unavailability of UV-B measurements. A study conducted in Qatar involved an experiment in which surface solar monitoring stations were spread all over the country to measure the global horizontal irradiance, UV-A, UV-B, and relative humidity using special instruments [58]. Evidently, such complex models can better account for confounding variables; however, it is not known whether the source of data used in this study took into consideration such intricate measures.

With regards to VDD and its association with chronic diseases, the most common chronic diseases that lead to VDD in patients in Bahrain are chronic kidney disease (CKD) and bariatric surgeries. CKD causes dysregulation of mineral metabolism and vitamin D, which means that there is a lack of proper intake of nutrients that are essential for the body. This has been linked to bone loss and fractures, cardiovascular disease, immune system suppression, and increased mortality, which is an important contributor to morbidity in CKD patients [59]. In addition, long-term morbidity following bariatric surgery might result from vitamin and mineral shortages. Furthermore, due to poor compliance, loss of follow-up, reduced food consumption, and malabsorption, bariatric surgery may worsen vitamin D and calcium intake or production in the body, leading to metabolic complications [60,61].

Table 3 shows increased $PM_{2.5}$ and $PM_{10}$ concentrations ($\mu g/m^3$) at $\leq$ 1000 m, exceeding the recommended US EPA standard levels of 35 $\mu g/m^3$ and 150 $\mu g/m^3$, respectively, over 24 h [48] in most months. The levels recorded in the current study also exceeded the WHO guidelines [50] in all months, indicating an increase in air pollutants during the studied period. The $PM_{2.5}/PM_{10}$ ratio is considered a good measure of a particle's origin [62,63]. Higher ratios of $PM_{2.5}/PM_{10}$ attribute particle pollution to anthropogenic sources, whereas smaller ratios might be associated with natural sources such as dust storms [64]. Table 4 shows that the $PM_{2.5}/PM_{10}$ ratio was less than 0.5 in the years 2019, 2021, and 2022, indicating dust pollution; this is consistent with a previous study in the region, in which the average $PM_{2.5}/PM_{10}$ ratio in Saudi Arabia was 0.33 [65].

Table 8 also shows a strong positive correlation between dusty days at all altitudes and $PM_{10}$, indicating the presence of high amounts of $PM_{10}$ particles at all altitudes. Several studies have shown that $PM_{2.5}$ and $PM_{10}$ concentrations tend to increase with increasing altitude due to different environmental factors such as solid dust, smoke, and liquid droplets [66,67]; dust transported from the Arabian Peninsula and the Thar Desert [68]; and air pollution [69,70] and atmosphere instability [71]. Climate change is producing and circulating more dust, with surprising impacts on the flow of rivers and the spread of diseases; therefore, high levels of vitamin D deficiency in the Gulf region should be investigated in relation to $PM_{2.5}$ and $PM_{10}$ particles at higher altitudes and the possibility of hindering UV-B rays from reaching the earth in this region. Further studies in which accurate measurements of UV-B, dusty days, and dust particles ($PM_{2.5}$ and $PM_{10}$) at higher altitudes (20–30 Km) are recorded are recommended. Such limitations of the current study prevent the drawing of a final concise conclusion regarding the relationship between dust particles ($PM_{2.5}$ and $PM_{10}$), UV-B, and high incidences of VDD in the region. Health and environmental impacts, in addition to economic costs of dust, are thoroughly documented in the World Bank report on sand and dust storms in the Middle East and North Africa (MENA) regions, showing that the MENA region is suffering from high dust concentrations that reach well beyond acceptable levels, with tremendous impacts [72].

## 5. Conclusions

In this study, the number of dusty days measured at $\leq$1000 m, $\leq$3000 m, and $\leq$5000 m, together with the concentrations of $PM_{2.5}$ and $PM_{10}$ particles at $\leq$1000 m, UV index, and Vitamin D levels were used to investigate the possible relationship between dusty days and UV index and its effect on vitamin D concentration. No significant trend was found in the number of dusty days during the studied period (2017–2022) since the total number of dusty days fluctuated across the years. However, increased $PM_{2.5}$ and $PM_{10}$ concentrations ($\mu g/m^3$) at $\leq$ 1000 m that exceeded the recommended WHO guidelines (2021) and US EPA (2024) standard levels were found in most months, indicating an increase in air pollutants during the studied period. A strong positive correlation was found between dusty days at all altitudes and $PM_{10}$, indicating the presence of high amounts of $PM_{10}$ particles at altitudes close to ground level. The average range of the $PM_{2.5}/PM_{10}$ ratio was low (0.24–0.35), indicating dust pollution. A positive correlation was also found between the number of vitamin D tests, VDD patients, and $PM_{2.5}$ and $PM_{10}$ concentrations, indicating a strong relationship between vitamin D deficiency and air pollution. However, no correlation was found between dusty days, vitamin D deficiency, and the UV index due to several factors, including the unavailability of UV-B data. Measurement of the number of dusty days at a maximum height of 5000 m instead of 20 to 30 km and measurement of $PM_{2.5}$ at $\leq$1000 m are other factors that need to be overcome in future studies. Such studies might reveal a hidden reason behind the high number of vitamin D deficiencies in the Gulf region despite the long sunlight period.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos15121497/s1, Figure S1. Scatter plot between months and dusty days at ≤5000 m per month. Figure S2. Scatter plot between number of vitamin D tests and dusty days at ≤5000 m per month. Figure S3. Scatter plot between vitamin D deficient patients and dusty days at ≤5000 m per month. Figure S4. Scatter plot between UV index and dusty days at ≤5000 m per month. Figure S5. Scatter plot between dusty days at ≤1000 m and dusty days at ≤5000 m per month. Figure S6. Scatter plot between dusty days at ≤3000 m and dusty days at ≤5000 m per month.

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