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Vitamin D intake and status in Ireland: a narrative review

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Vitamin D is crucial for musculoskeletal health, with evidence suggesting non-skeletal benefits. Cutaneous vitamin D synthesis is limited in Ireland due to its northern latitude (52–55°N) and the population is dependent on dietary sources, yet intakes are inadequate. No study to-date has comprehensively examined vitamin D intakes and status in Ireland (Northern Ireland and the Republic). We aimed to review the evidence since 2010 and summarise the results in subgroups of the Irish population. We found that in the largest studies prevalence of deficiency [25-hydroxyvitamin D (25(OH)D) < 30 nM/l] was 15–17 % in pregnancy, 15–23 % in children and 13 % in adults. Approximately half the population had 25(OH)D < 50 nM/l. There were only four small studies in an ethnic population with the largest in Southeast Asians finding that 67 % were deficient. All studies found higher rates of deficiency and levels <50 nM/l in winter *v.* summer. Vitamin D intake was lowest in children (mean 2·3–4·2 μg/d) and pregnant women (mean 1·9–5·1 μg/d) and highest in older adults (6·9 μg/d), with over 90 % of the population not meeting the recommended daily allowance. This review indicates that low vitamin D status and dietary vitamin D intake are widespread with children, adolescents, younger adults, pregnant women and ethnic minorities most at-risk. However, data are sparse in at-risk groups including the Travelling community, non-Europeans and institutionalised adults. Given the significant prevalence of deficiency, public health policies to promote better awareness of recommended vitamin D intakes and explore the options of food fortification are needed to address this issue.

Vitamin D: Ireland: Childhood: Adults: Ageing

Vitamin D is crucial for musculoskeletal health, being required for the adequate absorption of calcium from the gastrointestinal tract. Vitamin D is a secosteroid synthesised via the action of UVB light on the skin, forming cholecalciferol (vitamin D_3) (Fig. 1)[1]. While this is the predominant physiological source of vitamin D, it can also be obtained from the diet in animal and plant foods (ergocalciferol or vitamin D_2) and from fortified foods[2,3]. Its role in bone health is well established[4], with deficiency increasing the risk of rickets in childhood

Abbreviations: 25(OH)D, 25-hydroxyvitamin D; EU, European Union; TILDA, The Irish longitudinal study on ageing.
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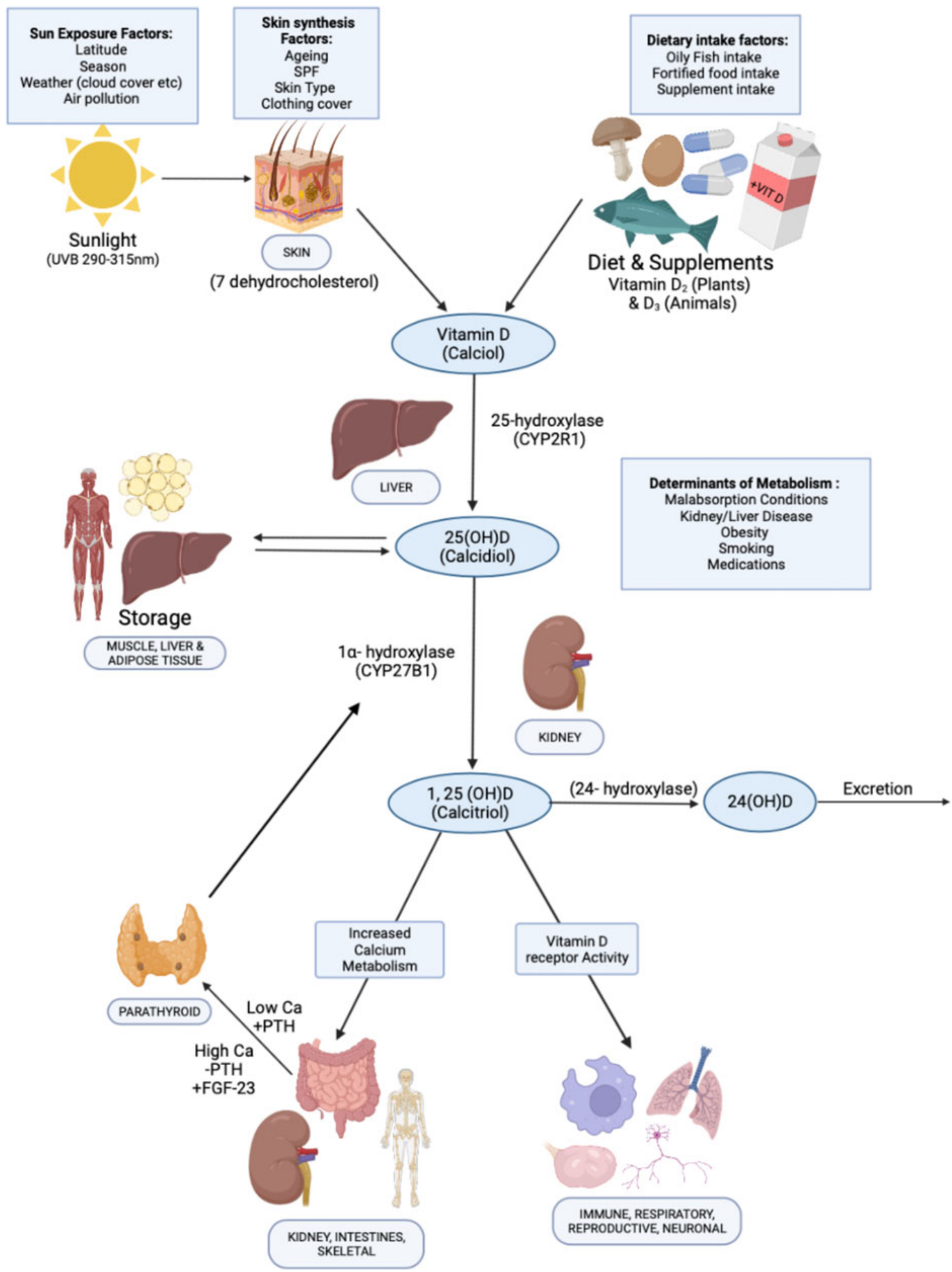

Fig. 1. Vitamin D metabolism. 25(OH)D, 25-hydroxyvitamin D; Ca, calcium; FGF-23, fibroblast growth factor 23; PTH, parathyroid hormone; SPF, sun protection factor.

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and osteomalacia in adults[1]. Secondary hyperparathyroidism due to vitamin D deficiency can result in musculoskeletal pains and muscle weakness[5]. Peak bone mass, which may determine up to 60 % of osteoporosis risk in later life can only be achieved with sufficient vitamin D and calcium intake[1]. The role of vitamin D may also extend beyond bone health. For example, vitamin D receptors are found in numerous cells including immunological (T- and B-cells), osteoblasts, β cells and mononuclear cells, and in many organs such as the brain, heart, reproductive and the gut[6]. Interaction of transcription factors [1,25-hydroxyvitamin D_2 (1,25(OH)D_2)] with the vitamin D receptors modulates gene expression, influencing numerous physiological functions including anti-cancer, immunological and anti-inflammatory effects[7,8]. Thus, it may be involved in the pathogenesis of hypertension, stroke and CVD and may also play a role in immunity, autoimmune diseases, type I and II diabetes, multiple sclerosis, cancer, depression and dementia[6,8–12]. While plausible physiological mechanisms exist for these potential extra-skeletal effects, evidence from robust randomised controlled trials is limited and causality has not been established[4,6]. However, maintaining adequate vitamin D status (>50 nM/l) has been associated with decrease in all-cause mortality in a recent large prospective cohort study[13].

Vitamin D status is determined by a number of intrinsic, environmental and lifestyle factors. Biosynthesis of vitamin D from UVB sunlight (290–315 nm) is dependent on the correct latitude, and for countries above 40°N such as Ireland (52–55°N) this is negligible between October and March[3,14]. Cloud cover, time of day, altitude and air pollution can also affect production and give rise to regional variations in status[15]. Factors including age, skin type, sunscreen use and clothing cover also determines dermal synthesis[16]. Finally, the absorption and bioavailability of vitamin D is affected by malabsorption conditions (e.g. Crohn's/coeliac disease), medication, smoking and obesity[3,17].

As a result of limited sun exposure, the Irish population is dependent on dietary sources of vitamin D, though intakes remain low, and most do not meet the RDA[18]. The RDA as set by the Food Safety Authority of Ireland varies by age as shown in Fig. 2[19–22]. In addition, the proportion at risk of deficiency is rising due to demographic and other changes[20]. For example, the population is ageing, with the proportion over 65 years set to double by 2050[23] and there has also been an increase in those of 'non-white' ethnicity[24]. Levels of overweight and obesity are also on the rise, increasing from 55 and 19 % in 2006 to 61 and 25 %, respectively, in 2016[23]. While there are relatively few cases of rickets, the number reported has increased with twenty-three cases recently described in two Dublin hospitals[20]. For these reasons, knowledge of both trends and current vitamin D status and intake is important in several subgroups of the population.

There is no universal agreement on definitions of deficiency and sufficiency by professional bodies (Table 1). Vitamin D > 125 nM/l is suspected by the National Academy of Medicine as being harmful to health with potential negative effects on falls, depression and possibly other outcomes including cancer and all-cause mortality in some studies[25–27]. However, the National Academy of Medicine takes a precautionary approach that also factors in ethnic/genetic differences so as to maximise public health protection[27]. Despite this, overt vitamin D toxicity causing hypercalcaemia is rare and usually occurs at levels above 375 nM/l[4,28].

Due to the limited half-life of the biologically active 1,25(OH)D (4–6 h) and its tight feedback control, vitamin D status is assessed by monitoring concentrations of 25(OH)D (half-life 3–4 weeks) which is under no feedback regulation[29]. There are several types of vitamin D analytical techniques, with varying sensitivities and specifications[30]. These include binding assays; RIA, chemiluminescence immunoassay, protein-binding assay, and bioanalytical assays such as HPLC and liquid chromatography tandem mass-spectrometry (LC-MS/MS). Binding assays are relatively quick and inexpensive but are subject to interference from other vitamin D metabolites and may overestimate 25-hydroxyvitamin D [25 (OH)D] concentration[29]. HPLC and LC-MS/MS allows for the quantification of a large number of samples, but require more technical skill[30]. LC-MS/MS is now considered the gold standard of vitamin D assessment and

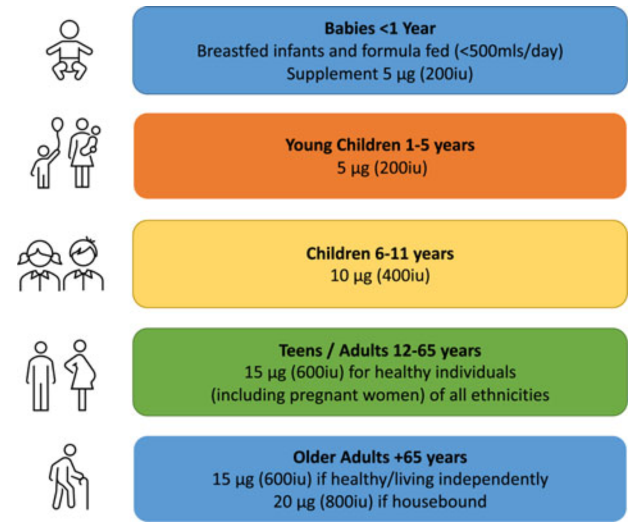

Fig. 2. Irish vitamin D supplement recommendations by age group.

Table 1. Serum 25-hydroxyvitamin D recommendations

Report	Location	Deficiency	Sufficiency
IOM 2011 Report[25]	USA	<30 nM/l	>50 nM/l
Endocrine Society Guidelines 2011[204]	USA	<50 nM/l	>75 nM/l
Nordic Nutritional Recommendations Report 2012[205]	Nordic countries		>50 nM/l
SACN 2016 Report[4]	UK	<25 nM/l	
EFSA 2016 Report[206]	EU		>50 nM/l

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allows for the measurement of both 25(OH)D_2 and 25(OH)D_3[29]. The vitamin D standardisation programme and vitamin D external quality assessment scheme were developed to improve the accuracy and repeatability of vitamin D assessments[31,32]. Vitamin D intake is typically assessed with FFQ that include 24-h re-calls and 3–7-d food diaries. Weighed food diaries are most commonly utilised in Irish national nutrition surveys and calculate vitamin D intake using nutrient composition databases[33].

To date, no study has comprehensively reviewed vitamin D research with regards to vitamin D status and intakes on the island of Ireland. We aim to summarise the peer-reviewed studies and official reports published since 2010 or earlier for specific sub-groups where no other data was available. For the purpose of this review, we defined deficiency as <30 nM/l and excess as >125 nM/l unless otherwise stated[25].

Vitamin D status and intake by population categories

Pregnancy and fertility

The largest Irish study (*n* 1768) in pregnant women found a prevalence of deficiency of 17 %[34], which was similar to other large studies where it ranged between 15 and 17 %[35,36]. In other studies, it varied between 13 and 65 % but sample sizes were small and were not likely to be representative[37–40]. In general, deficiency was less prevalent in early pregnancy (13–29 %)[34,36–38,41–47] with rates increasing with gestation in most studies[41,42,45,47]. A high proportion of mothers (25–65 %) were also found to be deficient at delivery[39,40]. As expected, a seasonal variation in vitamin D deficiency in pregnancy was found[34,38,43,45,48–50], with the lowest prevalence of 3–7 % detected in summer/autumn[34,38].

The prevalence of levels <50 nM/l in the largest studies were between 42 and 44 %[34–36], while in smaller studies variance was pronounced (44–91 %)[38,40]. A seasonal effect was also evident, with prevalence generally higher in winter *v.* summer[34,38,45,48]. Prevalence of levels below <50 nM/l is similar to some pregnancy studies in Northern Europe where it affected approximately 50 % in the UK[51] and Belgium[52]. Only one Irish study (*n* 138) looked at men and women undergoing fertility treatments and found that one out of five was deficient[53].

Dietary and supplement intakes in pregnancy. Dietary intakes in pregnant women ranged between 1·9 and 10·7 μg/d[46,54], with 80–99 % not meeting the recommendations[54–56]. By comparison, in the UK, 98–100 % were found not to meeting the advised intake of 10 μg/d[57]. In Ireland the RDA in pregnancy is no different from the general adult population at 15 μg/d[22]. However, evidence suggests that pregnant women require 20 μg/d to meet sufficiency (>50 nM/l)[58] with 10–15 μg/d advised by a European consortium[59]. In Finland, the 2003 food fortification of liquid milk resulted in a significant increase in vitamin D intakes in pregnant women[60], and as such should be considered as a public health measure to improve vitamin D status in Ireland.

Nearly 40 % of pregnant Irish women reported taking a specific vitamin D supplement in a Dublin study (*n* 175) in 2016, though the sample was from a confined area[61]. However, when including a multivitamin containing vitamin D, 74·3 % were actually taking some form of supplementary vitamin D[61]. Importantly, less supplement use in pregnancy has been associated with an increased risk of low vitamin D status in Irish infants[49]. Supplementation in Irish pregnant women was also the strongest predictor of 25(OH)D > 30 nM/l with Caucasian females more likely to supplement than those of other ethnicities[37].

Children/adolescents

In the largest study to date (*n* 5524), 15 % of children (5–19 years) were deficient[62], while the second largest (*n* 1226) found a deficiency rate of 23 %[63], though both were conducted in the Dublin area. In most studies deficiency prevalence varied between 5 and 23 %[62–68]. The most recent nationally representative study that measured vitamin D levels in teenagers (aged 13-18 years) found that 21.7 % were deficient though sample size was small (*n*=246)[69]. The highest prevalence of deficiency (63–68 %) was reported in adolescents (aged 12 or 15 years) in Northern Ireland[70]. However, vitamin D was assessed over 20 years ago, was not checked in the months of July or August and the study population was derived after stratified sampling so may not be more broadly representative. Furthermore, the results are discordant with other studies. As expected, the prevalence of deficiency was lower in the summer[66,71,72] and higher in winter when it affected 18–30 % of teens[71,72], and 26 % of children aged 1–17[63]. In general, female children also had lower vitamin D status[63,65,70,73,74], but not in all studies[64].

Notably, there was a ‘U-shaped’ relationship between deficiency prevalence and age, being lower in younger children (1–12 years) and greatest in adolescents and older children (>12 years)[62,63,65]. For example, a recent large study found a greater prevalence of deficiency in over *v.* under 12s (24 *v.* 16 %)[63]. Lower rates of deficiency (2 %) have been found in toddlers (aged 2 years) and children under 5 (13 %)[64,66], with higher 25(OH)D also reported in those under *v.* over 4 years (61·0 *v.* 46·1 nM/l, $P < 0·001$)[65]. Similarly, in a recent large study, deficiency was lower (5 %) in toddlers (1–4 years) but much higher (15·4 %) in older children (5–19 years)[62]. Better vitamin D status in younger children (<5 years) may relate to Ireland’s infant supplementation policy[75]. Conversely, lower rates of supplements and fortified food consumption has also been found in Irish teens compared to younger children[76]. One study also reported that older teens (15–18 years) had lower mean 25(OH)D and were more likely to be deficient than younger teens (13–15 years)[69]. Greater screen time/sedentary behaviour and increased obesity rates in this age group may be important factors[77–79]. Socioeconomic status may also explain some of this variation as it has been associated

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with a higher prevalence of deficiency in Irish children[63]. Overall, reports are broadly consistent with findings in northern European countries (47–69°N)[80–83] and in the UK 19 % of 11–18-year-olds were deficient, compared to just 2 % of those aged 4–10[84].

Despite in general, less deficiency in younger children, this was not apparent for those aged <1 year. For example, deficiency in new-borns was high ranging from 34 to 63 % (based on cord blood samples)[35,39,42,49] while in preterm infants 64 % were deficient at delivery[40].

Overall, approximately half of children aged 1–17 years had levels <50 nM/l[62,63,65,68,69], with a seasonal variation identified[63,66,73], similar to findings in the European Union (EU)[75,80–85]. Similar to deficiency, prevalence was lower in younger children (1–5 years), at 21–39 %[62,64,66], and higher in teens at 36–89 % as in UK studies[81]. The prevalence of 25(OH)D < 50 nM/l in new-born cord blood was particularly high (between 80 and 92 %)[35,39,42,49], and similar (79–92 %) in preterm and term infants[35,40,42,44,49].

Dietary and supplement intakes in children. The first nationally representative dietary survey in 2010/2011 in Irish children aged 12–59 months found that 70–84 % had intakes <5 μg/d (mean of 3·2 μg/d)[86]. In a small study (*n* 97) of 5-year-olds in 2019, intake remained low with just 6·2 % having consuming above 5 μg/d[64]. Recent nationally representative surveys of older children (5–12 years) and teens (13–17 years) found the majority (94 %) had intakes <10 μg/d, with little improvement between 2003/2004 and 2017/2018[78,87,88]. In fact, comparing surveys, intakes had improved only a little, from 2·7 to 3·7 μg/d for teens and from 2·3 to 4·2 μg/d for children[87,89–91]. Similarly, in a recent nationally representative study of teenagers (aged 13-18) median intake was 2.9 μg/d[69].

In Irish infants, milk/formula comprised of 29 % of total intakes[86], similar to that in UK children aged 12–18 months[92]. Milk/products were also the greatest source of vitamin D in children <4 years in Ireland followed by meat and its products as found in the UK[86,92]. However, in Irish children aged 5–12 years, fortified cereals were the largest contributor, followed by meat and then milk products[87] as also identified in Belgium and the UK[81,93]. Meat and its products also account for the primary source of vitamin D in Irish children over 13[78,94], despite its relatively low content. This is also reflected in the UK, where it comprised of 35 % of dietary vitamin D intake[4].

Children aged 1–5 years in Ireland are recommended to receive 5 μg/d, supplementing if necessary, with older children (aged 6-11 years) advised to consume 10 μg/d[20,22]. Overall, supplements are an important contributor to vitamin D status in children and adolescents in Ireland[65,95], as found elsewhere in Europe[96–98]. The most recent national dietary survey (2017/2018) of Irish children aged 5–12 years indicated that just 10 % consume a vitamin D supplement[87] which compares to 17 % in a representative sample (aged 1–4 years)[95]. Supplement use has also been found to decrease with age, with 21 % of 5–8, 16 % of 9–12 and 15 % of 13–17-year-olds consuming a vitamin D containing supplement[65,66,76,95]. Similar findings have been reported in the UK, with higher supplementation rates in younger children (14–16 %) compared to teens (5–6 %)[57]. Indeed, since the introduction of an infant supplementation policy in Ireland, initiation of a 5 μg/d supplement from birth increased to 92 %, with 30 % of parents compliant during the first year[99]. In one study, supplement use was reported in 23 % of Irish children (aged 1–17) attending hospital though this could be due to underlying medical reasons[65].

Adults (<50 years)

The largest study (*n* 63 290) revealed that 13 % of Irish adults (<50 years) were deficient between 2020 and 2021[62]. In a nationally representative study, deficiency affected 7 % whereas it was much more common (38 %) in hospital-based inpatients with COVID[18,100]. Deficiency was also more prevalent in younger adults and in winter[101–103]. In Dublin (53°N), between 25 and 30 % were deficient[104,105], though there was a lower prevalence of 10–11 % (<25 nM/l) at a similar latitude in the west of Ireland[106]. In Coleraine (55°N, Northern Ireland) there was a wide variation in deficiency (2–23 %) and in two studies it affected only 0–2 %, though sample sizes in all were small (*n* < 100)[72,107–109]. Overall, deficiency in Ireland appears similar to other European countries[4,59,81,110–112].

Despite not generally being considered an 'at-risk' group, studies indicate that deficiency is more prevalent in younger *v.* older adults (>50 years)[62,100–104,113]. For example, 18 % of younger adults (aged 18–39) *v.* 15 % (aged 40–49) were deficient[101,114]. In addition, urban dwelling younger adults had higher levels of deficiency (<25 nM/l) than rural ones[113]. This nadir in younger adults has also been reported in Romania[115], Canada[116], the USA[117] and Brazil[118]. Lack of sunshine exposure due to time spent indoors in a working environment and reduced dietary and supplementary intakes of vitamin D may be factors[18,94,119].

Levels <50 nM/l were found in more than half of adults living in Dublin[104,105] and 44 % in those living in the West[106]. In several locations across Ireland, a similar prevalence (40–55 %) was also identified[18,120]. In younger Irish adults (aged 18–39) nearly half (45 %) had levels <50 nM/l[101,114] and up to 58 % had <50 nM/l in winter[72,101–103], with this proportion being higher in Cork[72] and Dublin[101–103]. Indeed, studies showed higher rates of deficiency and levels <50 nM/l in winter in Irish adults aged under 50[101,102,113] consistent with findings in the UK[4]. By comparison, in the EU, 34–64 % of adults under 65 had 25(OH)D < 50 nM/l[81,111,121,122].

In general, Irish females had higher 25(OH)D than males[62,101,102,106,113,114] though are twice as likely to consume a supplement and are more likely to be taking vitamin D which might explain this[18,123,124]. Large global meta-analyses have also found that females had a borderline increased vitamin D status compared to males[125,126].

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Older adults

Vitamin D deficiency is prevalent in older Irish adults (>50 years) and in large studies ranged between 11 and 13 %[62,101,127]. In the largest nationally representative TILDA study (The Irish longitudinal study on ageing) of 5356 older adults, 13 % were deficient, similar to the findings of an EU meta-analysis[9,81]. In the large Trinity, Ulster, Department of Agriculture cohort study, prevalence of deficiency ranged from 13·8 and 27·3 % in older unsupplemented adults, and up to 43·6 % in those who were frail and cognitively impaired[128]. However, participants were in disease-defined cohorts, included hospital outpatients and were not representative of the wider population. As expected, deficiency was more prevalent during winter[71,72,127,129].

Regional variation in the prevalence of deficiency has been found in the nationally representative TILDA study where it was lower in Leinster compared to other provinces, likely reflecting in part variances in UVB exposure[127]. However, prevalence rates have also varied within the same areas with widely varying deficiency rates of 11–86 % in Dublin[101,130], 2–17 % in Cork[72], 10–42 % in Galway and 14–35 % in Northern Ireland[9,131]. Socioeconomic factors may play a role as suggested by the TILDA study and one large investigation in the Dublin and surrounding areas[114,132]. Urban residing older adults also had increased rates of deficiency[113], in keeping with UK findings[133], as did community dwelling older adults and nursing home residents[113] where it ranged between 35 and 42 %[114,131]. Hospital in-patients also had lower vitamin D status than those in primary care[62]. Similarly, non-community dwelling adults had lower vitamin D status in the UK[134] and in Europe at similar latitudes[135–137]. This is likely due to reduced physical activity, lack of sun exposure and poor adherence to supplementation[137,138].

In recent studies of Irish adults (>50 years), between 30 and 50 % had levels <50 nM/l, which was more prevalent in those living in northern locations and urban areas[101,114,127]. Similar findings were reported in the UK English longitudinal study of ageing and in other EU countries where it ranged from 50 to 59 %[59,81,133,139]. Seasonal decline in status was also greater with increasing age, with levels <50 nM/l in winter occurring in 64 % (aged 70–75) *v.* 34 % (aged 51–69) in 2006[72]. This was replicated by the TILDA study in 2018 which found 43 % with <50 nM/l, with higher rates in the winter in those aged 70+ *v.* 50+[127,140]. Despite a reduced capacity for dermal synthesis, UVB light and sun enjoyment were still identified as an important contributor to vitamin D status in older Irish adults[15].

Dietary and supplement intakes in adults. The most recent (2011) dietary survey in adults found that vitamin D intake in Ireland was 6·9 μg/d in older adults (>65 years), and 4·3 μg/d in those aged 18–64 years[94]. The majority (90 %) of adults aged 18–64 had intakes <10 μg/d, as did 87 % of men and 77 % of women over 65 years[94]. This indicates little improvement since the first dietary survey in 1997/1999. In fact, overall mean intake of vitamin D then was 3·4 μg/d[141,142] while 74 % of 18–64-year-olds had intakes <5 μg/d[143] and 93 % had <10 μg/d[144]. Lowest intakes were identified in younger adults (18–35 years) (mean 2·8 μg) compared to those aged 36–50 years (mean 3·4 μg) or 51–64 years (mean 5·8 μg) in 2001[141]. Recent findings are similar to those reported in the UK, Germany, Denmark, and the Netherlands though higher than that in Portugal, Spain and Italy[59]. By comparison, dietary intakes have been found to be higher in northern European countries such as Iceland, Norway, Sweden and Finland[59,145].

Meat, fish and supplements were the greatest contributors of vitamin D in the diet of Irish adults[18] similar to some EU countries such as the Netherlands. However, in countries such as France and Spain, fish and eggs are the primary and secondary sources[110,146,147]. Overall, fortified cereal/products found to contribute to 10 % of intake in the Irish diet[148], compared to 13–20 % in the UK[4].

Adolescents and adults (12–65 years) are recommended to consume 15 μg of vitamin D daily, with older adults (>65 years) who are housebound with little access to sunlight advised to take 20 μg/d[19,22]. However, only 10–17 % of Irish adults were found to be taking vitamin D supplements[18,103,140], but received more of their intake this way than from dietary sources[18,123]. In a recent (2019) TILDA report, just over 10 % of over 70s reported consuming a vitamin D supplement[140]. Supplement use was also a predictor of vitamin D status in adults[18,109,120] and older adults[15,127,128,139,140]. In fact, supplement use has been found to be the strongest determinant of vitamin D status in the Trinity, Ulster, Department of Agriculture[128] and TILDA[140] cohorts of older adults, with a mean increase of 21·4–35·4 nM/l detected[128]. Supplementation was also found to increase with age[18,143], with its contribution to dietary intake nearly twice as high in older adults aged 50+ (17 %) *v.* younger adults (9 %)[18]. This has been confirmed elsewhere[149], with higher rates in older adults (24–32 %) in the UK[57]. Supplements relating to bone health (calcium with/without vitamin D) are the most consumed in older adults[124]. Irish women are more likely to take supplements than men[15,123,124,127], where they contributed more to total vitamin D intake[143] as also found in the UK[150].

At-risk populations

Ethnic populations. The largest study to focus on an ethnic population discovered that more than two-thirds (67 %) of Southeast Asians were vitamin D deficient, but only included 186 patients who lived in the Dublin area[151]. There were only three other studies that reported vitamin D status in those of non-white ethnicity, with small sample sizes and the largest only having eighty-one adults[34,37,65]. Non-white pregnant women had greater deficiency (59–88 %) compared to Caucasians (36 %)[37], while another study identified a 19 nM/l difference in mean 25(OH)D between white and non-white pregnant women[34]. Mean 25(OH)D was also lowest in children of African ethnicity living in Ireland[65]. Ethnic minorities living in northern

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locations are known to be at increased risk of low vitamin D status due to reduced cutaneous synthesis[59,110]. By comparison, in the UK, 96 % of Southeast Asian women had levels <50 nM/l in winter and had lower serum 25(OH)D compared to white women[152]. Similarly, non-European populations, particularly pregnant women, living in Europe were at greater risk compared to their indigenous counterparts[153–156]. Despite recommendations by the European Calcified Tissue Society, there are currently no specific guidelines for higher vitamin D intake in ethnic populations in Ireland[59].

Medical conditions. Malabsorption disorders: There were five studies of adults with Crohn's disease[157–161] though sample sizes were small ($n < 100$). Prevalence of levels <50 nM/l were 50–64 %[157,158,160] in keeping with a global meta-analysis where half had levels <50 nM/l[162]. A strong seasonal effect was also found, with about 20 % having levels <50 nM/l post-summer *v.* 50 % post-winter[159,161] and with up to 90 % with levels <80 nM/l[158]. Furthermore, wintertime levels <50 nM/l were twice as common (50 %) compared to healthy controls (25 %)[159]. Crohn's patients in Ireland who had bowel surgery were also three times more likely to have levels <50 nM/l compared to non-Caucasians[163]. Comparatively in the UK, 66 % of adults with Crohn's disease had levels <50 nM/l, with significantly lower status in the winter[163]. The vast majority (88 %) of Irish patients with refractory coeliac disease had levels <50 nM/l, as did those with a recent diagnoses (58 %) compared to patients with controlled disease[164].

Other disorders. In Irish patients with multiple sclerosis, significantly greater deficiency (<25 nM/l) was found compared to age-/sex-matched controls (28·3 *v.* 19·2 %)[165]. Mean 25(OH)D levels were also higher in areas with a lower prevalence of multiple sclerosis[165]. Nearly two-thirds (65 %) of patients with systemic lupus erythematosus had levels <75 nM/l after the summer in one 2008 study[166]. In psoriasis patients, 75 % were found to have wintertime levels <50 nM/l[167] and, in individuals attending a rheumatology clinic 26 % were vitamin D deficient (<25 nM/l) and 70 % had levels <53 nM/l[168]. Deficiency prevalence was 41 % in patients with total knee arthroplasty (41 %)[169].

In adults with chronic obstructive pulmonary disease, vitamin D status was low (<50 nM/l) in 47 %, particularly in winter (75 %) and in house-bound patients[170]. In patients with obstructive sleep apnoea, 72–89 % had levels <50 nM/l, and 98 % had <75 nM/l[171,172]. This is similar to the findings of a global meta-analysis, which identified that disease severity was associated with lower vitamin D status[173]. Prevalence of levels <50 nM/l was also high in renal patients (69 %)[174] and those who had thyroidectomy (75 %)[175]. Between 35 and 50 % of Irish asthmatic children had vitamin D levels <50 nM/l[176,177], in keeping with a recent global meta-analysis[178]. Up to 40 % of children with autism had levels <50 nM/l and 75 % had <75 nM/l[176,179], consistent with a meta-analysis in 2016 that attributed lower status to factors such as increased dietary restriction and lack of time outdoors[180].

Vitamin D excess

The most recent and largest (n 100 505) cross-sectional study of adults in 2022 found a prevalence of 25(OH) D > 125 nM/l of 1·7–2·3 % though included patients mainly in the Dublin area[62]. It also identified that excess levels were higher during *v.* before the COVID pandemic (2·1 *v.* 1·7 %, $P < 0{\cdot}001$) which could be due to increased dosage of new-to-market vitamin D supplements[62]. Previously, it was estimated that up to 5 % of the Irish adults in the population may be at-risk of levels >125 nM/l, with apparent increases between 1994 and 2013[104,105]. However, most studies have found a prevalence of vitamin D excess of between <1 and 3 %[18,53,101,105,113,151]. Importantly though, all of these studies are subject to significant bias as they include patients who had their vitamin D checked by request of their doctor. Higher levels of excess has been identified in Irish females (4 %) and older adults (4 %)[101] as found elsewhere[181,182]. This is likely due to females being twice as likely to use supplements, especially those over 50[123,124]. A particularly high prevalence of excess of 9 % was identified in Irish pregnant women in a randomised controlled trial though they were supplemented with up to 20 μg/d of vitamin D[38]. Vitamin D toxicity (25(OH)D level of 1617 nM/l) resulting in severe hypercalcaemia was also reported in one patient, though was explained by high-dose supplementation (250 μg/d for 2 years)[183]. Conversely, lower levels of excess (0·3–0·9 %) has been identified in nursing homes, hospital outpatient clinics, in ethnic minorities and in pregnant women[34,35,113,114,151], groups that are already at greater risk of deficiency. In the largest study of children aged over 4 (n 5524) prevalence of vitamin D excess was 0·5 % but was in higher in toddlers (4·6 %) and infants (12·1 %)[62]. A similar prevalence (0·4–0·6 %) has been found in children (>4 years) in other studies[63,66] or has not been detected at all[35].

Vitamin D status over time

There have only been two studies that have specifically examined changes in vitamin D status over time. In one that included individuals (n 43 782) in the Dublin area over 20 years (1993–2013) an average increase in 25(OH)D of 0·68 nM/l per year was estimated[184]. However, it is possible that the reason for testing may have changed over time and it did not account for potential variation in factors affecting vitamin D. More recently when comparing annual change in vitamin D status prior to *v.* during the pandemic, a 3-fold increase was noticed with a higher annual rise of 2·8 nM/l. This result however, may not be generalisable as it was based on vitamin D results from a Dublin hospital, though was attributed to a greater availability of high-dose supplements and increased public awareness[62]. While vitamin D status may have increased, particularly in some sections of the population, nearly all of the most recent studies still identify a significant of level of deficiency and levels <50 nM/l[62,101,113,140].

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Discussion

This is the first review of vitamin D status in Ireland and identifies that deficiency is commonly affecting 15–23 % of children, 13 % of adults and 15–17 % of pregnant women in the largest and most recent (<5 years) studies[34–36,62–64,66–68,127]. Deficiency was more prevalent in adolescents *v.* younger children (1–12 years), and in younger (<50 years) *v.* older adults (>50 years). There was also a particularly high prevalence in infants (<1 year) and it was also more common with increasing gestation in pregnancy. A very high rate of deficiency (67 %) was identified in Southeast Asians, though other studies of non-white ethnicity are sparse. Similarly, those with medical conditions had increased prevalence of vitamin D inadequacy, with more than half of those with respiratory conditions and the majority of those with malabsorption conditions having levels <50 nM/l.

The seasonal variation of vitamin D status was also evident with higher levels of deficiency and prevalence of levels <50 nM/l in winter. The overall prevalence of deficiency remains significant though there is some evidence to suggest a small increase in 25(OH)D levels in the past decade particularly during the COVID pandemic. The lowest vitamin D intakes were found in children (2·3 µg/d)[95] and pregnant women (1·9 µg/d)[55], with the highest (6·9 µg/d) in older adults[94]. This review indicates that low vitamin D status is widespread in the population among several groups who also have inadequate vitamin D intake.

Implications for public health

Fortification/supplementation

Guidelines for vitamin D intake in those aged 12-65 years, including at-risk groups such as pregnant women, adolescents and dark skinned ethnicities, were recently published by the FSAI and advise 15 µg/d[22]. These were based on minimising the risk of deficiency and were similar to a previously calculated 12 µg/d to avoid deficiency in most of the population[185]. However preventing winter deficiency in 97·5 % of individuals of South Asian and Black ethnicity at Irelands' latitude may require an even higher respective daily intake of 27·3 µg (1092 IU) and 33·2 µg (1328 IU). Furthermore, the guidelines do not cover a proportion of the population who have levels between 30–50 nm/l and may still be at risk of vitamin D inadequacy. For example, an intake of 25–28 µg/d may be needed to maintain wintertime sufficiency in the Irish population (>50 nM/l)[186,187] though achieving this via diet alone is not possible, so supplementation and a multi-food fortification strategy may be necessary.

Currently, fortified foods provide 11 % of total dietary vitamin D intake in adults, where they have the potential to reduce inadequacy[188]. In Irish children age 1–4 years, fortifying cow's milk and a 5 µg/d supplement in modelling studies were estimated to reduce inadequate intakes (<10 µg/d) from 95 to 12–36 %[189]. However, this would be insufficient for meeting the European Food Safety Authority (EFSA) adequate intake level (15 µg/d)[190]. Fortification of milk and bread was reported as having the potential to ensure that 70 % of older Irish adults (>50 years) meet a daily allowance of 10 µg/d[191]. In older adults, an association has been found between fortified milk and better vitamin D status[128]. Fortifying food staples such as milk and bio-enriched eggs was also estimated to reduce the wintertime decline in serum vitamin D Irish adults[192,193]. However, in a modelling study, numerous food items would need fortification to ensure vitamin D (>50 nM/l) all year around in Irish adults[194]. A more novel way using 'biofortification of foods' with vitamin D via feed modification and UV radiation in Ireland has shown potential, particularly enriched meat and could be further explored[195].

In 2003, mandatory fortification of butter/spreads and milk products in Finland enabled 91 % of the population to reach sufficiency by 2011[196], a public health measure that could be considered in Ireland. Nonetheless, some groups of the population consume less fortified foods and are less likely to benefit[197]. Exploring a multi-food system fortification approach that includes bread as well as dairy products could be considered to target a wider population[110]. Hence, care is required to ensure that excessive vitamin D consumption is avoided[198] as a small percentage of the population consuming high-dose supplements could be at risk of vitamin D toxicity[105,184]. Reassuringly, a national monitoring survey in Finland after food fortification concluded that levels above 125 nM/l were rare, though ongoing surveillance was advised[199]. Given the higher prevalence of vitamin D levels >125 nM/l recently reported in Ireland and the increased proportion of new-to-market supplements above the tolerable upper-intake level, monitoring would seem prudent[62]. Additionally, a code of practice for food business to control the level of fortification and limit its addition to designated food vehicles would be useful[200].

We acknowledge there are a number of factors that may result in a variation in vitamin D status between studies. Some were small in size, were in different geographical locations, included non-representative populations (e.g. clinical or hospital outpatient setting) and used different vitamin D assays. There is also likely to be differences in supplementation rates and other factors affecting vitamin D status between studies. While some nationally representative studies were small, the review includes several very large and recent studies.

Future research

There are limited studies of vitamin D status in non-white ethnic individuals that now comprise 5 % of the Irish population[24]. Additionally, there are no studies in minority groups such as Irish Travellers and institutionalised younger adults, all of which are groups where research is required. Furthermore, in light of low vitamin D intakes in the homeless population and nearly 9000 people in emergency accommodation in Ireland, attention could also be focused here[201,202]. Finally, meat is the primary source of dietary vitamin D in Irish adults

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though nearly one in five are vegetarian or vegan and are at-risk of deficiency, though no studies have specifically examined their vitamin D status[203].

Conclusions

Prevalence of vitamin D deficiency in Ireland was 15–17 % in pregnancy, 15–23 % in children and 13 % in adults and remains high despite some increase after the pandemic. Those at increased risk include infants (below 1 year), adolescents (12–18 years), adults (<50 years), those in the third trimester of pregnancy and non-white minorities. There is limited data in institutionalised adults, the Travelling community and those of non-European ethnicity. Given the prevalence of widespread deficiency, an updated public health policy to increase vitamin D intake, including a vitamin D awareness campaign and the careful fortification of key food groups frequently consumed by the population may be required.

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Conflict of Interest

None.

Authorship

Conceptualisation: E. L., J. B. W. and K. McC.; formal analysis: H. S.; funding acquisition: E. L., J. B. W. and K. McC.; investigation: H. S.; methodology: H. S.; project administration: H. S.; supervision: K. McC. and E. L.; writing – original draft: H. S.; writing – review and editing: H. S., E. L., M. H., J. B. W. and K. McC. All authors have read and agreed to the published version of the manuscript.

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