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Overview of the Vital Role of Vitamin D: Functions, Deficiency Syndromes, and Impact Throughout Life

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Abstract

The recent study provides a comprehensive overview of vitamin D, emphasizing its biological roles, sources, and health implications. Vitamin D, a fat-soluble prohormone, is essential for bone health, immune function, mental well-being, reproductive health, and the prevention of chronic diseases. Discovered in the early 20th century due to the anti-rachitic effects of cod liver oil, vitamin D includes two main inactive precursors: vitamin D3 and vitamin D2. Vitamin D3 is endogenously synthesized in the skin through ultraviolet B (UVB) radiation (290–320 nm), while vitamin D2 originates from plants and is obtained through dietary intake. The synthesis and activation of vitamin D are influenced by factors such as UVB exposure, with excessive exposure leading to the formation of inactive metabolites like tachysterol and lumisterol. This overview underscores the critical importance of maintaining adequate vitamin D levels for optimal health outcomes.

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1. Introduction

Vitamin D is a fat-soluble vitamin that plays a crucial role in bone health, immune function, mental well-being, reproductive health, and chronic disease prevention. Vitamin D is a group of fat-soluble prohormones first identified in the early 20th century following the discovery of the anti-rachitic properties of cod liver oil. It was named "D" after the previously discovered vitamins A, B, and C [1]. The two primary biologically inactive precursors of vitamin D are vitamin D3 (cholecalciferol) and vitamin D2 (ergocalciferol). Vitamin D3 is synthesized when 7-dehydrocholesterol in the skin is exposed to ultraviolet B (UVB) rays (290–320 nm), leading to the formation of pre vitamin D3, which is then converted into vitamin D through a heat-dependent process. However, excessive UVB exposure degrades pre vitamin D3 into inactive metabolites such as tachysterol and lumisterol. In contrast, vitamin D2 is derived from plants and is produced exogenously through the irradiation of ergosterol, entering circulation via dietary intake [2].

Both vitamin D precursors—obtained either through sunlight exposure or diet are converted into 25-hydroxyvitamin D [25(OH)D] (calcidiol) upon reaching the liver. This metabolite serves as the primary circulating form of vitamin D and is commonly used to assess vitamin D status. However, for full biological activity, an additional hydroxylation step occurs in the kidneys, producing the active form, 1,25-dihydroxyvitamin D [1,25(OH)2D] (calcitriol) [3]. Dietary sources of vitamin D are limited, with oily fish such as salmon, mackerel, and sardines being among the richest natural sources. Other sources include egg yolks, though their vitamin D content varies, and their high cholesterol content makes them a less ideal option. Certain foods, including milk, orange juice, and some bread and cereals, are fortified with vitamin D to help meet dietary needs [4].

This review addresses a critical gap in the current literature by emphasizing the regulation of hepatic protein synthesis not only under pathological conditions but also across diverse physiological contexts such as female reproductive stages, aging, and nutrient co-factors like vitamin D, B12, iron, and folate. The hormonal fluctuations during menstruation, pregnancy, and menopause significantly influence liver metabolism and protein synthesis, yet these effects remain underexplored in mainstream hepatology research [5]. Age-related hepatic decline, marked by reduced mitochondrial efficiency and impaired translational machinery, also affects the liver's synthetic capacity, particularly in elderly populations at risk of sarcopenia and chronic liver disease. Moreover, micronutrients such as vitamin D and B12, often deficient in older adults and women, modulate hepatic gene expression, enzymatic activity, and cellular homeostasis either independently or through interaction with steroid hormones and cytokine pathways. The review also highlights the potential co-action or antagonism among these micronutrients and hormones, which may amplify or inhibit hepatic protein synthesis pathways, offering a more integrative and sex-sensitive understanding of liver function across the lifespan [6].

According to the World Health Organization (WHO), vitamin D deficiency affects nearly 1 billion individuals worldwide, with prevalence rates exceeding 40% in the general population. Women of reproductive age, pregnant women, lactating mothers, and the elderly are among the most vulnerable groups, owing to hormonal fluctuations, reduced outdoor activity, and increased nutritional demands. In India, studies have shown that approximately 70–90% of the population is vitamin D deficient, a trend confirmed by the National Family Health Survey (NFHS-5), which reports significantly higher deficiency rates in urban females (up to 76%) compared to urban males (around 59%) [7]. A multicentric study published in the Indian Journal of Endocrinology and Metabolism found that 84.2% of postmenopausal Indian women were vitamin D deficient, underscoring a substantial risk for hepatic and systemic disorders. This widespread deficiency has been linked not only to bone-related disorders such as osteoporosis and rickets but also to non-skeletal effects, including impaired liver enzyme activity, dysregulation of hepatic protein synthesis, altered lipid metabolism, insulin resistance, and immune dysfunction [8]. Geographic and lifestyle factors, such as limited sun exposure due to cultural clothing practices, air pollution, urbanization, sedentary behavior, darker skin pigmentation, and poor dietary intake, further contribute to this problem. Populations in South Asia, the Middle East, and Africa are particularly affected, with some studies reporting deficiency rates of over 90% in Gulf countries and Northern India. Global health experts now recommend population-wide interventions including fortification, supplementation, and public health awareness to combat this silent epidemic [9].

Table 1 presents a comprehensive overview of the global and regional prevalence of vitamin D deficiency, emphasizing its widespread nature and public health significance. Globally, approximately 40–50% of the general population is affected by vitamin D deficiency, as reported by the WHO and others. In India, the situation is particularly severe, with urban women and the elderly showing deficiency rates between 70–90% and 80–86%, respectively, highlighting age and gender-specific vulnerabilities. Similarly, countries in the Middle East such as Saudi Arabia and the UAE report extremely high deficiency rates of 80–90%, despite abundant sunlight, due to cultural and lifestyle factors limiting sun exposure [10]. African nations like Morocco and Egypt also exhibit high prevalence among women and children. In the United States, African American women are disproportionately affected due to melanin's effect on UVB absorption, with prevalence rates reaching 50–60%. European countries, especially in the north, experience seasonal fluctuations with deficiency rates peaking at 20–40% during winter months. South Asian countries such as Pakistan and Bangladesh also reflect alarmingly high deficiency levels, particularly among women and the elderly. This data underscores the urgent need for region-specific strategies to combat vitamin D deficiency worldwide [11].

Table 1: Global and Regional Prevalence of Vitamin D Deficiency.

S. No.	Region/Country	Deficiency Prevalence (%)	Affected Population	Reference
1.	Global Average	40–50%	General population	[12]
2.	India (Urban Women)	70–90%	Reproductive age, postmenopausal women	[13]
3.	India (Elderly Population)	80–86%	Above 60 years	[14]
4.	Middle East (Saudi Arabia, UAE)	80–90%	General population	[15]
5.	Africa (Morocco, Egypt)	60–85%	Women and children	[16]
6.	USA (African American Women)	50–60%	Reproductive age	[17]

7.	Europe (Northern countries)	20–40% (winter months)	General population	[18]
8.	South Asia (Pakistan, Bangladesh)	70–90%	Women, elderly	[19]

Figure 1 illustrates the biochemical pathway of vitamin D production and activation in the human body. The process initiates in the epidermis, where 7-dehydrocholesterol is converted to vitamin D_3 (cholecalciferol) under the influence of UV-B radiation from sunlight. Dietary sources also contribute vitamin D_2 (ergocalciferol) and vitamin D_3, typically found in fortified foods, mushrooms, and oily fish. Once absorbed or synthesized, both forms are transported to the liver, where they undergo the first hydroxylation step via 25-hydroxylase enzymes, producing 25-hydroxyvitamin D [25(OH)D], the major circulating and storage form of the vitamin [20]. Subsequently, this metabolite is transported to the kidneys, where 1α-hydroxylase catalyzes a second hydroxylation, forming 1,25-dihydroxyvitamin D [1,25(OH)$_2$D], also known as calcitriol the biologically active, hormonal form of vitamin D. Calcitriol binds to vitamin D receptors (VDRs) in target tissues, playing a pivotal role in calcium and phosphate regulation, bone remodeling, immune modulation, and cell proliferation and differentiation [21].

This stepwise transformation highlights the necessity of functional skin, liver, and kidney systems for vitamin D to exert its biological effects, as disruptions at any stage may lead to clinical deficiency, even if sun exposure or dietary intake is adequate [22].

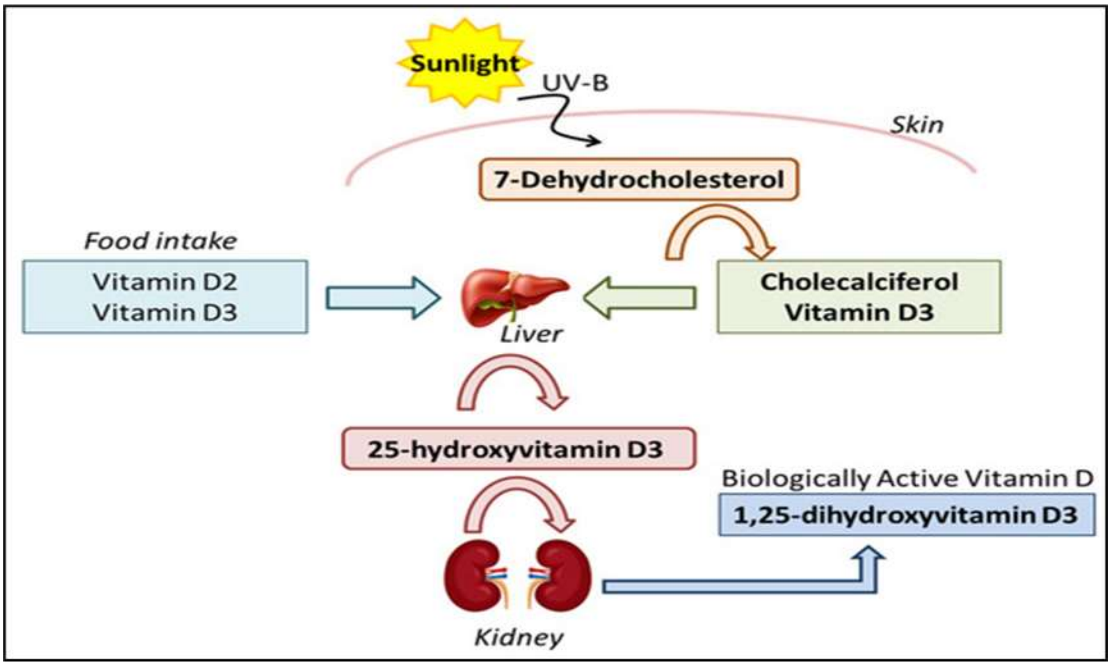

Figure 1: Pathway of Vitamin D Production. The vitamin D production pathway involves the conversion of 7-dehydrocholesterol in the skin to vitamin D_3 via UV-B. Vitamin D_3 (and D_2 from food) is hydroxylated in the liver to 25-hydroxyvitamin D_3 and then in the kidneys to 1,25-dihydroxyvitamin D_3, the biologically active form.

1.1. Role of Vitamin D in Female Health across Life Stages

Vitamin D plays a critical role in female health across all life stages, influencing skeletal development, reproductive function, immune balance, and chronic disease prevention. During childhood and adolescence, adequate vitamin D is essential for bone growth and mineralization, helping to prevent rickets and optimize peak bone mass. In reproductive years, it supports hormonal balance and fertility by modulating ovarian function and improving outcomes in conditions like polycystic ovary syndrome (PCOS). During pregnancy, sufficient vitamin D levels are linked to reduced risks of gestational diabetes, preeclampsia, low birth weight, and impaired fetal bone development [23]. In lactating mothers, it ensures adequate vitamin D transfer to the infant through breast milk. For postmenopausal women, who are at higher risk for osteoporosis due to declining estrogen levels, vitamin D is crucial in maintaining bone density and reducing fracture risk [24]. Additionally, vitamin D contributes to immune regulation and may reduce the risk of autoimmune diseases, cardiovascular disorders, and mood-related conditions such as depression throughout a woman's lifespan. Thus, maintaining optimal vitamin D status is vital for promoting long-term health and disease prevention in females at every stage of life [25].

Table 2 highlights the vital role of vitamin D at various stages of a woman's life, emphasizing its influence on development, immunity, hormonal balance, and long-term health outcomes. In infancy, vitamin D is crucial for bone mineralization and calcium absorption, helping prevent rickets and skeletal deformities. During childhood, it strengthens bones and supports immune function, thereby reducing infection risks and aiding brain development [26]. In adolescence, vitamin D contributes to the regulation of puberty, menstrual cycles, and mood, with deficiencies linked to delayed puberty, irregular menstruation, and increased risk of depression. In adulthood, it supports reproductive health and pregnancy, lowering the risk of conditions such as PCOS, gestational diabetes, and hypertension. For postmenopausal women, maintaining adequate vitamin D levels is essential to preserve bone density and muscle strength, while also protecting against osteoporosis, fractures, and age-related cognitive decline. This table underscores the importance of lifelong vitamin D sufficiency for optimal female health [27].

Table 2: Role of Vitamin D in Female Health Across Life Stages.

S. No.	Life Stage	Role of Vitamin D	Health Impact	References
1.	**Infancy (0-12 months)**	Supports bone mineralization and calcium absorption	Prevents rickets and skeletal deformities	[28]
2.	**Childhood (1-12 years)**	Strengthens bones and boosts immunity	Reduces infection risk and supports brain development	[29]
3.	**Adolescence (13-19 years)**	Regulates puberty, menstrual cycles, and mood	Deficiency may cause delayed puberty, irregular periods, depression	[30]
4.	**Adulthood (20-50 years)**	Supports fertility, pregnancy, and cardiovascular health	Reduces risk of PCOS, gestational diabetes, and hypertension	[31]
5.	**Postmenopause (50+ years)**	Maintains bone density and muscle strength	Prevents osteoporosis, fractures, and cognitive decline	[32]

1.2. Symptoms of Vitamin D Deficiency

Vitamin D deficiency can manifest through a variety of subtle and often overlooked symptoms. Individuals may experience persistent fatigue and low energy levels, even when getting enough sleep. Bone pain and muscle weakness, especially in areas like the lower back, hips, and legs, are common indicators. A weakened immune system can lead to frequent infections such as colds or respiratory illnesses. Many people with low vitamin D levels report mood disturbances, including depression, irritability, and anxiety [33]. Wound healing may become noticeably slower, as vitamin D is involved in controlling inflammation and supporting tissue repair. In some cases, hair loss occurs, particularly among women, and may be linked to autoimmune responses associated with deficiency.

In children, a lack of vitamin D can impair bone growth, potentially resulting in rickets or skeletal deformities. Adults may develop osteomalacia, a condition characterized by soft, weakened bones and a higher risk of fractures. Because these symptoms are often non-specific, confirming vitamin D deficiency usually requires a blood test measuring serum 25-hydroxyvitamin D levels [34].

Table 3 presents an overview of the diverse symptoms associated with vitamin D deficiency, highlighting its systemic impact across various body functions. General symptoms include fatigue, weakness, muscle aches, and joint pain, which are often the earliest signs of deficiency. In terms of skeletal health, insufficient vitamin D can lead to rickets in children, osteomalacia in adults, and increased risk of osteoporosis in the elderly due to impaired calcium metabolism [35].

Immune system dysfunction is another critical consequence, with deficiency linked to greater susceptibility to infections and a heightened risk of autoimmune disease. Mental health may also be affected, as low vitamin D levels are associated with depression, anxiety, mood instability, and even cognitive decline in older adults [36]. Hormonal imbalances can result in menstrual irregularities, fertility issues, and worsened symptoms of PCOS. Lastly, hair and skin-related problems such as hair thinning, alopecia, and delayed wound healing are increasingly recognized as signs of deficiency. This table emphasizes the need for awareness and early detection of vitamin D deficiency to prevent long-term health complications [37].

Table 3: Vitamin D deficiency can have widespread effects on the body, leading to various symptoms.

S. No.	Category	Symptoms	References
1.	General Symptoms	Fatigue, weakness, muscle pain, and joint discomfort	[38]
2.	Skeletal Issues	Rickets (children), osteomalacia (adults), osteoporosis (elderly)	[39]
3.	Immune Dysfunction	Increased susceptibility to infections, colds, and autoimmune diseases	[40]
4.	Mental Health Issues	Depression, anxiety, mood swings, cognitive decline	[41]
5.	Hormonal Imbalance	Menstrual irregularities, PCOS, fertility issues	[42]
6.	Hair and Skin Problems	Hair thinning, alopecia, slow wound healing	[43]

The recommended daily intake (RDI) of vitamin D varies according to age, life stage, and individual health status. For infants (0–12 months), 400 IU/day is advised. Children and adolescents (1–18 years) typically require 600 IU/day. Adults aged 19–70 years need 600–800 IU/day, while those over 70 may require up to 800–1,000 IU/day to maintain skeletal and immune health. Pregnant and lactating women are recommended 600–800 IU/day. Higher doses may be necessary for individuals with limited sun exposure, obesity, darker skin, or fat malabsorption disorders like celiac or Crohn's disease, as per clinical guidance [44].

Table 4 summarizes the recommended daily intake (RDI) of vitamin D across various age groups and physiological stages, as suggested by key health authorities and scientific literature. For infants (0–12 months), 400 IU/day is considered adequate to support early skeletal development and immune function. Children aged 1–13 years and teenagers up to 18 years require 600 IU/day to sustain bone growth and support immune health [45]. Adults between 19–50 years also need about 600 IU/day to maintain calcium balance and overall health. Pregnant and lactating women are advised to consume between 600–800 IU/day to support fetal bone development and maternal well-being. Older adults (51 years and above), due to reduced skin synthesis and absorption, are recommended a higher intake of 800–1000 IU/day to prevent osteoporosis, fractures, and immune decline. These guidelines serve as a baseline, with adjustments often required based on individual health status, lifestyle, and sun exposure [46].

Table 4: The recommended daily intake (RDI) varies based on age, gender, and health status.

S. No.	Age Group	Recommended Daily Intake (IU/day)	References
1.	Infants (0-12 months)	400 IU	[47]
2.	Children (1-13 years)	600 IU	[48]
3.	Teenagers (14-18 years)	600 IU	[49]
4.	Adults (19-50 years)	600 IU	[50]
5.	Pregnant & Lactating Women	600-800 IU	[51]
6.	Older Adults (51+ years)	800-1000 IU	[52]

1.3. Best Sources of Vitamin D

In situations where sun exposure and dietary intake are insufficient, vitamin D supplementation becomes a vital tool to achieve and maintain adequate serum levels. Supplements are available primarily in two forms: vitamin D2 (ergocalciferol) and vitamin D3 (cholecalciferol). Studies suggest that vitamin D3 is more effective than D2 in raising serum 25-hydroxyvitamin D concentrations and sustaining those levels over time. Therefore, cholecalciferol is generally preferred in clinical and public health settings [53]. Certain groups such as individuals with limited sunlight exposure, people with darker skin pigmentation, those with obesity, elderly populations, and patients with fat malabsorption syndromes (e.g., celiac disease, Crohn's disease) often require supplementation beyond dietary sources. Additionally, because vitamin D is fat-soluble, taking supplements with meals that contain dietary fat significantly enhances absorption [54].

For individuals with diagnosed deficiency, high-dose regimens such as 50,000 IU weekly for 6 to 8 weeks may be medically recommended, followed by a maintenance dose ranging from 800 to 2,000 IU daily, depending on clinical evaluation. However, long-term intakes exceeding the Upper Safe Limit of 4,000 IU/day should only be followed under medical supervision to avoid toxicity-related outcomes like hypercalcemia, vascular calcification, nephrocalcinosis, and renal failure [55]. This multi-modal approach combining sensible sunlight exposure, nutrient-rich diet, and evidence-based supplementation is the most reliable strategy for optimizing vitamin D levels and preventing deficiency-related disorders [56].

Table 5 presents a summary of common dietary sources of vitamin D along with their approximate content per serving. Among these, cod liver oil stands out as the richest source, providing approximately 1,360 IU of vitamin D per tablespoon. Fatty fish such as salmon and tuna are also excellent sources, offering 600–1,000 IU and 200–400 IU per 3.5-ounce serving, respectively. Egg yolks, though consumed in smaller quantities, contribute 40–50 IU per large egg. Fortified milk, a widely accessible dietary staple, provides 100–150 IU per cup, making it a significant contributor to daily vitamin D intake in many populations. Additionally, sun-exposed mushrooms serve as a plant-based source, delivering 200–400 IU per half-cup, particularly valuable for individuals following vegetarian or vegan diets. This table highlights the importance of incorporating a variety of these foods to help maintain optimal vitamin D levels [57].

Table 5: Common Dietary Sources of Vitamin D and Their Approximate Content per Serving.

S. No.	Food Source	Vitamin D Content (IU per serving)	Referencing
1.	Cod liver oil (1 tbsp)	1,360 IU	[58]
2.	Salmon (3.5 oz)	600-1000 IU	[59]
3.	Tuna (3.5 oz)	200-400 IU	[60]
4.	Egg yolk (1 large)	40-50 IU	[61]
5.	Fortified milk (1 cup)	100-150 IU	[62]
6.	Mushrooms (sun-exposed, ½ cup)	200-400 IU	[63]

1.4. Supplements

Vitamin D supplements are widely used to help individuals maintain adequate levels, especially when natural sources are insufficient. There are two main types of vitamin D supplements: vitamin D2 (ergocalciferol), which is plant-based, and vitamin D3 (cholecalciferol), which is derived from animal sources and is generally considered more effective in raising and maintaining vitamin D levels in the body. Supplementation is particularly important for people who have limited sun exposure, such as those living in northern latitudes or those who spend most of their time indoors [64]. It is also essential for individuals with certain digestive disorders like inflammatory bowel disease (IBD) or celiac disease, which impair nutrient absorption. Additionally, people with osteoporosis, pregnant women, and the elderly are often advised to take vitamin D supplements to support bone health and overall well-being [65].

1.5. Health Benefits Beyond Bones

Vitamin D is widely recognized for its role in maintaining bone health, but its benefits extend far beyond the skeletal system. One major advantage is its role in enhancing immune function it helps lower the risk of infections like colds, influenza, and respiratory illnesses by modulating immune responses. Additionally, vitamin D offers protection against autoimmune disorders such as multiple sclerosis, rheumatoid arthritis, and type 1 diabetes by regulating immune tolerance [66]. It also contributes to cardiovascular health by reducing inflammation and supporting blood pressure regulation, with deficiency linked to an increased risk of hypertension and heart disease. In reproductive health, sufficient vitamin D levels are associated with improved fertility, regulation of ovulation, and reduced risk of complications like gestational diabetes and preeclampsia. Collectively, these findings highlight that vitamin D functions as a hormone-like regulator in numerous physiological systems, reinforcing the importance of maintaining optimal levels for overall well-being [67].

1.6. Additional Health Benefits of Vitamin D

1.6.1. Strengthens the Immune System

Vitamin D plays a crucial role in supporting the immune system. It has been shown to reduce the risk of infections by lowering the chances of developing common illnesses such as colds, flu, and other respiratory diseases. Additionally, vitamin D may offer protection against autoimmune disorders by modulating immune responses. Research suggests that adequate levels of vitamin D may help in preventing conditions such as multiple sclerosis, rheumatoid arthritis, and type 1 diabetes [68].

1.6.2. Supports Mental Health

Vitamin D also plays a significant role in supporting mental health. It has been associated with reduced symptoms of depression and anxiety, partly due to its involvement in regulating neurotransmitters such as serotonin and dopamine, which are crucial for mood balance. Moreover, sufficient vitamin D levels have been linked to a lower risk of cognitive decline and may help in preventing neurodegenerative conditions such as Alzheimer's disease [69].

1.6.3. Improves Heart Health

Vitamin D contributes to cardiovascular and reproductive health in several important ways. A deficiency in vitamin D has been associated with an increased risk of hypertension and heart disease, suggesting that adequate levels may help lower blood pressure and support overall cardiovascular function. In terms of reproductive health, vitamin D plays a vital role during pregnancy, with low levels being linked to complications such as gestational diabetes, preeclampsia, and low birth weight. Additionally, vitamin D may benefit women with polycystic ovary syndrome (PCOS) by improving ovulation and reducing insulin resistance, thereby enhancing fertility outcomes [70].

2. Mechanism of Action of Vitamin D

Vitamin D is a fat-soluble secosteroid that plays a crucial role in calcium homeostasis, bone metabolism, immune function, and gene regulation. Its mechanism of action involves metabolic activation, receptor binding, and modulation of gene expression [71].

2.1. Metabolic Activation of Vitamin D

Vitamin D is biologically inactive when it is first synthesized in the skin through exposure to ultraviolet B (UVB) radiation or obtained from dietary sources. It must undergo two hydroxylation steps to become active. First, it is hydroxylated in the liver by vitamin D-25-hydroxylase (CYP2R1) to form 25-hydroxyvitamin D [25(OH)D], the primary circulating form [68]. Then, in the kidneys, 1α-hydroxylase (CYP27B1) converts it into 1,25-dihydroxyvitamin D [$1,25(OH)_2D$] (calcitriol), the active hormonal form responsible for regulating calcium, phosphate, and other physiological processes [72].

2.2. Binding to the Vitamin D Receptor (VDR)

Calcitriol enters target cells and binds to the Vitamin D Receptor (VDR), a nuclear receptor expressed in various tissues including the bone, intestines, kidneys, and immune cells such as T and B lymphocytes and macrophages. This receptor-ligand complex forms a heterodimer with the Retinoid X Receptor (RXR), initiating transcriptional activation of vitamin D-responsive genes [73].

3. Gene Transcription and Regulation

The VDR-RXR complex binds to Vitamin D Response Elements (VDREs) in the promoter regions of target genes to modulate their transcription. These genes play critical roles in calcium/phosphate metabolism, immune modulation, and cellular differentiation [74].

Table 6 highlights several key target genes regulated by vitamin D and outlines their crucial biological functions. Notably, vitamin D upregulates genes such as TRPV6 and CALB1, which play a vital role in increasing calcium absorption in the intestines, thereby contributing to the enhancement of serum calcium levels. Additionally, the regulation of RANKL by vitamin D facilitates osteoclast activation, a process essential for bone resorption and the subsequent release of calcium into the bloodstream [75]. Vitamin D also influences FGF23, a gene responsible for maintaining phosphate balance by controlling phosphate excretion in the kidneys. Moreover, vitamin D modulates the immune system by regulating IL-10 and TGF-β, two anti-inflammatory cytokines that help suppress excessive immune responses and maintain immune homeostasis. Collectively, these gene targets underscore the multifaceted role of vitamin D in maintaining mineral balance, bone health, and immune regulation [76].

Table 6: Key Target Genes Regulated by Vitamin D and Their Biological Functions.

S. No.	Target Gene	Function	Biological Effect	Reference
1.	TRPV6, CALB1	Increases calcium absorption in intestines	Enhances serum calcium levels	[77]
2.	RANKL	Stimulates osteoclast activation	Bone resorption for calcium release	[78]
3.	FGF23	Regulates phosphate metabolism	Controls phosphate excretion in kidneys	[79]
4.	IL-10, TGF-β	Modulates immune response	Suppresses inflammation	[80]

4. Biological Effects of Vitamin D

Vitamin D exerts a wide range of biological effects that extend far beyond its classical role in bone health. It is essential for calcium and phosphate homeostasis, facilitating their absorption in the intestines and reabsorption in the kidneys to maintain adequate serum levels necessary for bone mineralization. In bones, vitamin D stimulates the activity of osteoblasts and osteoclasts, promoting remodeling and maintaining skeletal integrity [81].

It also modulates the immune system by enhancing innate immunity through the production of antimicrobial peptides such as cathelicidin and defensins, while simultaneously downregulating pro-inflammatory cytokines like IL-6 and TNF-α to prevent excessive immune responses. Furthermore, vitamin D supports cellular differentiation and regulates the cell cycle, thereby playing a protective role against certain cancers by inhibiting tumor growth and promoting apoptosis. It also contributes to neurological and reproductive health, supporting neurotransmitter synthesis, cognitive function, and hormonal balance. These diverse actions illustrate vitamin D's role as a pleiotropic hormone essential for maintaining systemic physiological stability and overall health [82].

4.1. Calcium and Phosphate Homeostasis

Vitamin D plays a vital role in maintaining calcium and phosphate homeostasis by acting on multiple organs. In the intestines, it enhances the absorption of calcium and phosphate by upregulating the expression of transport proteins such as TRPV6 and CALB1. In bones, vitamin D promotes remodeling by stimulating the activity of both osteoblasts and osteoclasts, primarily through the regulation of RANKL signaling. In the kidneys, it helps regulate calcium reabsorption and phosphate excretion by modulating the actions of fibroblast growth factor 23 (FGF23) and parathyroid hormone (PTH), ensuring mineral balance and skeletal integrity [83].

4.2. Immune System Modulation

Vitamin D significantly contributes to immune system modulation through various mechanisms. It enhances the production of antimicrobial peptides such as cathelicidin and defensins, which play a crucial role in the body's defense against infections. Additionally, vitamin D helps suppress excessive immune responses by reducing the levels of pro-inflammatory cytokines like IL-6 and TNF-α, thereby lowering the risk of autoimmune diseases. It also modulates T-cell differentiation, promoting the development of regulatory T cells that maintain immune tolerance and prevent overactivation of the immune system [84].

4.3. Cell Growth & Differentiation

Vitamin D plays an important role in regulating cell growth and differentiation by influencing the expression of genes involved in the cell cycle, apoptosis, and cellular maturation. Through these mechanisms, it helps maintain normal tissue development and prevent uncontrolled cell proliferation. This regulatory function has significant implications in cancer prevention, as vitamin D has been shown to inhibit tumor growth and promote the differentiation of cancerous cells, thereby reducing malignancy potential [85].

Table 7 outlines the intricate interactions between vitamin D and various essential nutrients, emphasizing their collective impact on biological functions. Vitamin A works synergistically with vitamin D in regulating immune function and gene expression; however, excessive intake of vitamin A may diminish the positive effects of vitamin D, highlighting the need for a balanced intake to support bone health and immunity. Vitamin K complements vitamin D by activating proteins such as osteocalcin and matrix Gla-protein (MGP), which are crucial for calcium metabolism [86]. This interaction prevents arterial calcification and promotes bone mineralization. Vitamin C contributes to collagen synthesis—an essential component of the bone matrix and cooperates with vitamin D in modulating immune responses, thereby enhancing bone strength and reducing oxidative stress. Vitamin E, known for its antioxidant properties, protects vitamin D from oxidative degradation, thereby amplifying its immune and anti-inflammatory benefits. The B vitamins—particularly B6, B12, and folate—play a vital role in homocysteine metabolism, which intersects with vitamin D pathways, supporting both cardiovascular and neurological health. Lastly, magnesium is indispensable for the activation and optimal functioning of vitamin D, especially in maintaining calcium homeostasis. A deficiency in magnesium can severely impair vitamin D metabolism, underscoring its fundamental role in ensuring the vitamin's efficacy. These nutrient interactions collectively demonstrate the complex yet harmonious interplay required for maintaining health and preventing disease [87].

Table 7: Nutrient Interactions with Vitamin D and Their Biological Significance.

S. No.	Nutrient	Interaction with Vitamin D	Biological Significance	References
1.	Vitamin A	Works together to regulate immune function and gene expression but excessive vitamin A may counteract vitamin D benefits.	Balances bone health and immune function.	[88]
2.	Vitamin K	Enhances calcium metabolism by activating proteins like osteocalcin and matrix Gla-protein (MGP).	Prevents arterial calcification and supports bone mineralization.	[89]
3.	Vitamin C	Supports collagen synthesis, essential for bone matrix formation. Works with vitamin D to regulate immune function.	Improves bone strength and reduces oxidative stress.	[90]

4.	Vitamin E	Acts as an antioxidant, protecting vitamin D from oxidative degradation.	Enhances immune and anti-inflammatory benefits of vitamin D.	[91]
5.	B Vitamins (B6, B12, Folate)	Important for homocysteine metabolism, which interacts with vitamin D pathways.	Supports cardiovascular health and neurological function.	[92]
6.	Magnesium	Essential for vitamin D activation and function in calcium homeostasis.	Deficiency impairs vitamin D metabolism.	[93]

5. Scientific Explanation of Coaction

Vitamin D interacts synergistically with several other nutrients to perform its biological functions effectively. For instance, vitamin D enhances calcium absorption in the gut, while vitamin K plays a crucial role in directing this calcium into bones by activating proteins like osteocalcin, thereby preventing calcium deposition in soft tissues such as arteries. Magnesium is another essential cofactor, as it is required for the enzymatic hydroxylation steps that activate vitamin D in the liver and kidneys, enabling it to exert its physiological effects [94]. Although vitamin A and vitamin D both regulate gene expression, an excess of vitamin A can interfere with vitamin D's positive impact on bone health by disrupting this balance. Additionally, B vitamins particularly B6, B12, and folate are involved in homocysteine metabolism. Elevated homocysteine levels, often due to B vitamin deficiency, are associated with reduced bone density and impaired cognitive function, highlighting the importance of their interaction with vitamin D in maintaining skeletal and neurological health [95].

6. Future Importance

As awareness of vitamin D's broad physiological impact continues to grow, its future importance in public health, clinical nutrition, and preventive medicine will only increase. Advancements in nutrigenomics may further clarify the genetic factors influencing vitamin D metabolism, allowing for more personalized supplementation strategies [96]. Moreover, with a global shift toward indoor lifestyles and urban living, future health policies may focus more on routine screening, food fortification programs, and targeted supplementation for high-risk groups, especially women. Enhanced public education and technology-driven monitoring (like wearable UV exposure trackers) could also play pivotal roles in tackling deficiency at a population level. Ensuring optimal vitamin D status may ultimately become a cornerstone of proactive, lifespan-oriented healthcare for women worldwide [97].

Conclusion

Vitamin D plays an indispensable role in maintaining optimal health across various stages of a woman's life from infancy to postmenopause. It is vital not only for bone health and calcium metabolism but also for immune regulation, mental well-being, hormonal balance, and reproductive function. Despite its importance, vitamin D deficiency remains alarmingly common, especially among women, due to limited sun exposure, dietary insufficiency, and physiological changes during pregnancy, menstruation, and menopause. The health implications of deficiency are far-reaching, contributing to musculoskeletal disorders, compromised immunity, psychological disturbances, and chronic conditions like PCOS and osteoporosis.

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Author Contributions

S. A. Conceptualized the study, **J. A.** Supervised the review, **M. O.** Prepared the manuscript draft**, A. R. K.** Contributed to data analysis, **M. K.** Reviewed the manuscript critically for intellectual content, **M. S.** Data collection, **M. N.** Provided technical support, **M. A.** helped with the literature review.

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Conflicts of Interest

No conflicts of interest are disclosed by the authors.

References

1. R. Zhang and D. P. Naughton, "Vitamin D in health and disease: Current perspectives," Nutrition Journal. 2010. doi: 10.1186/1475-2891-9-65.
2. M. Hewison, "An update on vitamin D and human immunity," Clinical Endocrinology. 2012. doi: 10.1111/j.1365-2265.2011.04261.x.
3. R. B. Jäpelt and J. Jakobsen, "Vitamin D in plants: A review of occurrence, analysis, and biosynthesis," Frontiers in Plant Science. 2013. doi: 10.3389/fpls.2013.00136.
4. F. Y. Ideraabdullah et al., "Maternal vitamin D deficiency and developmental origins of health and disease (DOHaD)," Journal of Endocrinology. 2019. doi: 10.1530/JOE-18-0541.
5. M. C. Carrillo, C. E. Carnovale, C. Favre, J. A. Monti, and C. Scapini, "Hepatic protein synthesis and serum aminoacid levels during liver regeneration in young and old malnourished rats," Mech. Ageing Dev., 1996, doi: 10.1016/0047-6374(96)01779-4.
6. F. W. Schmitges et al., "Attachment-1 copy 2.jpeg.pdf," Skelet. Muscle, 2016.
7. P. Puri et al., "Nutrition in Chronic Liver Disease: Consensus Statement of the Indian National

Association for Study of the
8. Liver," Journal of Clinical and Experimental Hepatology. 2021. doi: 10.1016/j.jceh.2020.09.003.
9. Renstra kemenkes, "Peraturan Menteri Kesehatan Repblik Indonesia No 21 Tahun 2020 Tentang Rencana Strategis Kemenentrian Kesehatan 2020-2024," Kemenkes, 2020.
10. D. A. Ofori, P. Anjarwalla, and L. Mwaura, "ASUHAN KEPERAWATAN PADA PASIEN DENGAN GAGAL GINJAL KRONIS YANG DI RAWAT DI RUMAH SAKIT," Molecules, 2020.
11. A. Cui, T. Zhang, P. Xiao, Z. Fan, H. Wang, and Y. Zhuang, "Global and regional prevalence of vitamin D deficiency in population-based studies from 2000 to 2022: A pooled analysis of 7.9 million participants," Frontiers in Nutrition. 2023. doi: 10.3389/fnut.2023.1070808.
12. K. Amrein et al., "Vitamin D deficiency 2.0: an update on the current status worldwide," European Journal of Clinical Nutrition. 2020. doi: 10.1038/s41430-020-0558-y.
13. K. Amrein et al., "European Journal of Clinical Nutrition Vitamin D deficiency 2.0: an update on the current status worldwide," Eur. J. Clin. Nutr., 2020.
14. A. K. Yerra, S. Bala, R. K. Yalamanchili, R. K. Bandaru, and A. Mavoori, "Menopause-Related Quality of Life among Urban Women of Hyderabad, India," J. Midlife. Health, 2021, doi: 10.4103/jmh.jmh_272_20.
15. C. Kohli, K. Gupta, B. Banerjee, and G. K. Ingle, "Social security measures for elderly population in Delhi, India: Awareness, utilization and barriers," J. Clin. Diagnostic Res., 2017, doi: 10.7860/JCDR/2017/21271.9814.
16. K. H. et al., "The management of parkinson's disease in the middle east countries: The MDS-middle east task force survey," Mov. Disord., 2017.
17. ECDC, "COVID-19 situation update worldwide, as of 13 May 2020," Eur. Cent. Dis. Prev. Control, 2020.
18. S. Wongsawat, "Predicting factors for quality of life of elderly in the rural area," Int. J. Arts Sci., 2017.
19. C. Stival et al., "Prevalence and Correlates of Overweight and Obesity in 12 European Countries in 2017-2018," Obes. Facts, 2022, doi: 10.1159/000525792.
20. A. H. Sufi, "Sustainability and Changing Care Programs in the South Asian Countries," in Cross-cultural Perspectives on Well-Being and Sustainability in Organizations, 2022. doi: 10.1007/978-3-030-86709-6_15.
21. D. Bikle, "Nonclassic actions of vitamin D," Journal of Clinical Endocrinology and Metabolism. 2009. doi: 10.1210/jc.2008-1454.
22. D. Bikle, Vitamin D: Production, Metabolism, and Mechanisms of Action. 2000.
23. N. Latic and R. G. Erben, "Interaction of Vitamin D with Peptide Hormones with Emphasis on Parathyroid Hormone, FGF23, and the Renin-Angiotensin-Aldosterone System," Nutrients. 2022. doi: 10.3390/nu14235186.
24. G. H. Jeon, "The Associations of Vitamin D with Ovarian Reserve Markers and Depression: A Narrative Literature Review," Nutrients. 2024. doi: 10.3390/nu16010096.
25. H. Elkafas, M. Wall, A. Al-Hendy, and N. Ismail, "Gut and genital tract microbiomes: Dysbiosis and link to gynecological disorders," Frontiers in Cellular and Infection Microbiology. 2022. doi: 10.3389/fcimb.2022.1059825.
26. Y. H. Chiu, J. E. Chavarro, and I. Souter, "Diet and female fertility: doctor, what should I eat?," Fertility and Sterility. 2018. doi: 10.1016/j.fertnstert.2018.05.027.
27. J. R. Soto, C. Anthias, A. Madrigal, and J. A. Snowden, "Insights Into the Role of Vitamin D as a Biomarker in Stem Cell Transplantation," Frontiers in Immunology. 2020. doi: 10.3389/fimmu.2020.00966.
28. F. Fiorillo et al., "Role of Vitamin D: Current evidence in Gynecology," Giornale Italiano di Ostetricia e Ginecologia. 2016. doi: 10.11138/giog/2016.38.4.331.
29. M. Aguiar et al., "Global consensus recommendations on prevention and management of nutritional rickets," J. Clin. Endocrinol. Metab., 2016, doi: 10.1210/jc.2015-2175.
30. J. M. Saavedra and A. M. Prentice, "Nutrition in school-age children: a rationale for revisiting priorities," Nutrition Reviews. 2023. doi: 10.1093/nutrit/nuac089.
31. L. B. Alloy, J. L. Hamilton, E. J. Hamlat, and L. Y. Abramson, "Pubertal development, emotion regulatory styles, and the emergence of sex differences in internalizing disorders and symptoms in adolescence," Clin. Psychol. Sci., 2016, doi: 10.1177/2167702616643008.
32. N. M. Shawky, "Cardiovascular disease risk in offspring of polycystic ovary syndrome," Frontiers in Endocrinology. 2022. doi: 10.3389/fendo.2022.977819.
33. E. L. Yong and S. Logan, "Menopausal osteoporosis: Screening, prevention and treatment," Singapore Medical Journal. 2021. doi: 10.11622/SMEDJ.2021036.
34. M. J. McKenna and M. Kilbane, "Vitamin D Deficiency," in Endocrinology and Diabetes: A Problem Oriented Approach: Second Edition, 2022. doi: 10.1007/978-3-030-90684-9_23.
35. K. D. Cashman et al., "Vitamin D deficiency in Europe: Pandemic?," Am. J. Clin. Nutr., 2016, doi: 10.3945/ajcn.115.120873.
36. A. Gupta, V. Chandail, and R. Sharma, "Prevalence of Vitamin D Deficiency in Patients with Inflammatory Bowel Disease," JK Sci., 2024, doi: 10.1093/ecco-jcc/jjw019.442.
37. Z. M. Isa, N. R. M. Nordin, M. H. Mahmud, and S. Hashim, "An Update on Vitamin D Deficiency Status in Malaysia," Nutrients. 2022. doi: 10.3390/nu14030567.
38. L. Vranić, I. Mikolašević, and S. Milić, "Vitamin D deficiency: Consequence or cause of obesity?," Medicina (Lithuania). 2019. doi: 10.3390/medicina55090541.
39. M. T. Nestares Pleguezuelo, L. Montoya Lozano, M. López Frías, and C. De Teresa Galván, "Effect of gluten free diet consumption on the clinic progress of chronic musculoskeletal pathology," Ann. Nutr. Metab., 2017.
40. M. F. Holick, "The vitamin D deficiency

pandemic: A forgotten hormone important for health," Public Health Reviews. 2010. doi: 10.1007/BF03391602.

41. D. McCloskey, "Other Things Equal - Economical Writing: An Executive Summary," East. Econ. J., 1999.
42. J. Mathew, V. TJ, S. Jose, R. E.F, and S. K.J, "MAINTAINING PHYSICAL AND MENTAL HEALTH AMONG ELDERS DURING COVID 19," UGC Care J., 2020.
43. A. Mohan et al., "Vitamin D and polycystic ovary syndrome (PCOS): a review," Ann. Med. Surg., 2023, doi: 10.1097/ms9.0000000000000879.
44. H. Morinaga et al., "Obesity accelerates hair thinning by stem cell-centric converging mechanisms," Nature, 2021, doi: 10.1038/s41586-021-03624-x.
45. A. R. Beauchesne et al., "Vitamin D intakes and health outcomes in infants and preschool children: Summary of an evidence report," Annals of Medicine. 2022. doi: 10.1080/07853890.2022.2111602.
46. L. Dalle Carbonare, M. T. Valenti, F. Del Forno, E. Caneva, and A. Pietrobelli, "Vitamin D: Daily vs. Monthly Use in Children and Elderly-What Is Going On?," Nutrients, 2017, doi: 10.3390/nu9070652.
47. K. Fujimoto et al., "The effects of minodronate and activated Vitamin D on bone mineral density and muscle mass in postmenopausal women with osteoporosis," Spine Surg. Relat. Res., 2018, doi: 10.22603/ssrr.2017-0016.
48. S. Tuovinen et al., "Effect of High-Dose vs Standard-Dose Vitamin D Supplementation on Neurodevelopment of Healthy Term Infants: A Randomized Clinical Trial," JAMA Netw. Open, 2021, doi: 10.1001/jamanetworkopen.2021.24493.
49. G. Asghari, E. Yuzbashian, C. L. Wagner, Y. Park, P. Mirmiran, and F. Hosseinpanah, "Daily vitamin D3 in overweight and obese children and adolescents: a randomized controlled trial," Eur. J. Nutr., 2021, doi: 10.1007/s00394-020-02406-x.
50. J. A. Laub, "Assessing the servant organization; Development of the Organizational Leadership Assessment (OLA) model. Dissertation Abstracts International," Procedia - Soc. Behav. Sci., 1999.
51. H. J. Shi et al., "Clinical Characteristics and Risk Factors for Mortality in Critical COVID-19 Patients Aged 50 Years or Younger During Omicron Wave in Korea: Comparison With Patients Older Than 50 Years of Age," J. Korean Med. Sci., 2023, doi: 10.3346/jkms.2023.38.e217.
52. F. G.E.-H., "Defining the target level for vitamin D," Endocr. Abstr., 2010.
53. B. Dawson-Hughes, "Calcium and vitamin d," in The Bone and Mineral Manual, 2005. doi: 10.1016/B978-012088569-5/50020-6.
54. W. Z. Mostafa and R. A. Hegazy, "Vitamin D and the skin: Focus on a complex relationship: A review," Journal of Advanced Research. 2013. doi: 10.1016/j.jare.2014.01.011.
55. R. L. Peters, S. Mavoa, and J. J. Koplin, "An Overview of Environmental Risk Factors for Food Allergy," International Journal of Environmental Research and Public Health. 2022. doi: 10.3390/ijerph19020722.
56. K. L. Milan et al., "Vitamin D resistant genes - promising therapeutic targets of chronic diseases," Food and Function. 2022. doi: 10.1039/d2fo00822j.
57. S. Lee et al., "Programmatic approaches to screening for active tuberculosis," Int. J. Tuberc. Lung Dis., 2018.
58. M. Cortese et al., "Timing of use of cod liver oil, a vitamin D source, and multiple sclerosis risk: The EnvIMS study," Mult. Scler., 2015, doi: 10.1177/1352458515578770.
59. B. Brodziak-Dopierała, A. Fischer, M. Chrzanowska, and B. Ahnert, "Mercury Exposure from the Consumption of Dietary Supplements Containing Vegetable, Cod Liver, and Shark Liver Oils," Int. J. Environ. Res. Public Health, 2023, doi: 10.3390/ijerph20032129.
60. W. I. Atlas et al., "Indigenous Systems of Management for Culturally and Ecologically Resilient Pacific Salmon (Oncorhynchus spp.) Fisheries," Bioscience, 2021, doi: 10.1093/biosci/biaa144.
61. J. Xie, Z. Bian, Q. Wu, L. Tao, F. Wu, and T. Lin, "Global knowledge domain and prospects in tuna research: A bibliometric analysis," Aquac. Fish., 2023, doi: 10.1016/j.aaf.2021.09.005.
62. F. Zhao, R. Li, Y. Liu, and H. Chen, "Perspectives on lecithin from egg yolk: Extraction, physicochemical properties, modification, and applications," Frontiers in Nutrition. 2023. doi: 10.3389/fnut.2022.1082671.
63. Y. Osuka et al., "Effects of aerobic and resistance training combined with fortified milk on muscle mass, muscle strength, and physical performance in older adults: A randomized controlled trial," J. Nutr. Heal. Aging, 2017, doi: 10.1007/s12603-016-0864-1.
64. R. W. Mwangi, J. M. Macharia, I. N. Wagara, and R. L. Bence, "The antioxidant potential of different edible and medicinal mushrooms," Biomedicine and Pharmacotherapy. 2022. doi: 10.1016/j.biopha.2022.112621.
65. L. Bialy, T. Fenton, J. Shulhan-Kilroy, D. W. Johnson, D. A. Mcneil, and L. Hartling, "Vitamin D supplementation to improve pregnancy and perinatal outcomes: an overview of 42 systematic reviews," BMJ Open. 2020. doi: 10.1136/bmjopen-2019-032626.
66. C. Clifopoulos, "Vitamin D: An overview," Mediterr. J. Rheumatol., 2017, doi: 10.31138/mjr.28.4.206.
67. H. F. DeLuca, "Overview of general physiologic features and functions of vitamin D.," The American journal of clinical nutrition. 2004. doi: 10.1093/ajcn/80.6.1689s.
68. A. Muñoz and W. B. Grant, "Vitamin D and Cancer: An Historical Overview of the Epidemiology and Mechanisms," Nutrients. 2022. doi: 10.3390/nu14071448.
69. S. Pilz et al., "The role of vitamin D in fertility and during pregnancy and lactation: A review of clinical data," International Journal of Environmental Research and Public Health. 2018. doi: 10.3390/ijerph15102241.
70. W. Asare-Doku, C. James, J. L. Rich, K. Amponsah-Tawiah, and B. Kelly, "'Mental health is

not our core business': A qualitative study of mental health supports in the Ghanaian mining industry," Saf. Sci., 2022, doi: 10.1016/j.ssci.2021.105484.
71. "Heart Foundation," Hear. Lung Circ., 2022, doi: 10.1016/s1443-9506(22)00064-6.
72. F. Vernia, M. Valvano, S. Longo, N. Cesaro, A. Viscido, and G. Latella, "Vitamin D in Inflammatory Bowel Diseases. Mechanisms of Action and Therapeutic Implications," Nutrients, 2022, doi: 10.3390/nu14020269.
73. N. Charoenngam, A. Jaroenlapnopparat, S. K. Mettler, and A. Grover, "Genetic Variations of the Vitamin D Metabolic Pathway and COVID-19 Susceptibility and Severity: Current Understanding and Existing Evidence," Biomedicines. 2023. doi: 10.3390/biomedicines11020400.
74. D. D. Bikle, "Vitamin D metabolism, mechanism of action, and clinical applications," Chemistry and Biology. 2014. doi: 10.1016/j.chembiol.2013.12.016.
75. P. Weidemüller, M. Kholmatov, E. Petsalaki, and J. B. Zaugg, "Transcription factors: Bridge between cell signaling and gene regulation," Proteomics. 2021. doi: 10.1002/pmic.202000034.
76. G. Voltan, M. Cannito, M. Ferrarese, F. Ceccato, and V. Camozzi, "Vitamin D: An Overview of Gene Regulation, Ranging from Metabolism to Genomic Effects," Genes. 2023. doi: 10.3390/genes14091691.
77. D. I. Fitriana, ANALISIS KANDUNGAN VITAMIN C, ZAT BESI, DAN KALSIUM PADA BUBUR BAYI HOMEMADE YANG BEREDAR DI KABUPATEN TULUNGAGUNG SEBAGAI MAKANAN
78. PENDAMPING ASI. 2021.
79. R. Kamata, F. Shiraishi, and K. Nakamura, "Avian eggshell thinning caused by transovarian exposure to o,p′-DDT: Changes in histology and calcium-binding protein production in the oviduct uterus," Journal of Toxicological Sciences. 2020. doi: 10.2131/jts.45.131.
80. T. Ono, M. Hayashi, F. Sasaki, and T. Nakashima, "RANKL biology: Bone metabolism, the immune system, and beyond," Inflammation and Regeneration. 2020. doi: 10.1186/s41232-019-0111-3.
81. B. B. Ho and C. Bergwitz, "FGF23 signalling and physiology," Journal of molecular endocrinology. 2021. doi: 10.1530/JME-20-0178.
82. S. Mia, A. Warnecke, X. M. Zhang, V. Malmström, and R. A. Harris, "An optimized protocol for human M2 macrophages using M-CSF and IL-4/IL-10/TGF-β yields a dominant immunosuppressive phenotype," Scand. J. Immunol., 2014, doi: 10.1111/sji.12162.
83. D. Vergara, W. H. Catherino, G. Trojano, and A. Tinelli, "Vitamin D: Mechanism of action and biological effects in uterine fibroids," Nutrients. 2021. doi: 10.3390/nu13020597.
84. E. Kotake-Nara, S. Komba, and M. Hase, "Uptake of Vitamins D2, D3, D4, D5, D6, and D7 solubilized in mixed micelles by human intestinal cells, Caco-2, an enhancing effect of lysophosphatidylcholine on the cellular uptake and estimation of Vitamins D' biological activities," Nutrients, 2021, doi: 10.3390/nu13041126.
85. J. Blaine, M. Chonchol, and M. Levi, "Renal control of calcium, phosphate, and magnesium homeostasis," Clin. J. Am. Soc. Nephrol., 2015, doi: 10.2215/CJN.09750913.
86. N. Yeşilyurt, B. Yılmaz, D. Ağagündüz, and R. Capasso, "Involvement of Probiotics and Postbiotics in the Immune System Modulation," Biologics, 2021, doi: 10.3390/biologics1020006.
87. D. Grimm et al., "The effects of microgravity on differentiation and cell growth in stem cells and cancer stem cells," Stem Cells Translational Medicine. 2020. doi: 10.1002/sctm.20-0084.
88. B. Hu et al., "Epigenetic Activation of WNT5A Drives Glioblastoma Stem Cell Differentiation and Invasive Growth," Cell, 2016, doi: 10.1016/j.cell.2016.10.039.
89. A. Halim, Q. Luo, Y. Ju, and G. Song, "A mini review focused on the recent applications of graphene oxide in stem cell growth and differentiation," Nanomaterials. 2018. doi: 10.3390/nano8090736.
90. S. W. Chang and H. C. Lee, "Vitamin D and health - The missing vitamin in humans," Pediatrics and Neonatology. 2019. doi: 10.1016/j.pedneo.2019.04.007.
91. M. Fusaro et al., "Vitamin K and osteoporosis," Nutrients. 2020. doi: 10.3390/nu12123625.
92. A. C. Carr and S. Maggini, "Vitamin C and immune function," Nutrients. 2017. doi: 10.3390/nu9111211.
93. G. Y. Lee and S. N. Han, "The role of vitamin E in immunity," Nutrients. 2018. doi: 10.3390/nu10111614.
94. K. Woolf, N. L. Hahn, M. M. Christensen, A. Carlson-Phillips, and C. M. Hansen, "Nutrition assessment of B-vitamins in highly active and sedentary women," Nutrients, 2017, doi: 10.3390/nu9040329.
95. J. Song, J. She, D. Chen, and F. Pan, "Latest research advances on magnesium and magnesium alloys worldwide," Journal of Magnesium and Alloys. 2020. doi: 10.1016/j.jma.2020.02.003.
96. A. J. Van Ballegooijen, S. Pilz, A. Tomaschitz, M. R. Grübler, and N. Verheyen, "The Synergistic Interplay between Vitamins D and K for Bone and Cardiovascular Health: A Narrative Review," International Journal of Endocrinology. 2017. doi: 10.1155/2017/7454376.
97. V. Singh, S. Jain, S. Prakash, and M. Thakur, "Studies on the synergistic Interplay of Vitamin D and K for Improving Bone and Cardiovascular Health," Curr. Res. Nutr. Food Sci., 2022, doi: 10.12944/CRNFSJ.10.3.3.
98. M. S. Calvo and C. J. Lamberg-Allardt, "Vitamin D research and public health nutrition: A current perspective," Public Health Nutrition. 2017. doi: 10.1017/S1368980017001835.
99. J. Jakobsen, A. Melse-Boonstra, and M. Rychlik, "Challenges to Quantify Total Vitamin Activity: How to Combine the Contribution of Diverse Vitamers?," Curr. Dev. Nutr., 2019, doi: 10.1093/cdn/nzz086.