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Published in:
Clinical Nutrition

DOI:
10.1016/j.clnu.2020.11.035

Publication date:
2021

Document version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Bakaloudi, D. R., Halloran, A., Rippin, H. L., Oikonomidou, A. C., Dardavesis, T. I., Williams, J., Wickramasinghe, K., Breda, J., & Chourdakis, M. (2021). Intake and adequacy of the vegan diet. A systematic review of the evidence. *Clinical Nutrition*, *40*(5), 3503-3521. https://doi.org/10.1016/j.clnu.2020.11.035

Clinical Nutrition 40 (2021) 3503–3521

Contents lists available at ScienceDirect

Clinical Nutrition

journal homepage: http://www.elsevier.com/locate/clnu

Original article

Intake and adequacy of the vegan diet. A systematic review of the evidence

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ARTICLE INFO

Article history:
Received 2 June 2020
Accepted 28 November 2020

Keywords:
Vegan diets
Veganism
WHO
European population
Health impact

ABSTRACT

Background: Vegan diets, where animal- and all their by-products are excluded from the diet, have gained popularity, especially in the last decade. However, the evaluation of this type of diet has not been well addressed in the scientific literature. This study aimed to investigate the adequacy of vegan diets in European populations and of their macro- and micronutrient intakes compared to World Health Organization recommendations.
Methods: A systematic search in PubMed, Web of Science, IBSS, Cochrane library and Google Scholar was conducted and 48 studies (12 cohorts and 36 cross-sectional) were included.
Results: Regarding macronutrients, vegan diets are lower in protein intake compared with all other diet types. Veganism is also associated with low intake of vitamins B_2, Niacin (B_3), B_{12}, D, iodine, zinc, calcium, potassium, selenium. Vitamin B_{12} intake among vegans is significantly lower (0.24–0.49 μg, recommendations are 2.4 μg) and calcium intake in the majority of vegans was below recommendations (750 mg/d). No significant differences in fat intake were observed. Vegan diets are not related to deficiencies in vitamins A, B_1, B_6, C, E, iron, phosphorus, magnesium, copper and folate and have a low glycemic load.
Conclusions: Following a vegan diet may result in deficiencies in micronutrients (vitamin B_{12}, zinc, calcium and selenium) which should not be disregarded. However, low micro- and macronutrient intakes are not always associated with health impairments. Individuals who consume a vegan diet should be aware of the risk of potential dietary deficiencies.

1. Introduction

Vegetarianism in any of its different forms has become popular in recent years. The main difference between the various forms of vegetarianism is the exclusion of specific food categories from the diet. These forms include vegans, who have the strictest dietary exclusions, omitting any animal-source foods and their by-products from the diet. Other categories of vegetarians include lacto-vegetarians (excluding meat, fish and eggs, but consuming dairy products), ovo-vegetarians (excluding meat, fish and dairy products, but consuming eggs), lacto-ovo-vegetarians (excluding meat and fish, but consuming eggs and dairy products) and pescatarians (restricting their meat consumption to fish and seafood only) [1,2].

The focus of this review is on vegans, who, especially in high-income countries, comprise a growing proportion of the total population. Veganism has increased in popularity and exposure across the Western world and in millennials have been suggested as an important driver of the trend [3,4]. The prevalence of vegans in Europe has been estimated to be between 1 and 10% [5]; however,

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https://doi.org/10.1016/j.clnu.2020.11.035
0261-5614/

Clinical Nutrition 40 (2021) 3503–3521

Abbreviations:

AA	Amino Acids
BMI	Body Mass Index
CVD	Cardiovascular Diseases
DMT2	Diabetes Mellitus Type 2
DRI	Dietary Reference Intake
eGFR	Estimated Glomerular Filtration Rate
FAO	Food and Agriculture Organization
GI	Glycemic Index
Hg	Mercury
IBS	Irritable Bowel Syndrome
MUFA	Monounsaturated Fatty Acids
n-3	Omega 3
n-6	Omega 6
NAFLD	Non-Alcoholic Fatty Liver Disease
NNR	Nordic Nutrition Recommendations
NCD	Non-Communicable Diseases
PDCAAS	Protein Digestibility–Corrected Amino Acid Score
PTH	Parathyroid Hormone
PUFA	Polyunsaturated Fatty Acids
RAE	Retinol Activity Equivalents
RCT	Randomized Control Trial
RE	Retinol Equivalents
RNI	Reference Nutrient Intake
SFA	Saturated Fatty Acids
TEI	Total Energy Intake
WHO	World Health Organization

the exact number is not clear and varies among countries [6]. The vegan diet is mainly associated with religious and ethical beliefs, environmental concerns, cultural and social values, as well as potential health benefits [7,8].

Several studies have shown the beneficial effects of a vegan diet on human health due to the higher daily consumption of fresh fruits, vegetables, cereal grains [9], nuts, legumes and seeds [10] suggesting that vegan individuals have healthier lifestyle behaviors, compared to individuals following different types of diet [5]. Such health benefits have been suggested to include, among others, a lower incidence of non-communicable diseases (NCD), such as colon cancer, type 2 diabetes mellitus (DMT2), as well as obesity, non-alcoholic fatty liver disease (NAFDL) and cardiovascular diseases (CVD) [11,12].

On the other hand, less is known about whether any negative health implications could result from nutrient deficiencies arising from a vegan diet. Studies suggest that subjects following this type of diet are more likely to show deficiencies in macro-as well as micronutrients and there is debate on whether a vegan diet should be supplemented with various nutrients, including iron, zinc, iodine, selenium, calcium, long-chain n-3-fatty acids, vitamin B_{12}, vitamin D and vitamin B_2 [5,9].

There is insufficient information about the diversity of vegan diets, whether they are balanced and whether they adequately provide all necessary nutrients. A recent report by the EAT-Lancet Commission, stated that dietary patterns based on vegetables, fruits, vegetables, legumes, nuts and whole grains could be beneficial but further information about following a strict vegan diet is missing [13]. In almost all countries national food based dietary guidelines include meat and dairy as well as the other food groups [14].

This systematic review aims to investigate the intake and adequacy of the vegan diet in terms of macro- and micronutrient intakes in adult European populations and to evaluate whether this type of diet can be characterized as acceptable in providing all necessary nutrients for human health according to the WHO recommended nutrient intakes. This information will support development of guidelines and inform public health policy makers about the latest evidence related to different dietary scenarios.

2. Materials and methods

An electronic search was conducted in PubMed and modified accordingly to Web of Science, IBSS and the Cochrane Library. Google Scholar was used to search grey literature. Subject index terms included “vegan”, “vegan diet”, “Europe”, “European population”, “adults” and the final search builder was (((vegan diet OR vegan OR veganism) AND (Europe OR European population)) AND (adults)) (see Supplementary File 1). The populations of interest were non-supplement consuming vegans in Europe and the comparison was any control diet, such as omnivores, vegetarians, semi-vegetarians.

The searches identified 126 studies from PubMed library, nine from Web of Science, nine from the Cochrane library, 2086 from IBSS ProQuest and 319 from Google Scholar. In total 2549 studies were characterized as acceptable, including cross-sectional, randomized control trials (RCTs) and cohort studies. After removing duplicates, 48 studies included were eligible for our systematic review, as seen in Fig. 1.

Primary outcomes were the adequate intake of energy, macronutrients and micronutrients in vegan diets and secondary outcomes were the risk of deficiencies and the impact of veganism on health and on Body Mass Index (BMI). Results were evaluated and compared to the WHO recommended nutrient intakes (Table 1) [15–22].

This systematic review was performed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (Supplementary Table 1). The quality of the eligible studies was evaluated using a version of the Newcastle–Ottawa quality assessment scale for case–control and cohort studies and the modified Newcastle Ottawa scale for cross sectional studies (Supplementary Table 2). The protocol of our systematic review was submitted inPROSPERO library (CRD42020181979). Characteristics of the 48 included studies are shown in Table 2.

3. Results

The overall sample included in this study consists of 12,096 vegans. Among them, the main socioeconomic characteristics do not vary significantly between vegans and non-vegans. Between 5 and 30% of vegans are highly educated (i.e. Bachelor, Master, PhD) [23–25] and the majority have never been employed or are manual workers with low incomes [5,10]. Some included studies find vegans to be younger and more physically active [6,10,26] and are more likely to be single or have families without children, while meat-eaters are more likely to be part of families with multiple children [5,10,25–27].

The assessment quality of the 48 included studies (with no RCTs) was conducted using the Newcastle–Ottawa scale (Supplementary Table 2). According to this rating system only four included studies are characterized as “satisfactory” [12,28–30] whereas 36 included studies evaluated as “good” [5,6,9–11,24–27,31–56] and eight as “very good” [23,57–63].

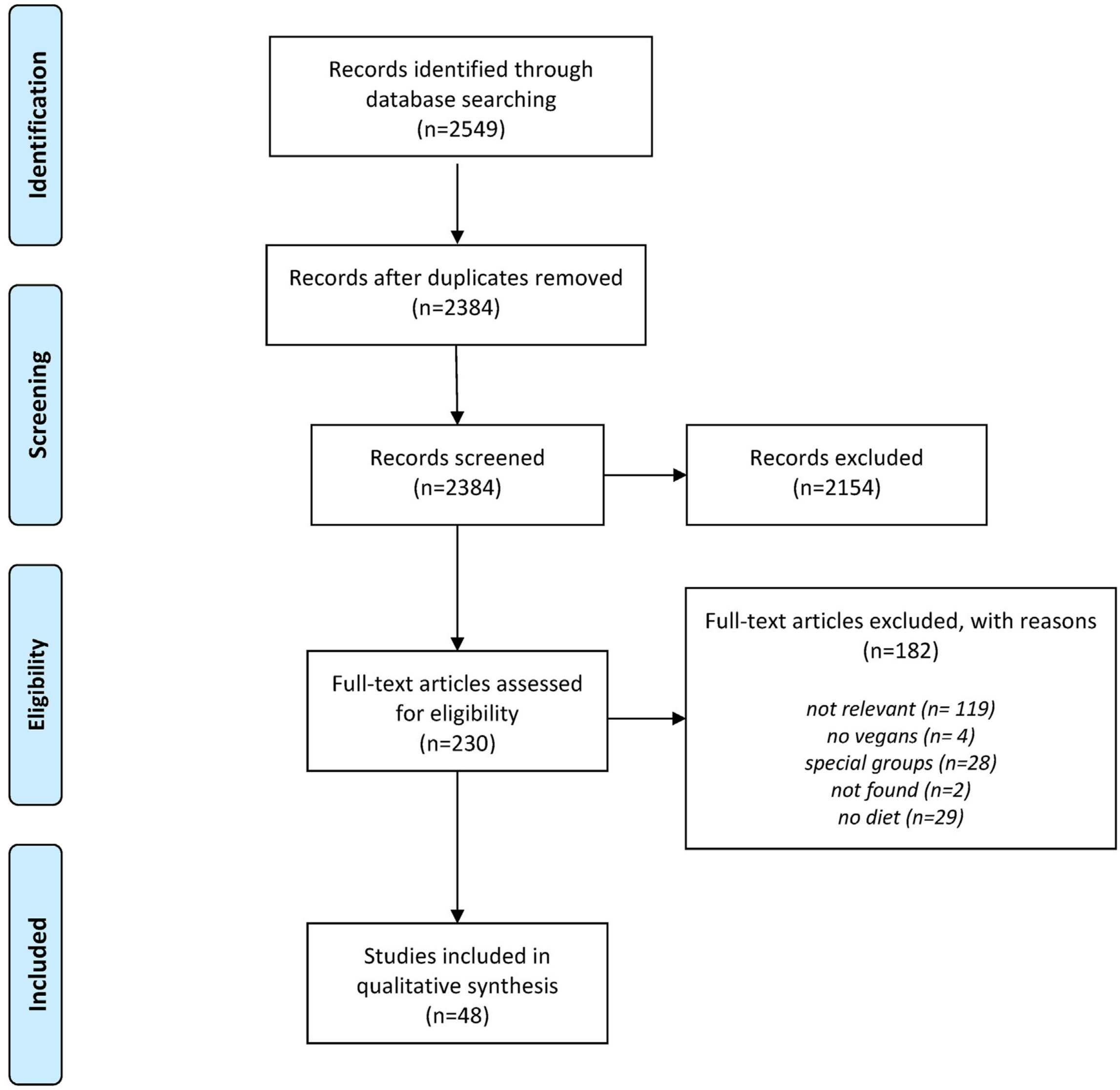

Fig. 1. PRISMA flow diagram of study selection process.

3.1. Energy intake

Energy intake was examined in 26 studies with a total of 11.024 participants [5,6,10,12,25–28,30–32,35,38,39,41,46–48,50,51,53,57–59,62,64]. In the majority of studies, a vegan diet was characterized by the lowest total energy intake (TEI), as can be observed in Table 3, followed by vegetarians [6,10,25–28,32,38,47,48,50,57–59,62,64]. Only Alles et al. [5] reported a lower energy intake among vegetarians ($p < 0.001$), and Elorinne et al. [35] found that TEI among vegans and non-vegetarians did not differ ($p = 0.867$). Despite having a lower TEI, vegans met the recommended daily intake [41] with intakes ranging between 1672 and 2055 kcal/d (7.0–8.6 MJ/d) [12,27,30,31,51,53]. Carbohydrates and soy protein are the main energy sources for vegans [46]. According to the WHO/FAO 23–27 kcal/kg/d would be adequate for a healthy BMI maintenance (18.5–24.9 kg/m^2) for healthy and normally active individuals aged 18–60 and slightly lower for those above 60 years old (19–22 kcal/kg/d). However, energy requirements should be adapted for body weight, sex, age, physical activity and health status, and therefore can substantially differ between individuals [21].

3.2. Carbohydrates and fibers

Carbohydrate consumption was examined by 23 studies with a total of 9.441 participants [5,6,10,12,25–28,30–32,35,38,41,46–48,50,53,58,59,62,64]. A vegan diet was characterized by a high consumption of carbohydrates [6,49] (Table 3). Furthermore, fiber intake was higher in vegans than in omnivorous subjects [5,26,50,58,59]. In various studies [6,10,25–28,31,35,38,46–48,50,53,60,62], over 50% of TEI derived from carbohydrates and fibers for vegans of both sexes, whereas in other studies TEI from carbohydrates was close to 50% in non-vegans, but lower than among vegans. The WHO recommendations report that a healthy diet includes a daily intake of 400 g fruits and/or vegetables combined [20]. The highest consumption of fruits, vegetables and cereals was found in vegans and the daily fiber intake was more than 30 g/

Table 1
WHO daily dietary recommendations.

Recommendations					
Total Energy Intake[a]			23–27 kcal/kg for 18–60 years old[h] 19–22 kcal/kg for >60 years old[h]		
Carbohydrates and fibers[b]			At least 400 g (i.e. five portions) of fruit and vegetables per day *(excluding potatoes, sweet potatoes, cassava and other starchy roots)*		
Fats[b]			Less than 30% of total energy intake from fats. Saturated fats: <10% of total energy Trans-fats: <1% Replacing both saturated fats and trans-fats with unsaturated fats		
Proteins[c]			15% of total energy intake 0.66 g/kg average requirement for healthy adults 0.75 g/kg for elderly		
Vitamin A[d]			F: 19–65 years: 500μg/>65 years: 600 μg M: 19–65 years: 600μg/>65 years: 600 μg		
Vitamin B_1[d]			F: 1.1 mg M: 1.2 mg		
Vitamin B_2[d]			F: 1.1 mg M: 1.3 mg		
Vitamin B_3[d]			F: 14 mg NEs M: 16 mg NEs		
Vitamin B_6[d]			F: 18–50 years: 1.0 mg/>51 years: 1.5 mg M: 18–50 years: 1.3 mg/>51 years: 1.7 mg		
Vitamin B_{12}[d]			18–65 years: 2.4 μg >65 years: 2.4 μg		
Vitamin C[d]			45 mg		
Vitamin D[d]			19–50 years: 5 μg 51–65 years: 10 μg >65 years: 15 μg		
Vitamin E[d]			Data are not sufficient to formulate recommendations for vitamin E intake for different age groups except for infancy		
Iron[d]		Bioavailability 15%	Bioavailability 12%	Bioavailability 10%	Bioavailability 5%
	F (62 kg mean BW)	19.6 mg	24.5 mg	29.4 mg	58.8 mg
	Postmenopausal (62 kg mean BW)	7.5 mg	9.4 mg	11.3 mg	22.6 mg
	M (75 kg mean BW)	9.1 mg	11.4 mg	13.7 mg	27.4 mg
Zinc[d]		High Bioavailability	Moderate Bioavailability	Low Bioavailability	
	F	3.0 mg	4.9 mg	9.8 mg	
	M	4.2 mg	7.0 mg	14.0 mg	
Calcium[d]			F: 18-prior to menopause: 1000 mg/Postmenopausal: 1300 mg M: 18–65 years: 1000 mg/>65 years: 1300 mg		
Potassium[e]			At least 90 mmol (3510 mg)		
Sodium[f]			<2 g sodium (5 g salt)		
Iodine[d]			150 μg (2.0 μg/kg)		
Magnesium[d]			F: 18–65 years: 200 mg/>65 years: 190 mg M: 18–65 years: 260 mg/>65 years: 224 mg		
Selenium[d]			F: 18–65 years: 26 μg/>65 years: 25 μg M: 18–65 years: 34 μg/>65 years: 33 μg		
Copper[g]			12.5 μg/kg		
Folate[d]			400 μg		

F: Female; M: Male; NE: Niacin Equivalents; BW: Body weight.
[a] World Health Organization, Food and Agriculture Organization of the United Nations, United Nations University, Human energy requirements 2004.
[b] Geneva: World Health Organization; Fact Sheet No 394: Healthy Diet 2015.
[c] Food and Agriculture Organization of the United Nations, World Health Organization & United Nations University. Protein and amino acid requirements in human nutrition 2007.
[d] World Health Organization, Vitamin and mineral requirements in human nutrition 2005.
[e] World Health Organization, Guideline: potassium intake for adults and children 2012.
[f] World Health Organization, Guideline: sodium intake for adults and children 2012.
[g] World Health Organization, Trace elements in human nutrition and health 1996.
[h] Energy requirements should be adapted for body weight, sex, age, physical activity and health status.

d [5,9,35,41,53,59]. In Alles et al. study [5] mean daily fruit and vegetable intake in vegans was recorded 364.2 g and 366.0 g respectively and in Elorinne et al. study [35] mean daily consumption was 233 g for fruits and 277 g for vegetables. Individuals following a vegan diet consume brown rice, whole meal pasta and brown bread more often [58].

Conversely, a Danish study showed lower consumption of carbohydrates among vegan females ($p = 0.027$), whereas no differences were observed for vegan men in comparison to non-vegan men ($p = 0.63$) [41]. Another study found no significant differences between diet groups in absolute carbohydrate consumption, and stated that the % energy from carbohydrates rises as greater dietary restrictions are observed [59].

3.3. Fats

Fat consumption was examined by 27 studies of a total 10.003 participants [5,6,10,12,24–28,30,31,33,35,37,38,41,46–48,50,53,55,57–59,62,64]. TEI from fats (~30%) did not vary significantly between diet groups. In several studies [5,22,25,35,41,57,59], total fat

Table 2
Characteristics of the 48 included studies.

Identity	Type of study	Central measure of tendency	Year of assessment	Country	Control Group	Dietary survey method	Duration of diet (years)	Number of participants	F/M	BMI (kg/m^2)
Allen, 2000	cross-sectional	NA	1993–1997	UK	Meat-eaters	FFQs Blood test	NA	233	NA	22.7 (22.3–23.1)
Allen, 2002	cross-sectional	NA	1993–1999	UK	Meat-eaters Vegetarians	FFQs Blood test	NA	94	NA	22.0 (3.01)
Allen, 2008	cross-sectional	mean (SD)	1993–1999	UK	Meat-eaters Lacto-ovo vegetarians	FFQs Blood test	>1	46	46/0	21.7 (3.1)
Alles, 2017	cross-sectional	mean ± SEM	2009	France	Meat-eaters Vegetarians	FFQ	NA	789	595/194	NA
Appleby, 2002	cohort	mean	1993–1999	UK	Meat eaters Fish-eaters Vegetarians	FFQs Blood test	>1	739	467/272	F: 22.0 M: 22.6
Appleby, 2007	cohort	mean (SD)	1998–2004	UK	Meat eaters Fish-eaters Vegetarians	FFQs	>5	1126	62.2/37.8 (%)	F: 22.0 (3.1) M: 22.5 (2.9)
Bradbury, 2014	cross-sectional	mean (SD)	1993–1998	UK	Meat eaters Fish-eaters Vegetarians	FFQs	NA	422	255/167	F: 21.8 (2.9) M: 22.4 (3.2)
Bradbury, 2017	cohort	mean (SD)	2011–2012	UK	Regular Meat-Eaters Low Meat-Eaters Poultry-Eaters Fish-Eaters Vegetarians	FFQs	NA	248	146/102	F: 24.1 (4.9) M: 24.7 (3.3)
Brantsaeter, 2018	cross-sectional	median (P25, P75)	2014–2015	Norway	Lacto-ovo vegetarians	Urine test	NA	19	16/3	NA
Clarys, 2014	cross-sectional	mean	2012	Belgium	Omnivores Pesco-vegetarians Semi-vegetarians Vegetarians	FFQs	≥1	104	NA	<18.5: 9 18.5–25: 82 25.0–30: 11 >30: 2
Crowe, 2011	cross-sectional	mean (SD)	NA	UK	Meat-eaters Fish-eaters Vegetarians	FFQs Blood test	>1	89	61/39 (%)	22.3 (2.6)
Davey, 2003	cohort	mean (SD)	1993–1999	UK	Meat-eaters Fish-eaters Vegetarians	FFQs Blood test	F: 4 years M: 5 years	2596	1659/937	NA
Elorinne, 2016	cross-sectional	mean (SD)	NA	Finland	Non-vegetarians	FFQs Blood test Urine test	8.6 (2–16)	22	16/6	21.9 (18.1–25.7)
Fleury, 2017	cohort	mean (SD)	2009	France	No control	FFQs	NA	NA	NA	NA
Fokkema, 2000	cross-sectional	mean (SD)	1997–1998	The Netherlands	Omnivores	FFQs Blood test	≥2	12	4/8	F: 20.6 ±1.7 M: 20.6 ±2.3
Gallego-Narbon, 2019	cross-sectional	mean (SD)	NA	Spain	Lacto-ovo vegetarians	FFQs Blood test	NA	16	NA	NA
Gallego-Narbon, 2019	cross-sectional	mean (SD)	NA	Spain	Lacto-ovo vegetarians	FFQs	NA	55	43/12	F: 21.7 (2.5) M: 23.0 (2.5)
Gilsing, 2010	cross-sectional	mean (SD)	1994–1997	UK	Omnivores Vegetarians	FFQs Blood test	7	232	0/232	22.7 (3.1)
Hansen, 2018	cohort	mean (SD)	2013–2014	Denmark	Omnivores	Blood test	>1	78	NA	21 (2)
Krajcovicova-Kudlackova, 2000	cross-sectional	mean ± SEM	NA	Slovakia	Omnivores Vegetarians	FFQs Blood test	7.87 ± 0.41	32	22/10	21.39 ± 0.40

(continued on next page)

Table 2 (*continued*)

Identity	Type of study	Central measure of tendency	Year of assessment	Country	Control Group	Dietary survey method	Duration of diet (years)	Number of participants	F/M	BMI (kg/m^2)
Krajcovicova-Kudlackova, 2003	cross-sectional	mean ± SEM	NA	Slovakia	Mixed diet Vegetarians	FFQs Urine test	9.7 ± 0.9	15	6/9	21.8 ± 0.4
Kristensen, 2015	cross-sectional	median [IQR]	12.2013 –07.2014	Denmark	DANSDA[b]	Diary	>1	70	37/33	21.0 [19.8–22.2]
Lightowler, 2002	cross-sectional	mean (SD)	NA	UK	No control	Diary	F: 11.7 ± 12.2 M: 9.9 ± 4.0	26	15./11	F: 21.1 (2.9) M: 22 (3.0)
Mądry, 2012	cohort	mean ± SEM	NA	Poland	Vegan diet based on B_{12} fortified food	Blood test	5	10	7/3	21.2 ±0.3
Majchrzak, 2006	cross-sectional	mean (SD)	NA	Austria	Omnivores Vegetarians	Blood test Urine test	>5 y: 67% 1-5 y: 25–31% <1 y: 2–8%	42	21/21	21.8 (3.6)
Newby, 2005	cross-sectional	mean (SD)	1997	Sweden	Omnivores Semi-vegetarians Lacto-vegetarians	FFQs	NA	83	83/0	23.3 (3.8)
Outila, 2000	cohort	mean (SD)	1994–1995	Finland	Lacto-vegetarians Omnivores	FFQs Blood test Urine test	7 (2–16)	6	6/0	20 (3)
Papier, 2019	cohort	mean (SD)	2010	UK	Regular Meat-Eaters Low Meat-Eaters Poultry-Eaters Fish-Eaters Vegetarians	FFQs	NA	801	532/269	F: 22.1 (2.9) M: 22.8 (3.3)
Pinto, 2017	cross-sectional	mean (SD)	NA	UK	Omnivores	FFQs Blood test	≥2	23	15/8	23.5 (4.4)
Sebeková, 2001	cross-sectional	mean ± SEM	NA	Finland	Omnivores Semi-vegetarians Lacto-vegetarians	FFQs Blood test	7.2 ± 1.0	9	NA	20.6 ± 0.8
Salvador, 2019	cross-sectional	mean [IQR]	NA	Spain	Lacto-ovo vegetarians	FFQs Blood test	NA	55	43/12	21.50 [3.0]
Schmidt, 2013	cross-sectional	mean (SD)	1993–1999	UK	Meat-eaters Fish-eaters Vegetarians	FFQs Blood test	NA	422	255/167	F: 21.8 (3.0) M: 22.4 (3.2)
Schmidt, 2015	cross-sectional	median [IQR]	2011	UK	Meat-eaters Fish-eaters Vegetarians	FFQs Blood test	(several years)	96	0/96	22.1 [20.5, 23.8]
Schmidt, 2016	cross-sectional	median [IQR]	2013	UK	Meat-eaters Fish-eaters Vegetarian	FFQs Blood test	(several years)	98	0/98	22.1 [20.4, 24.0]
Schupbach, 2017	cross-sectional	mean (SD) median (min –max)	NA	Switzerland	Omnivores Lacto-ovo vegetarian	Blood test	9.5 (1.0–30.4)	53	60/40 (%)	21.6 ± 2.5
Selinger, 2019	cross-sectional	mean (SD)	2012–2019	Czech Republic	Omnivores	Blood test	Self-reported (for years)	151	73/78	22.6 (2.7)
Sobiecki, 2016	cohort	mean (SD)	2010	UK	Meat-eaters Fish-eaters Vegetarians	FFQs	NA	803	534/269	NA
Spencer, 2003	cohort	mean	1993–1999	UK	Meat-eaters Fish-eaters Vegetarians	FFQs	NA	1553	983/570	F: 21.75 M: 22.34
Strohle, 2011	cross-sectional	mean (SD)	1996	Germany	Moderate vegans	FFQs Urine test	≥1 year prior to the study	154	87/67	21.3 (2.54)
Thorogood, 1987	cohort	mean ± SEM	1984–1986	UK	Meat-eaters Fish-eaters Vegetarians	FFQs	NA	114	69/45	NA

Trefflich, 2020	cross-sectional	mean (SD)	2017	Germany	Omnivores	FFQs Blood test	4.8 (3.1–8.7)	36	18/18	70.1 (13.9)
Waldmann, 2003	cross-sectional	mean (min –max)	1996	Germany	Moderate vegans	FFQs Blood test	≥1 year prior to study	98	50/48	F: 20.5 (16.5–25.3) M: 22.2 (17.5–26.4) Total: 21.2 (17.3 –26.2)
Waldmann, 2004	cross-sectional	mean (SD)	1996	Germany	Moderate vegans	FFQs Blood test	5.23 (3.60)	50	50/0	20.4 (2)
Waldmann, 2004	cross-sectional	mean (SD)	1996	Germany	Vegans ≥50 years	FFQs Blood test	7.14 (6.69)	86	48.8/51.2 (%)	21.5 (2.66)
Waldmann, 2005[a]	cross-sectional	mean (SD)	1996	Germany	Moderate vegans	FFQs Blood test	7.70 (6.40)	98	51/49 (%)	21.3 (2.73)
Waldmann, 2005[c]	cross-sectional	mean (SD)	1996	Germany	No control	FFQs Blood test	Total: 6.47 (6.27) F: 5.78 (4.08) M: 7.33 (8.21)	104	58/46	Total: 21.5 (2.44) F: 21.2 (2.36) M: 21.8 (2.53)
Waldmann, 2006	cross-sectional	mean (SD)	1996	Germany	Moderate vegans	FFQs Blood test	7.94 (7.98)	60	48.3/51.7 (%)	21.6 (2.56)
Welch, 2010	cohort	mean (SD)	1993–1997	UK	Fish-eaters Meat-eaters Vegetarians	Diary Blood test	NA	28	16/12	F: 27.5 (5.4) M: 28.0 (4.8)

NA: No info available; F: Female; M: Male, FFQs: Food Frequency Questionnaires, UK: United Kingdom.
[a] Strict vegans.
[b] DANSDA: Danish National Survey of Dietary Habits and Physical Activity: age-range-matched group of individuals, excluded vegetarians and vegans.
[c] Strict and moderate vegans.

intake was the lowest in vegan diets (Table 3). Nevertheless, overall TEI from fats among vegans is in agreement with the WHO guidelines (<30% of TEI) [20]. However, significant differences were noticed in the consumption of fat subgroups (MUFA, PUFA, SFA) [6,26,27,37,47,50,53,59,62]. Intake of monounsaturated fatty acids (MUFA) and saturated fatty acids (SFA) was lower among vegans [5,10,26–28,31,35,41,47,57,58,62], with the main source of fat being polyunsaturated fatty acids (PUFA) [24,26,28,31,35,41,50,57–59,62]. Mean daily intake of SFA was 21 g among vegans, rising to 54 g for omnivores ($p < 0.001$) [59]. The mean consumption of PUFA n-3 and n-6 among vegans was 1.7 g/d and 15.0 g/d respectively [5].

3.4. Proteins

Protein intake was examined in 26 studies of a total 9.862 participants [5,6,10,12,25–28,30,31,35,38,39,41,46–48,50,51,53,57–59,62–64]. Total protein intake in vegan groups was the lowest compared to other diet groups (Table 3) [5,12,57]. TEI from protein was approximately 13–15% [5,26,27,31,48,53,57,59,62,63]. WHO recommends protein intake 15% of TEI, dependent on factors such as sex, age, activity, health condition etc. [15] Alles et al. [5], reported that in total 27.3% of the vegan population were below the acceptable range of protein intake. In addition, 64.5% of vegans met the recommended daily protein intake and in 8.1% of vegans' intake of protein was reported to be above the acceptable range. In the study by Waldmann et al. [12], the protein intake of 31.3% of vegan males and 41.4% of vegan females was below the recommended levels of 0.8 g/kg body weight/d. Similarly, Kristensen et al. [41] described that the daily protein intake among vegans was below the amounts stated in the Nordic Nutrition Recommendations (NNR) (64.7–129.4 g/d for males and 51.8–103.5 g/d for females). Specifically tyrosine and the other essential AA (lysine, methionine and tryptophan) show the lowest plasma concentrations in vegan diets compared to other diet types ($p < 0.001$) [48]. Glycine and alanine are the AAs with the highest plasma concentrations in vegan individuals [48].

3.5. Vitamin A

The findings vary between diet groups regarding their micronutrient intake. Vitamin and mineral intake in vegan diets are shown in Tables 4 and 5 respectively. Vitamin A intake was examined in 5 studies of a total 1.736 participants [5,9,35,41,50,53]. Many studies reported that animal-based products provide a superior form of vitamin A [5,10,35,50]. However, vegans had been classified as the group least prone to developing vitamin A deficiencies [5,50]. Total vitamin A concentration was expressed as a fraction of retinol and β-carotene, where individuals consuming high amounts of meat demonstrated the highest levels [50]. Depending on the type of fraction, Retinol Equivalents (RE) or Retinol Activity Equivalents (RAE) could be calculated [50]. In three studies [9,41,50], vegans were characterized by higher β-carotene intake when compared to the intake of other diets [54]. However, lower serum β-carotene in vegans compared to non-vegetarians was observed in another study ($p = 0.988$) [35]. According to the WHO, daily recommended intake of Vitamin A is reported as 500 μg for females between 19 and 65 years and 600 μg for 65+ years and 600 μg for males of all ages [16].

3.6. Vitamin B complex

Intake of Vitamin B complex was examined by 15 studies of a total 5.031 participants [5,9,10,12,35,38,40,41,43,44,50,51,54,65,66]. The intake among the different types of B vitamins showed

Table 3
Macronutrients, energy and alcohol intake in vegans.

Study	TEI (Kcal/d)	CHO (% E)	Dietary fiber (g/d)	Total F (% E)	SFA (% E)	MUFA (% E)	PUFA (% E)	Pr (% E)
Allen, 2000	1930.3 [1861−2002]	NA	NA	29.9 [29.1−30.7]	4.87 [4.55−5.2]	8.57 [8.22−8.92]	8.17 [7.85−8.5]	12.7 [12.4−13.0]
Allen, 2002	1772.6 (492.1)	53.8 (6.91)	NA	30.6 (7.08)	5.37 (2.01)	8.42 (3.13)	8.10 (2.95)	13.5 (2.04)
Allen, 2008	1782.2 (489.7)	52.7 (5.5)	NA	31.8 (6.3)	5.8 (2.2)	8.7 (2.9)	7.8 (2.7)	13.2 (2.0)
Alles, 2017	1877.3 (684.02)	235.7 ± 1.6[a]	34.1 ± 0.3[a]	72.7 ± 0.7[a]	NA	19.4 ± 0.4[a]	13.3 ± 0.1[a]	62.0 ± 0.8[a]
Appleby, 2002	F: 1701.7 M: 2128.3	F: 55.5 M: 54.7	NA	F: 28.7 M: 31.1	F: 5.2 M: 4.9	NA	F: 7.6 M: 7.8	F: 13.4 M: 12.8
Appleby, 2007	F: 1696.2 (525.5) M: 1911.2 (573.3)	NA	NA	NA	NA	NA	NA	NA
Bradbury, 2014	F: 1691.4 (559.0) M: 1911.2 (559.0)	F: 55 (7) M: 54 (7)	F: 26 (9) M: 27 (9)	F: 29 (7) M: 29 (7)	F: 7 (2) M: 6 (2)	F: 10 (3) M: 10 (3)	F: 10 (3) M: 10 (3)	F: 13 (2) M: 13 (2)
Bradbury, 2017	NA	NA	NA	NA	M: 6 (2) F: 7 (2)	NA	NA	NA
Clarys, 2014	2383 (804)	336 (106)[a]	41 (14)	68 (36)[a]	21 (11)[a]	19 (12)[a]	28 (17)[a]	14 (4) *82 (39)*[a]
Crowe, 2011	1767.8 (525.5)	55.0 (7.1)	NA	29.4 (6.8)	NA	NA	NA	12.8 (2.0)
Davey, 2003	F: 1665.1 (520.8) M: 8.01 (597.2)	F: 56.1 (7.77) M: 54.9 (7.74)	NA	M: 28.2 (7.14) F: 27.8 (7.40)	F: 5.11 (2.03) M: 4.99 (1.85)	NA	F: 7.20 (2.79) M: 7.53 (2.91)	F: 13.5 (2.30) M: 12.9 (2.16)
Elorinne, 2016	2150.1 (630.7) [1003.3−3201.2]	49.3 [32.7−60.3] 252 (67) [135−401]	41 (14) [14−4]	36.5 (7.2) [25.6−52.9] *88 ±37* [35−187][a]	8.6 (2.3) [4.6−13] *21(9)* [9−46][a]	13.7 (4.8) [5.1−26] *33(18)* [11−92][a]	26 (11) [8−41] 26 *(11)* [8−41][a]	13.7 (2.8) [10−20.2] *74 (30)* [28−152][a]
Fokkema, 2000	NA	NA	NA	F: 40.0 (4.8) M: 29.9 (10.9)	F: 13.3 (4.3) M: 9.5 (4.5)	F: 13.3 (2.9) M: 10.3 (4.7)	F: 11.3 (4.6) M: 8.1 (3.8)	NA
Gilsing, 2010	2030.6 (621.1)	53.4 (7.8)	NA	29.9 (7.4)	NA	NA	NA	12.7 (1.9)
Hansen. 2018[b]	2390.0 (669.2)	NA	NA	NA	NA	NA	NA	1.1 (0.3)
Kristensen, 2015[a]	F: 2066.2 [1814.2−2298.7] M: 2798.7 [2476.0−3334.1]	F: 221.7 [191−274] M: 331.9 [274−365]	M: 56 [44−75] F: 40 [33−46]	F: 65.1 [49−79] M: 86.7 [63−105]	F: 13 [10−17] M: 17 [11−22]	F: 22 [17−29] M: 26 [20−39]	F: 19 [15−25] M: 26 [18−35]	F: 59.1 [51−67] M: 75.5 [66−96]
Newby, 2005	1143.8 ± 39.9	62.7 ± 0.6	23.0 ± 0.5	23.0 ± 0.6	9.0 ± 0.3	8.1 ± 0.2	4.1 ± 0.1	12.4 ± 0.2 *23.0 ± 0.6*[a]
Papier, 2019	F: 1880 (519.5) M: 2132 (633.4)	F: 56.4 (7.1) M: 56.6 (8.2)	NA	F: 31.0 (6.3) M: 31.0 (7.4)	NA	NA	NA	F: 13.0 (1.7) M: 12.5 (1.8)
Pinto, 2017	1832.3 (661.7)	56.5 (11.6)	NA	30.9 (9.5)	6.3 (1.7)	11.6 [9.3−14.4]	10.5 [7.3−18.5]	13.3 (2.4)
Sebeková, 2001[a]	NA	399.0 ± 28.9	NA	NA	NA	NA	NA	64.5 ± 5.6
Salvador, 2019	NA	NA	NA	23.3 (10.9)	26.20 (3.87)	25.15 (5.10)	48.24 (6.26)	NA
Schmidt, 2013	F: 1691.2 (500.9) M: 1912.2 (559.0)	F: 58.9 (7.6) M: 57.4 (7.2)	NA	F: 29.0 (6.9) M: 29.4 (7.4)	NA	NA	NA	F: 13.3 (2.2) M: 12.8 (1.8)
Schmidt, 2015	1828.8 [1454.1. 2119.0]	55.60 [52.27. 60.56]	NA	30.40 [25.39. 34.30]	6.21 [5.12. 7.66]	10.07 [7.90. 11.79]	9.71 [7.63. 11.98]	12.64 [11.68. 13.90]
Schmidt, 2016	1828.8 [1455.7. 2134.7]	55.6 [52.1. 60.9]	NA	30.4 [25.2. 34.4]	NA	NA	NA	12.6 [11.6. 13.9]
Sobiecki, 2016	Total: 1942.3 F: 1879.0 (519.5) M: 2131.6 (633.3)	Total: 54.0 F: 53.9 (6.8) M: 52.3 (6.1)	Total: 28.9 M: 30.3 (9.5) F: 27.7 (8.9)	Total: 30.5 F: 30.5 (6.2) M: 30.4 (7.2)	Total: 6.9 F: 6.9 (1.6) M: 6.8 (1.8)	NA	Total: 10.3 F: 10.3 (2.5) M: 10.3 (3.1)	Total: 13.1 M: 13.6 (1.9) F: 13.2 (1.8) *Total: 0.99* *M: 0.95 (0.29)* *F: 0.99 (0.34)*[b]
Spencer, 2003	F: 1680.4 M: 1966.6	F: 56.1 M: 54.3	F: 26.5 M: 28.1	F: 27.9 M: 28.5	F: 5.1 M: 5.1	F: 7.8 M: 8.2	F: 7.2 M: 7.7	F: 13.4 M: 12.9
Strohle, 2011	1966.1 (661.7)	57.1 (7.48)	NA	29.7 (7.82)	NA	NA	NA	11.6 (2.07) *0.89 ± 32*[a]
Waldmann, 2003	Total: 2052.1 (470.6) F: 1727.2 (470.6) M: 2389.0 (757.3)	Total: 56.4 (7.74) F: 56.9 (7.56) M: 55.8 (7.95)	F: 41.3 (15.5) M: 66.2 (25.5)	Total: 30.3 (8.22) F: 29.2 (7.76) M: 31.4 (8.61)	NA	NA	NA	Total: 11.9 (2.11) F: 12.4 (2.01) M: 11.4 (2.10) *Total:0.94 (0.34)* *F: 0.94 (0.3)* *M:0.95 (0.37)*[b]
Waldmann, 2004	1720.1 (456.3)	NA	52.3 (15.6)	NA	NA	NA	NA	11.9 (1.67) 0.90 (0.31)[b]
Waldmann, 2005	2052.1 (709.5)	56.4 (7.74)	58.6 (22.2)	30.3 (8.22)	5.91 (1.66)	12.5 (5.50)	9.06 (3.48)	11.9 (2.11)
Waldmann, 2006	NA	NA	NA	NA	NA	NA	NA	

Table 3 (*continued*)

Study	TEI (Kcal/d)	CHO (% E)	Dietary fiber (g/d)	Total F (% E)	SFA (% E)	MUFA (% E)	PUFA (% E)	Pr (% E)
Welch, 2010[a]	NA	NA	NA	NA	NA	NA	F: 0.91 (0.67) M: 1.04 (0.71)	11.7 (2.09) *60.7(23.3)*[a] NA

CHO: Carbohydrates. E: energy; F: Fat; F: Female; M: Male; MUFA: Monounsaturated fatty acids; NA: no info available; Pr: Protein; PUFA: Polyunsaturated fatty acids; SFA: Saturated fatty acids; TEI: total Energy intake.
Variables displayed as: mean (SD); median [IQR]; mean ± SE.
No info for any Vitamin in the following studies: Brantsaeter (2018). Fleury (2017). Gallego-Narbon (2019). Krajcovicova-Kudlackova (2000). Krajcovicova-Kudlackova (2003). Lightowler (2002). Mardy (2012). Majchrzak (2006). Outila (2000). Schupbach (2017). Salvador (2019). Selinger (2019). Thorogood (1987). Trefflich (2020). Waldmann (2004). Waldmann (2005).

[a] g/day.
[b] g/kg BW/day.

discrepancies (Table 4). Vegans had the highest intake of vitamin B_1 [9,10,12,35,44,50] and B_6 [5,9,41,44,63] (vitamin B_1 RNI 1.1 mg/d for females and 1.2 mg/d for males and vitamin B_6 RNI 14 mg/d for females and 16 mg/d for males [16]). However, vegans had the lowest intake of vitamins B_2, Niacin, and B_{12} [9,10,12,35,41,44,50,53]. Davey et al. [10] reported that there was no significant difference in the intake of vitamins B_2, B_6 and Niacin among all diet groups. In particular, studies have shown that a vegan diet might be unable to supply the recommended levels of dietary intake of vitamins B_2, B_6 and Niacin [41,43,50]. According to Alles et al., inadequate serum levels of vitamins B_1, B_6, Niacin and B_{12} might appear frequently among vegans ($p^2 < 0.0001$) [5]. Waldmann et al. [63] stated that although vitamin B_6 intake in vegan diets was adequate, its concentration in blood samples was characterized as insufficient for a healthy diet due to the reduced bioavailability in plant-based foods and/or in cases that the individuals consumed high amount of cereals in their diet rather than fruits.

On average, vitamin B_{12} intake was reported to be 0–0.9 μg/d in vegans [9,10,12,35,44,50,53], which is well below the RNI of 2.4 μg/d [16]. Only in Alles et al. study adequate B_{12} intake was found (2.7 μg) [5]. Higher incidence of vitamin B_{12} deficiency in vegans is also stated by Sellinger et al. and Krajcovicova-Kudlackova et al. [40,66] The dietary intake of vitamin B_{12} was highly correlated with the serum vitamin B_{12} concentration [35]. To avoid vitamin B_{12} deficiency, in Gilsing et al. study, it was recommended that vegans supplement their diets with vitamins B_2 and B_{12} [38].

In another study, although serum vitamin B_{12} in vegans was within the normal range, it was lower than in omnivores ($p < 0.01$) and vegetarian ($p < 0.05$) [44]. On the other hand, a vegan diet seems to adequately supply vitamin B_1 and showed equal or higher concentration of this vitamin when compared to the rest of the groups [9]. Overall, the duration of adherence to a vegan diet has been suggested to be the key factor due to the fact that as adherence is prolonged, the incidence of inadequacies increases [51]. However, Selinger et al. state that supplementation of vitamin B_{12} has a greater impact on the concentration of this micronutrient than the duration of the diet [66].

3.7. Vitamin C

Vitamin C intake was examined in 10 studies of a total 5.111 participants [5,9,10,12,30,35,41,46,50,54]. It has been reported that vegans show high intake of vitamin C [9,10,41,46,50], (Table 4) or that vegans have lower risk of developing vitamin C deficiencies than other diet groups ($p^2 < 0.0001$) [5]. Notably, a study conducted on the German population by Strohle et al. [30] found that vegans consumed higher amounts of vitamin C than the German Nutrition Society DRI of 100 mg/d. This is higher than the WHO RNI of 45 mg/d [16].

3.8. Vitamin D

Vitamin D was examined in 11 studies with a total 4.703 participants [5,9,10,12,30,35,41,45,50,62,64]. According to several studies, following a vegan diet characterized by a lower intake of vitamin D when compared to other diets [5,9,10,30,35,41,45,50,64], or lower than the intake reference value (5 μg/d for 19–50 years, 10 μg/d for 51–61 years and 15 μg/d for 65+ years) (Table 4) [16,30]. Elorinne et al. study [35] showed a difference between the serum concentration of total vitamin D and D_2 between vegans and non-vegetarian ($p < 0.001$), with vegans showing decreased serum concentration of total vitamin D and increased 25-hydroxyvitamin D_2. In the same study, vegans were also more likely than non-vegans to show vitamin D inadequacies [35]. While vitamin D intake was reported to be lower in vegans than omnivores, no major differences in serum vitamin D_2 concentrations have been observed among the different diet groups ($p = 0.854$) [62].

3.9. Vitamin E

Vitamin E was examined in eight studies with a total 4.431 participants [5,9,10,12,35,41,50,54]. Dietary intake of vitamin E is considered adequate in vegan diets [5,35], with several studies showing that vegans had the highest intakes (Table 4) [9,10,41,50]. The main dietary sources of vitamin E are vegetable oils, peanuts soybean, wheatgerm, sunflower and almonds [16]. The less diverse the vegan diet, the higher the vitamin E intake recorded [12]. Despite the high intakes of vitamin E in vegan diets, this was not correlated to higher serum concentrations of vitamin E, which were found to be higher among vegetarians [9,54].

3.10. Iron (Fe)

Iron was examined by 11 studies of a total 4.791 participants [5,9,10,12,35,41,50,52,59,61,66]. Several studies [5,9,10,12,35,41,50,61,66] found a higher iron intake among vegans in comparison with other diet types (Table 5). Waldmann et al. [52] reported a higher than recommended intake among German vegan females in both young and postmenopausal females. However, Kristensen et al. [41] and Gallego-Narbon et al. [61] highlighted that despite the higher iron intake, its absorption was not correspondingly high, due to the low bioavailability of iron in plant-based foods. This was reflected in ferritin, which seemed to be lower among long-term vegans [66]. In addition, Sobiecki et al. [50] found that iron requirements could be higher among vegans. Nevertheless, differences were not observed between vegans and non-vegans on iron plasma concentration according to Selinger et al. ($p = 0.392$) [66]. RNI for iron varies due to bioavailability, and is reported between 27.4 mg/d for males and 58.8 mg/d for females (with a

Table 4
Vitamin intake in vegans.

Study	Vitamin A (μg)	β-Carotene equivalents (μg)	Retinol (μg)	Vitamin B_1 (mg)	Vitamin B_2 (mg)	Vitamin B_3 (Niacin) (mg)	Vitamin B_6 (mg)	Vitamin B_{12} (μg/d)	Vitamin C (mg/d)	Vitamin D, (μg/d)	Vitamin E (mg/d)
Alles, 2017	1361.3 ± 48.9	NA	NA	1.6 ± 0.0	1.7 ± 0.0	18.2 ± 0.3	2.3 ± 0.0	2.7 ± 0.3	165.3 ± 4.1	1.9 ± 0.1	165.1 ± 4.1
Crowe, 2011	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.7 [0.6, 0.8]	NA
Davey, 2003	NA	NA	F: 76.6 (92.6) M: 74.2 (94.7)	F: 2.14 (0.78) M: 2.29 (0.82)	F: 2.13 (1.10) M: 2.26 (1.21)	F: 21.1 (8.32) M: 23.9 (9.52)	F:2.08 (0.72) M: 2.23 (0.74)	F: 0.49 (0.70) M: 0.41 (0.60)	F: 155 (86.0) M: 169 (96.6)	F: 0.88 (1.00) M: 0.88 (1.07)	F: 14.0 (7.19) M: 16.1 (8.42)
Elorinne, 2016	1100 (756) [267–3675]	5807 (4367) [1213–21076]	NA	1.7 (0.9) [0.5–4.5]	1.5 (1.2) [0.5–6.6]	27 (11) [11–60]	NA	0.9 (0.8) [0–4]	181 (134) [18–604]	5 (3) [1–15]	20 (9) [7–36]
Gallego-Narbon, 2019	NA	NA	NA	NA	NA	NA	NA	230.6 (70.9)[c]	NA	NA	NA
Gilsing, 2010	NA	NA	NA	NA	NA	NA	NA	122 [117–127][d]	NA	NA	NA
Krajcovicova-Kudlackova, 2000	NA	NA	NA	NA	NA	NA	NA	140.1 ± 4.9[c]	NA	NA	NA
Kristensen, 2015	F: 542 [358–932] M:592 [406–1006]	F: 6827 [3833–11130] M: 5307 [3319–9154]	F: 8.3 [0.0–33] M: 0.03 [0.0–29.7]	F: 1.5 [1.2–1.8] M: 2.1 [1.8–2.7]	F: 0 M: 0	F: 17.5 [15.0–21.2] M: 21.3 [19.4–29.3][i]	F: 1.9 [1.3–2.1] M: 2.5 [1.8–2.8]	F: 0 M: 0	F: 221 [170–254] M: 221 [144–330]	F: 0 M: 0	F: 15.3 [13–18] M: 19.6 [13–37][f]
Mądry, 2012	NA	NA	NA	NA	NA	NA	NA	*severe decrease of serum B12*	NA	NA	NA
Majchrzak, 2006	NA	NA	NA	2.14 (1.47)	1.27 (0.87)	NA	2.88 (1.80) *57.16 (39.6)*[a]	0.39 (0.64) 203.17 *(101.49)*[c]	NA	NA	NA
Outila, 2000	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.09 (0.06)	NA
Pinto, 2017	NA	NA	NA	NA	NA	NA	NA	NA	NA	55.6 (26.5)[a]	NA
Schmidt, 2013	NA	NA	NA	NA	NA	NA	NA	NA	F: 161 (85) M: 155 (71)	NA	NA
Schupbach, 2017	1562 (408)[a]	4137 (1456)[a]	739 [167–6280][g]	2.1 [0.9–5.7] *36.4 (11.5)*[a]	2.0 [0.8–3.7] 79.8 *[41.7]*[a]	17.6 [6–36.2] *416 [185–839]*[a]	2.9 [1.7–8.0] *27 [9–365]*[a]	0.2 [0–6.4] 289 [24–5166][c] 359 [61–1006][j]	239 [70–1873] *71.8 (23.4)*[b]	0.1 (0–0.9)	25.5 (9.2)[h] 22.1 (4.3)[b]
Selinger, 2019	NA	NA	NA	NA	NA	NA	NA		NA	NA	NA
Sobiecki, 2016	Total: 1083 F: 1048 (524) M: 1048 (416)	Total: 5524 F: 5416 (3125) M: 5189 (3019)	Total: 163 M: 165 (111) F: 145 (90)	Total: 2.26 F: 2.16 (0.65) M: 2.42 (0.80)	Total: 1.79 F: 1.69 (0.72) M: 1.98 (1.05)	Total: 21.5 F: 20.4 (6.7) M: 23.8 (9.4)	Total: 2.43 F: 2.59 (0.97) M: 2.59 (0.97)	Total: 0.78 F: 0.68 (0.56) M: 0.75 (0.71)	Total: 190 F: 187 (85) M: 189 (85)	Total: 1.77 F: 1.57 (1.05) M: 1.96 (1.54)	Total: 16.3 F: 15.6 (5.9) M: 17.2 (7.3)
Strohle, 2011	NA	NA	NA	NA	NA	NA	NA	NA	324.4 (194.3) *40.2 (20.6)*[e]	0.65 (0.64)	NA
Waldmann, 2003	NA	NA	NA	F: 1.77 (0.65) M: 2.16 (0.71) *F: 0.25 (0.09)* *M: 0.22 (0.05)*[e]	Total: 0.16 (0.04) F: 1.26 (0.67) M: 1.53 (0.65) *F: 0.18 (0.04)* *M: 0.15 (0.03)*[e]	F: 23.7 (6.74) M: 29.7 (9.66) *F: 3.3 (0.51)* *M: 3.0 (0.51)*[e]	Total: 0.33 (0.08) F: 0.35 (0.08) M: 0.30 (0.06)[e]	F: 0.78 (2.14) M: 0.84 (1.21)	F: 274 (133) M: 353 (248) *Total: 36.3 (18.6)* *F: 38.3 (17.6)* *M: 34.3 (19.4)*[e]	F: 0.50 (0.55) M: 0.78 (0.71)	F: 19.8 (7.76) M: 31.8 (15.2)
Waldmann, 2004	NA	NA	NA	NA	NA	NA	NA	0.81 (1.74) 130 [72.1–294][c]	NA	NA	NA
Waldmann, 2005[a]	NA	Total: 10.7 (5.26) F 10.6 (5.23) M: 10.7 (5.36)[k] *Total: 0.76 (0.49)* *F: 0.84 (0.45)* *(M: 0.65 0.53)*	NA	NA	NA	NA	NA	NA	Total: 352 (303) F: 326 (182) M: 386 (243) *Total: 117 (52.2)* *F: 116 (54.4) M: 118 (50.0)*[b]	NA	Total: 24.8 (12.6) F: 20.5 (7.68) M: 30.2 (15.4) *Total:26.6 (7.95)* *F: 28.2 (9.08)* *M: 24.6 (5.80)*[b]
Waldmann, 2005	NA	NA	NA	NA	NA	NA	2.88 (1.03) *0.33 (0.08)*[e]	NA	NA	NA	NA

Waldmann, 2006	NA	NA	NA	NA	NA	NA	NA	Total: 122 [71.2 –276] F: 113 [65.2 –274] M: 138 [88.0 –373][c]	NA	NA	NA

F: Female; M: Male; NA: No info available.
Variables displayed as: mean (SD); median [IQR]; mean ± SE.
No info for any Vitamin in the following studies: Allen (2000), Allen (2002), Allen (2008), Appleby (2002), Appleby (2007), Bradbury (2014), Bradbury (2017), Brantsaeter (2018), Clarys (2014), Fleury (2017), Fokkema (2000), Gallego-Narbon (2019), Hansen (2018), Krajcovicova-Kudlackova (2003), Lightowler (2002), Newby (2005), Papier (2019), Sebeková (2001), Salvador (2019), Schmidt (2015), Schmidt (2016), Spencer (2003), Thorogood (1987), Trefflich (2020), Welch (2010).

a nmol/l.
b μmol/l.
c pmol/l.
d pmol/l (mean (95% CI)).
e mg/MJ.
f αTE/d.
g RE equivalent.
h E equivalent (mg).
i NE/day.
j ng/l.
k mg/day.

bioavailability of 5%) and 9.3 mg/d for males and 19.6 mg/d for females (with a bioavailability of 15%) [16].

3.11. Zinc (Zn) and calcium (Ca)

Zinc was examined by eight studies of a total 4.525 participants [5,9,10,12,28,35,41,50]. Calcium was examined by 14 studies of a total 6.376 participants [5,9,10,12,27,30,32,35,41,45,46,50,59,64]. Intake of both Zinc and Calcium was recorded as the lowest in vegan populations compared to non-vegan individuals (Table 5) [5,9,50]. Furthermore, low intake of calcium among vegans was also found in other studies [9,10,12,27,30,32,35,36,41,46,50,59,64]. Approximately 76% of vegan subjects consumed less than the RNI (Table 1). Moreover, Alles et al. [5] found that calcium plasma concentration of vegan diet is lower compared to non-vegans ($p^2 < 0.0001$)and it is not clear if the bioavailability of calcium in plant foods plays any role on this. In general, vegan diets are more likely to contain inadequate amounts of serum zinc [5]. Similarly, vegans have shown the lowest zinc intake when compared to groups with different dietary habits [10,41]. WHO recommendations for Zinc and Calcium can be seen in Table 1.

3.12. Phosphorus (P)

Phosphorus was examined by five studies of a total 1.967 participants [5,9,12,30,41]. One study conducted in a German population reported that the dietary intake of phosphorus in vegans was higher than the German Nutrition Society recommended levels (580 mg/d) [12]. Intakes above this limit were also found in studies including different populations [5,9,30,41]. Outcomes from Kristensen et al. [41] and Alles et al. [5] showed that intake of phosphorus was lower among vegans than in non-vegans, but still higher than the NNR (600 mg/d). Conversely, a higher phosphorus intake in comparison with non-vegan groups was shown in three studies [9,12,30]. Phosphorus intake in vegan diets can be found in detail in Table 5.

3.13. Potassium (K) and sodium (Na)

Potassium was examined by eight studies of a total 5.302 participants [5,9,10,12,27,30,41,50]. Similarly, eight studies examined sodium in total participants 2.805 [5,9,12,27,30,41,50,59]. Several studies [5,9,10,12,27,30,41,50] showed that potassium and sodium intake were above the RNI (Table 1 [17,18]) among vegans. However, another study did not find any difference in either potassium or sodium intakes between vegans and other diet groups [50]. In some studies, vegans had the lowest intake of sodium (2.5–2.8 g/d) in comparison with vegetarian and omnivores (2.7–3.0 g/d) [27,41,59]. In contrast to the lower sodium consumption in vegans, which was reported by the latter three studies, higher sodium intake in the vegan group than in omnivores and lacto-ovo vegetarians was observed in three studies [9,12,30]. We have also found that sodium intake in studies published from 2016 onwards shows an upward trend (Table 5).

3.14. Iodine (I)

Iodine was examined by eight studies of total 1.890 participants [5,9,12,29,34,41,42,50]. Intake of iodine among vegans has been shown to be significantly lower compared to non-vegan population [29,34,41,42,50], especially among males [12,67] and frequently lower than the RNI (150 μg/d) (Table 5) [16]. Moreover, in both a Norwegian [34] and German vegan sample [12], high probability of deficient iodine daily intake was found which was defined by 24 h food record and FFQs accordingly. However, the

Table 5
Mineral intake in vegans.

Study	Iron intake, (mg/d)	Ferritin (ng/ml)	Zinc (mg/d)	Calcium (mg/d)	Phosphorus (mg/d)	Potassium (g/d)	Sodium (g/d)	Iodine (μg/d)	Magnesium (mg/d)	Selenium (μg/d)	Copper (mg/d)	Folate (μg/d)
Allen, 2002	NA	NA	10.0 (5.91)	NA	NA	NA	NA	NA	NA	NA	NA	NA
Alles, 2017	18.6 ±4.2	NA	10.0 ±0.2	760.0 ±0.2	1249.6 ±12.6	3676.12 ±30.5[a]	2589.6 ±34.5[a]	248.3 ±9.8[a]	495.2 ±12.6	64.1 ±1.3[a]	2.5 ±0.1	481.4 ±5.2
Appleby, 2002	NA	NA	NA	F: 1021 M: 589	NA	F: 3.836 M: 4.061	F: 2.539 M: 2.792	NA	F: 397 M: 444	NA	NA	NA
Appleby, 2007	NA	NA	NA	F: 586 (226) M: 603 (232)	NA	NA	NA	NA	NA	NA	NA	NA
Brantsaeter, 2018	NA	NA	NA	NA	NA	NA	NA	26 [15,42]	NA	NA	NA	NA
Clarys, 2014	23 (10)	NA	NA	738 (456)	NA	NA	1316 (666)[a]	NA	NA	NA	NA	NA
Crowe, 2011	NA	NA	NA	557 (188)	NA	NA	NA	NA	NA	NA	NA	NA
Davey, 2003	F: 14.1 (4.81) M: 15.3 (4.98)	NA	F: 7.22 (2.42) M: 7.99 (2.68)	F: 582 (242) M: 610 (241)	NA	F: 3.817 (1280) M: 4.029 (1265)	NA	NA	F: 391 (129) M: 440 (141)	NA	NA	M:431 (162) F: 412 (158)
Elorinne, 2016	21 ± 9 (8–46)	NA	12 ± 4 (4–23)	1004 ± 623 (449–3451)	NA	NA	NA	NA	NA	79 ± 65 (28–309)		586 ± 325 (203–1614)
Fleury, 2017	NA	NA	NA	580	NA	NA	NA	NA	NA	NA	NA	NA
Gallego-Narbon, 2019	F: 17.3 (8.0) M: 22.0 (8.1)[b]	F: 21.9 (16.1) M: 71.4 (19.1)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Gilsing, 2010	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	37.5 {35.8–39.3}
Krajcovicova-Kudlackova, 2000	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	497 ± 12 *20.19 ± 0.91*[c]
Krajcovicova-Kudlackova, 2003	NA	NA	NA	NA	NA	NA	NA	78 ± 13[d]	NA	NA	NA	NA
Kristensen, 2015	F: 13.5 [11.0–17.1] M: 18.5 [16.0–24.3]	NA	F: 8.6 [6.6–10.2] M: 10.5 [8.1–15.3]	F: 724 [591–927] M: 885 [786–1104]	F: 1249 [990–1400] M: 1555 [1325–1903]	F: 3.602 [2.852–4.179] M: 4.274 [3.648–5.623]	F: 1.589 [1.146–1.899] M: 2.068 [1.283–2.656]	F: 65 [54–86] M: 64 [43–91]	F: 484 [415–556] M: 645 [509–802]	F: 25 [19–30] M: 33 [25–40]	NA	F: 578 [526–725] M: 628 [465–787]
Lightowler, 2002	NA	NA	NA	NA	NA	NA	NA	M: 42 (46) F: 1448 (3878)	NA	NA	NA	NA
Majchrzak, 2006	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	454.53 (233.59) *22.11 ± (13.69)*[c]
Outila, 2000	NA	NA	NA	743 (180)	NA	NA	NA	NA	NA	NA	NA	NA
Schmidt, 2013	NA	NA	NA	F: 570 (233) M: 569 (209)	NA	NA	NA	NA	NA	NA	NA	NA
Schupbach, 2017	22.9 [12.8–43.0]	40 [9–277]	11.5 (4.1) *72 (10)*[e]	817 (285)	1427 (462)	5.375 (2.178)	2.994 (1.481)	56 [27–586][d]	702 ± 255 930 (70)[c]	90.1 (21.9)[f]	NA	662 [294–2107] 25.7 [4.2–88.3][c]
Selinger, 2019	19.0 [3.3–65.6][b]	43.6 [1.8–246][f]	NA	NA	NA	NA	NA	NA	NA	NA	NA	13.0 [3.63–40.5]
Sobiecki, 2016	Total: 18.3 F: 17.6 (5.1) M: 19.9 (7.2)	NA	Total: 8.7 F: 8.4 (2.8) M: 9.4 (3.1)	Total: 848 F: 839 (324) M: 862 (374)	NA	Total: 4.115 F: 3.972 (1.087) M: 4.243 (1.166)	Total: 2645 F: 2551 (904) M: 2.834 (1.056)	Total: 58.5 F: 54.1 (40.0) M: 55.5 (40.0)	Total: 470 F: 452 (134) M: 505 (157)	Total: 54.9 F: 51.7 (24.8) M: 62.1 (30.4)	Total: 2.07 F: 2.00 (0.66) M: 2.23 (0.78)	Total: 504 F: 480 (166) M: 539 (226)
Strohle, 2011	NA	NA	NA	839.8 (296.1) 106.0 (32.7)[g]	1343.2 (471.9) *164.7(29.3)*[g]	4.88 (1.68) 0.600 (130)[g]	2.01 (1.01) 260 (120)[g]	NA	618.4 (197.5) 76.6 (13.3)[g]	NA	NA	NA
Waldmann, 2003	F: 20.1 (5.65) M: 24.8 (8.03) *Total: 2.67*	NA	F: 10.5 (3.43) M: 13.5 (4.48) *Total: 1.42*	F: 790 (249) *M: 915 (346)* *Total: 103*	F:1251 (1187) M: 1601 (528) *Total: 168 (29.8)*	F: 4.46 (1.35) M: 5.46 (2.03)	F: 2.02 (0.86) M: 2.31 (1.19)	F: 82.0 34.4[a] M: 87.6 (30.6)[a] *Total:*	F: 585 (168) M: 706 (224) *Total: 76.8*	NA	F: 2.69 (0.7)5 M:3.39 (0.91) *Total: 0.39*	F: 482 (133) M: 571 (208) *Total: 63.2*

	(0.45) F: 2.83 (0.4) M: 2.51 (0.42)[g]		*(0.29) F: 1.46 (0.29) M: 1.37 (0.29)*[g]	*(30.6) F: 113 (34.0) M: 92.4 (22.5)*[g]	*F: 174 (30.2) M: 162 (28.2)*[g]			*10.4 (4.29) F: 11.8 (5.21) M: 8.91 (2.31)*[g]	*(13.6) F: 81.8 (13.0) M: 71.5 (12.1)*[g]		*(0.06) F: 0.41 (0.06) M: 0.37 (0.06)*[g]	*(16.8) F: 68.6 (18.4) M: 57.6 (12.9)*[i]
Waldmann, 2004	20.0 (5.77)	14.0 [5–84.6]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Waldmann, 2004	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	33.0 [18.1 –46.5][h]

Variables displayed as: mean (SD), median [IQR], mean ± SE, mean {95% CI}.
NA: no info available; F: Female; M: Male.
No info for any Vitamin in the following studies: Allen (2000), Allen (2008), Bradbury (2014), Bradbury (2017), Fokkema (2000), Gallego-Narbon (2019), Hansen (2018), Mądry (2012), Newby (2005), Papier (2019), Pinto (2017), Sebeková (2001), Salvador (2019), Schmidt (2015), Schmidt (2016), Spencer (2003), Thorogood (1987), Trefflich (2020), Waldmann (2005*), Waldmann (2005&), Waldmann (2006), Welch (2010).
[a] mg/d.
[b] μmol/l.
[c] nmol/l.
[d] μg/l urine.
[e] μg/dl.
[f] μg/l.
[g] mg/MJ.
[h] mmol/L.
[i] μg/MJ.

average daily intake of iodine in a Finnish population was 29 μg/d and iodine deficiency was observed in 80% of vegans (24 h urine excretion <100 μg/l) [29]. Furthermore, several studies [9,12,29,31,50], examining vegan samples of urinary and serum iodine concentrations found those to be near or below the recommended levels. High levels of iodine intake were observed in only one study for a minority of vegans (3 individuals). This was due to increased seaweed consumption [41]. Conversely, adequate mean iodine intake (248 mg/d) was only found in Alles et al. study [5]. Plant-based foods are generally characterized by a low iodine content, with the exception of seaweed [29]. Iodized salt was the main source of iodine for vegan individuals according to Schupbach et al. [9].

3.15. Magnesium (Mg)

Magnesium was examined by 8 studies of total 5.302 participants and its intake was found to be highest in vegan diets in comparison to other diet types [5,9,10,12,27,30,41,50], and higher than the WHO recommended levels (Table 1) (Table 5) [16]. However, two further studies [9,39] found no difference in serum magnesium concentrations between vegans and individuals adhering to different diets.

3.16. Selenium (Se), Copper (Cu)

Selenium was examined in five studies of a total 1.737 participants [5,9,35,41,50].These studies suggest that vegans are more likely to have a low selenium intake. [9,35,50], though this might not be significantly different compared to non-vegans [9]. Kristensen et al. [41], found that vegans had the lowest selenium intake, which was close to the WHO RNI (Table 1) [16]. However, in three studies of a total 1.690 participants, vegans were shown to have the highest intake of copper compared to other diet types in some studies [5,12,50].

3.17. Folate

In 12 studies that examined dietary folate intake in 4.974 participants, vegans met the WHO recommendations (400 μg/d) [16] and had higher folate intakes compared with other diet types [5,9,10,12,35,38,40,41,44,50,51,66], (Table 5). Blood concentration of folate did not vary substantially between diet groups, except in the vegan group where a slight increase was observed [40,51]. Schupbach et al. showed that omnivores were more prone to folate inadequacies compared to vegetarian and vegan individuals who consume high amounts of plant-based products ($p < 0.05$) [9].

3.18. BMI

Several studies examined the correlation between diet type and BMI among the study groups [5,9,10,12,23–27,29–33,35–45,47–49,51–55,57–59,61–63,67]. BMI results can be found in Table 2. Most studies concluded that vegan individuals compare favorably to individuals following other diets in all the aforementioned indicators. In particular, according to Allen et al. [31],the mean weight difference between vegan females and omnivore or vegetarian females was −5 kg, while the EPIC-Oxford study showed that mean BMI in vegans was lower compared to omnivores by 1.92 kg/m^2 and 1.54 kg/m^2 in males and females respectively [26]. Furthermore, the vegan group included the fewest overweight and obese individuals [26]. Also in further studies, omnivores were found to be the group with the highest BMI [32,47]. Overall, several studies agreed that vegan individuals had a healthier BMI in comparison to people who follow other diet types [25,32,33,47,59,62].

Table 6
Alcohol intake in vegans.

Study	Alcohol (% E)	
Allen, 2000	3.96 (3.22–4.70)	
Allen, 2002	2.12 (3.25)	
Allen, 2008	2.4 (3.2)	
Alles, 2017[a]	6.4 ± 0.5	
Appleby, 2002[a]	F: <1: 156 (33.4) 1-9: 223 (47.8) 10-19: 63 (13.5) 20+: 25 (5.4)	M: <1: 89 (32.7) 1-9: 97 (35.7) 10-19: 42 (15.4) 20+: 44 (16.2)
Appleby, 2007[a]	F: 6.4 (10.1)/M: 11.4 (17.9)	
Clarys, 2014[a]	7 (12)	
Davey, 2003	F: 2.63 (3.88)/M: 4.02 (5.78)	
Hansen, 2018[b]	2.0 [0.0, 6.8]	
Majchrzak, 2006[a]	5.6 (12.9)	
Newby, 2005[a]	2.0 (0.3)	
Papier, 2019[a]	F: 6.6 (10.4)/M: 11.3 (16.6)	
Schmidt, 2013[a]	F: 5.6 (9.2)/M: 10.6 (16.2)	
Schmidt, 2015[a]	1.92 [0.35, 6.04]	
Schmidt, 2016[a]	5.1 [1.0, 14.0]	
Sobiecki, 2016[a]	Total: 2.17 F: 2.3 (3.4)/M: 2.6 (3.9)	
Spencer, 2003	F: 6.5/M: 12.6	
Waldmann, 2003	Total: 0.22 (1.11) F: 0.32 (1.48)/M: 0.13 (0.52)	
Waldmann, 2005	0.66 (3.15)	
Waldmann, 2005	Total: 0.50 (1.59) F: 0.35 (1.03)/M: 0.69 (2.10)	
Waldmann, 2006	0.28 (0.94)	

F: Female; M: Male.
Variables displayed as: mean (SD), median [IQR], mean ± SE.
No info on Alcohol in the following studies: Bradbury (2014), Bradbury (2017), Brantsaeter (2018), Crowe (2011), Elorinne (2016), Fleury (2017), Fokkema (2000), Gallego-Narbon (2019), Krajcovicova-Kudlackova (2000), Krajcovicova-Kudlackova (2003), Kristensen (2015), Lightowler (2002), Mądry (2012), Outila (2000), Pinto (2017), Sebeková (2001), Salvador (2019), Schupbach (2017), Selinger (2019). Strohle (2011), Thorogood (1987), Trefflich (2020), Waldmann (2004), Welch (2010).
[a] g/d.
[b] Alcohol, units/week.

3.19. Alcohol

Low alcohol consumption is recorded frequently in vegan diets (Table 6) [5,6,10,25,27,28,32,39,44,46–48,53,54,57–59]. However, in some studies, differences in alcohol consumption between diet groups were not observed [12,31,50,63]. Alcohol intake among vegans ranged from 0.25 g/d to 12.6 g/d [5,6,25,26,32,39,44,46,47,53,54,59,63,68], and in one study [27] as high as 20 g/d for a minority of mainly male vegans. Energy percentage from alcohol for vegan individuals ranged from 0.22 to 4.02% [10,12,28,31,50,57].

4. Discussion

This is the first systematic review to assess the intake and adequacy of vegan diets. Even though vegan diets have gained popularity in recent years, an adequate assessment of this type of diet has not been established, preventing adequate review of assessing macro- and micronutrient intake in vegan diets. This systematic review aims to investigate the intake and adequacy of vegan diets.

The 48 included studies published from 1987 to 2020 examined the nutrient intake of a total 12.096 vegans. This constitutes an adequate reflection of vegan diet due to the large sample size and the geographic coverage. Moreover, results of studies assessment (only four out of 48 studies were characterized as satisfactory whereas the rest 44 studies were characterized as good and very good) strengthen our evidence.

Regarding the socioeconomic status of vegans, the fact that up to 30% of vegans were highly educated [23–25] and a great majority had never been employed or were manual workers with low incomes [5,10] and were single or had families without children [5,10,25–27], could mean that following a vegan diet is not always a lifestyle choice but can be adopted due to financial reasons. Therefore, manual workers with lower income could be part of this group too. Undoubtedly, there is lack of adequate data to elucidate on this.

The major food sources of vegans identified in this study according to our included studies are fruits, vegetables, legumes, starchy foods, bread, pastries, cereals, rye-flour products, soya products, brown rice, potatoes, meat substitutes, nuts, seeds, oils and olives [5,6,12,24,30,33,35,49,55,59,63].

4.1. Energy and macronutrients

TEI among vegans is reported as in the lower levels of the normal range. Only one study reports that TEI did not meet the recommended levels (3% below for males and 15% below for females) [10]. However, it is well known that the appropriate TEI varies among individuals and is associated with sex, weight, height and activity. In this context, it is difficult to directly conclude whether TEI in vegan individuals is sufficient since TEI is highly influenced by individualized parameters. Moreover, the majority of vegans are characterized by a lower body weight, which is often associated with a lower energy intake. This implies consumption of less food, which by definition makes vegans more prone to a lower nutrient intake.

A vegan food pattern can lead to an increased consumption of carbohydrates and fibers. High fiber intake (>30 g/d), mainly from fruits and vegetables, is common in vegan diets [69]. Such high fiber diets can play a significant role in glycemic control and can have a protective role against insulin resistance and DMT2 [70–72]. In a recent study, Chiu et al. reported that shifting from a non-plant-based diet to a plant-based diet can reduce the incidence of DMT2 by 53% [73]. In addition, a high fiber diet can reduce the incidence of diverticular disease due to increased bowel movement and lower transition time [74], in contrast to a diet high in meat [60]. However, a high fiber diet can result in a more frequent and/or intense bowel movement, which has been associated with irritable bowel syndrome (IBS) [75]. These findings suggest that more research in this field is needed.

We found that TEI from total fats does not differ among the diet groups; however, differences are observed regarding fat subgroups. Our study shows that vegan diets are characterized by lower consumption of MUFAs and SFAs, and higher consumption of PUFAs [24]. It should be noted that among the studies included in our analysis, consumption of PUFA increases over time (from 8% of TEI in 2000, to 10% in 2014 and up to 26% and 48% in 2016 and 2019 respectively) [24,35,57,58]. PUFAs are obtained from food and cannot by synthesized in the body. Rich-sources for PUFAs include rapeseed/canola, walnut, linseed oil and nuts (n-3-PUFAs) or corn and sunflower oil (n-6-PUFAs). N-3 fatty acids (e.g. a-linolenic acid) are strongly associated with the prevention of atherosclerosis [76] and can optimize the lipid profile by limiting inflammatory response and by reducing oxidative stress [77]. Among n-3 fats, only a-linolenic acid (ALA, 18:3, n-3), can be found in adequate amounts in plant sources (e.g. flaxseed, walnuts, chia seeds and their oils) [78]. However, the favorable omega fat profile of vegan individuals is the main reason for the potential protective role of vegan diets against CVD and stroke [24,79–83].

There is concern that vegan diets might contain low amounts of protein. Our results indicated that total protein intake is indeed lowest compared to other diet groups and recommended levels of protein are not always reached. However, as seen in Alles et al. study [5], achieving an adequate protein intake is feasible even when consuming only plant foods (only 27.3% of vegans was below the acceptable range). In particular, in the same study [5], a significant proportion of meat-eaters (27.5%) was above the acceptable distribution range of 2.2 g/kg/d which can be related with calcium homeostasis disorders, renal and live impairments, cancer as well as coronary diseases according to the French Agency for Food, Environmental and Occupational Health & Safety [84]. Vegans aim to meet their necessary protein intake by consuming protein-dense plant foods like seeds, nuts, legumes, processed meat analogues and soya protein foods [6]. Although intake of some essential amino acids in vegan diets is recorded lower than in non-vegan diets [48], according to Mariotti et al., where vegan diets include a variety of protein foods such as grains and legumes, insufficient intake is not expected [85]. Moreover, plant protein in comparison with animal protein is associated with decreased CVD [86–88], slow cancer growth [87] and lower mortality rates [89]. There are substantial differences in the level of digestibility among plant proteins, with soy protein or gluten reaching 95% that of animal protein sources and whole cereals and purses reaching levels between 80 and 90% [78]. The level of digestibility of plant proteins can be even lower (50–70%), or adversely influenced by food processing mechanisms, such as heating. Furthermore, using the Protein Digestibility–Corrected Amino Acid Score (PDCAAS) which was adopted by WHO [90] plant protein is not rated as highly as animal and milk protein [90,91]. In general, soya proteins are among the main protein sources for the majority of vegans [28]. Soya consumption has also been found to be related to a low incidence of prostate cancer [92,93]. However, animal-source foods are related to increased insulin-like growth factor-1 (IGF-1), which is related to a higher prevalence of prostatic adenocarcinoma [94]. Non-soy protein could characterized by low content of essential amino acids [28,85]. Insufficient protein intake in vegans could be observed, especially in cases where the consumption of legumes, seed and nuts is restricted [85].

4.2. Micronutrients

Vitamin intake and plasma concentrations in vegans vary between the studies. Despite lower intake of vitamin A and high intake of vitamin E, serum concentrations for vegan individuals are reported to be in a healthy range [41]. Vitamin E is used for oxidation of PUFAs, of which vegan intake is high and therefore the high intake of the vitamin is not reflected in its serum concentration [9,54]. Following a vegan diet allows for a higher intake of vitamin C, reflected in higher serum concentrations among vegan individuals, which is potentially positively correlated to chronic disease prevention [53,54].

Our results show that B_{12} intake is significantly lower among vegan individuals and serum deficiencies are frequently observed [9,10,12,35,41,44,50,53]. The low intake of vitamin B_{12} is one of the major issues in vegan diets because of the exclusion of vitamin B_{12} rich foods, such as meat, poultry and eggs [10,66,95]. According to Pawlak et al. [96], B_{12} serum deficiency among vegans was reported 0–86%, whereas among those reporting consumption of B_{12} fortified foods the deficiency rate was 0% [43]. Vitamin B_{12} deficiency is related to neurological and hematologic disorders [97]. It is clear that low vitamin B_{12} intake has important clinical implications, however deficiency symptoms manifest slowly after several years. High folate concentration could also partially and temporarily mask some of the typical vitamin B_{12} hematological changes [78]. Therefore, it is important that vegans are monitored on a regular basis for vitamin B_{12} concentration, and in most cases could easily maintain the recommended intakes through supplementation (under appropriate medical supervision) or/and through consumption of fortified foods.

This review shows that vitamin D intake is lower among vegans, but deficiencies are not often observed [5,9,10,12,30,35,41,45,50,60,62]. Vitamin D intake is limited in vegan diets, especially due to fish exclusion, but serum concentrations are not below healthy levels [62]. Eating mushrooms and ensuring adequate sun/UV-B exposure can help achieve adequate amounts of vitamin D [102,103]. However, environmental and/or lifestyle factors which reduce sunlight exposure can affect vitamin D production in the skin and also contribute to deficiencies [104]. Fortified bread and/or cereals could also provide a source of vitamin D for vegan individuals [103]. Seasonal changes for parathyroid hormone (PTH) concentrations due to the low intake of vitamin D have been reported only in menopausal women, which could increase the incidence of negative effects on bone health in this group [45].

Iron intake, in our review, is higher among vegans compared to individuals who follow other diet patterns [5,9,10,12,35,41,50,61,66], as green-leafy vegetables, grains, nuts and beans, which are highly consumed in vegan diets, are iron-rich foods [105]. However, this does not always translate to higher ferritin levels [66]. Similar results were also reported in a review examining iron status in vegetarian and vegan populations, where despite the lower level of ferritin, the risk of iron deficiency was not higher than in non-vegetarian diets [106]. However, lower levels of ferritin in vegan individuals can have a protective role against metabolic syndrome and CVD in post-menopausal women [107,108] and tumor development [109]. Moreover, vegans' iron requirements are higher than those following other diet types [66], primarily because non-heme iron from plant-based food has lower bioavailability. This could be improved by the parallel consumption of vitamin C rich foods (e.g. citrus, oranges, lemons, strawberries, kiwis) and foods rich in organic acids (e.g. citric and malic acid) [110,111]. Nevertheless, despite the low ferritin concentration that can be observed in vegans, the overall incidence of iron deficiency anemia is no greater than in individuals following other diets [105]. However, iron supplements are often recommended in specific populations (e.g. premenopausal vegan females), or in the presence of specific needs (e.g. due to higher iron losses) [52].

A low intake of calcium among vegans is found in many studies in our review [9,11,22,24,29,32,33,39–41,57–59]. Calcium intake among vegans is lacking not only due to the exclusion of dairy products but also due to bioavailability issues of calcium in plant-based foods [5,10,111]. However, the calcium added to food products like some brands of tofu show the same level of bioavailability as milk [113]. Low calcium intake has been linked with several clinical conditions [32,114]. Extremely low levels of calcium are related to high incidence of fractures and vegans have been shown to present a 30% higher rate of bone fractures than omnivores [32]. In our results we found that vegan calcium intake was low compared to other diet types but over the WHO limit of 525 mg/day. However, in three studies calcium intake was recorded near this threshold which in combination with low vitamin D intake makes vegans more prone to bone fractures [32,36,64]. On the other hand, lower calcium intake in parallel with the low protein intake in vegans are associated with lower incidence of prostate cancer [92]. Vegan individuals could ameliorate their calcium status by consuming more broccoli, sprouts, tofu, fortified plant milks and juices [118] as well as fortified mineral waters [119].

Our results show that zinc intake is reduced among vegans and frequently risk of deficiency is observed [5,9,10,12,28,35,41,50]. These results agreed with the results of a recent meta-analysis which examined zinc status among individuals following a vegetarian diet compared to other diets [120]. Meat, dairy and eggs are zinc-rich foods, whereas some zinc-rich plant foods (e.g. nuts, seeds and whole grains) present bioavailability issues due to the presence of phytate, which lowers absorption in the intestine [78,121]. However, phytate content could be reduced after applying specific methods of soaking, germination, fermentation, enzymatic interventions or even genetic-modification in grains [122,123]. Zinc is an important part of the regulation of the immune system and in the function of many enzymes. Inadequate zinc intake could be related to some conditions such as mental health disorders (e.g. depression), dermatitis, diarrhea and alopecia, whose incidence is higher in vegans [124].

According to our results, sodium intake among vegans appears higher than the recommended levels, but lower compared to non-vegans [5,9,12,27,30,41,50,59]. Vegans appeared to engage less in the practice of adding salt when cooking at home [27]. However, sodium intake among vegans has increased over time, as shown in studies from 2016 onwards. One explanation may be the increased intake of processed foods and the high salt content in plant-based fast food or convenience meals [130]. Salt intake above of 7.2 g/d is strongly related to elevated blood pressure and can lead to cardiovascular and renal disease [131,132]. Consequently, WHO strongly recommends that salt intake should not exceed 5 g/d [18]. Hypertension still remains less prevalent among vegans in comparison with other diet types [27,133].

Our results showed that iodine intake is lower among vegans [5,12,34,40,41,50,67] and intake below the WHO limit of 150 μg/d [19] was reported for the majority of vegans in several studies [9,12,34,41,42]. High iodine intake in vegans is recorded only in cases of increased seaweed consumption [41]. Low iodine intake, combined with soy products and vegetables is linked to lower prevalence of hypothyroidism [2] and vegans have a lower prevalence of hyperthyroidism compared with omnivorous diets [134]. Iodized salt, cranberries, seaweeds and prunes are some of the foods that can consumed by vegans with a view to iodine status improvement [118].

Our results show that vegans demonstrate decreased selenium intakes [5,9,35,41,50]. Selenium plays a key role in thyroid function regulation, the immune system, mental health and acts as an antioxidant [135]. Reproduction disorders and muscle weakness have been reported in cases of low selenium levels [135]. In Fallon et al. study, it is also underlined the low intake of both iodine and selenium in vegan population and fortified foods or/and supplementation maybe required [137].

Deficiencies in other minerals and trace elements have not been detected in our results. In particular, phosphorus, copper and magnesium intakes are recorded as adequate and not related to any health problems in vegans [5,9,12,27,30,41,50]. Evidence regarding whether potassium intake is higher or lower in vegan diets than in omnivorous diets is not clear, although in all included studies the adequate levels of potassium were reached [5,9,10,12,27,30,41,50]. Similarly, folate intake is high among vegans according to our results, but serum concentrations of folate seem to differ significantly compared to non-vegan diets [9,40,41,44,51]. Folate supplementation can have a positive effect on preventing or alleviating folate deficiencies [38].

Vegans seem to have the lowest BMI of all the diet groups and subsequently a lower risk of becoming obese [26]. High BMI is strongly associated with higher risk for DMT2 [138] and vegans may have a protective advantage due to their lower BMI and their nutrient intake profile [139].

Alcohol consumption in vegan individuals is lower in comparison to other diet groups [5,6,10,25,27,28,32,39,44,46–48,53,54,57–59]. Low alcohol consumption (<30 g/d) acts protectively against the incidence of hypertension, cognitive impairments, bone fractures, DMT2, colon polyps and cancer, chronic pancreatitis, alcoholic liver cirrhosis as well as breast cancer [140–143]. Moreover, the fact that vegans consume lower amounts of alcohol might be beneficial for the prevention of gallstones (~5 g alcohol/d reduce gallstone incidence by 40%) [142]. The production of beer and wine can often use animal-derived products in the processing stage. Therefore, vegans might avoid wines and beers that are not "vegan certified" [144].

4.3. Further considerations

Following a vegan diet has positive and negative aspects when accounting for the clinical conditions discussed, which might result from a low intake of specific nutrients (vitamin B_{12}, calcium, zinc, selenium). Although vegan diets may protect against obesity [26], DMT2 [70,139,145,146] and CVD risk [24,79–83], veganism could potentially be related to nervous [98,99,147], skeletal [32,148] and immune system impairments [68,124,125], as well as hematological disorders [98] due to the low intake and/or risk of deficiencies of specific nutrients that can affect body function. Moreover, the higher incidence of mental health issues found in vegans in comparison with other diet types may contribute to a lower quality of life [100,101].Mental health issues, especially depression symptoms could not be solely attributed to certain are not only associated with food exclusion due to being vegan.

Overall, following specific strategies such as choice of cooking method, parallel consumption or avoidance of other nutrients and seeking advice from healthcare professionals can help overcome potential deficiencies. Vegan individuals should always consult a dietician or appropriate medical professional (trained in nutrition) regarding their nutrition status and any occurring symptoms, aiming to prevent nutrient inadequacies early and minimize any negative health consequences.

The strength of our review is the number of the studies examined and, therefore, the large sample of vegan individuals investigated. Moreover, all the included studies according to the Newcastle–Ottawa quality assessment tool (Suppl. Table 2) were characterized from satisfactory (5*) to very good (9*) quality. A comprehensive set of energy intake, macronutrients, micronutrients and alcohol have been examined. Limitations include the fact that the population might not be representative of all countries in Europe as little information was available for specific regions (e.g. the Balkans, Baltic, parts of the former Soviet Union). However, a substantial part of the European population and territory is covered. In some studies, information on vegan diets was self-reported, reducing reliability, and the duration of adhering to a vegan diet differed among the studies. The fact that different tools were used to assess nutrient intake across the studies, including food frequency questionnaires (FFQs) [5,6,10,12,23–33,35–38,40,45–54,56–63,65], blood [9,10,12,23,24,27,28,31,35,37–40,43–49,51–55,57,60–63,66] and urine test [29,30,34,35,44,45] and food diary reports [41,55,67], made comparison between studies more problematic. Moreover, individual parameters and the heterogeneity of vegan diets could influence our results but were adapted occasionally. In some studies [10,50,59,64,65], fortified foods like cereals or drinks were used and this could affect the nutritional status, especially vitamin D, calcium, iodine and selenium intake in vegans.

5. Conclusion

This review found that vegan energy intakes are lower, but not below the RNI. Macronutrient consumption is largely adequate in vegans, with the exception of protein, where vegans have lower intakes that fell slightly below the RNI. Micronutrients of concern in vegan diets are vitamins B_2, Niacin, B_{12}, vitamin D, iodine and calcium, where intakes are lower compared to those of other diet types and do not meet the RNI. Iron intakes in vegan diets are higher than in non-vegans, but this is not always reflected in ferritin levels due to the low bioavailability. Moreover, vegans have sodium intakes that exceeded the RNI. Finally, as with other diet types, vegans have a lower BMI and lower prevalence of overweight and obesity.

Our results suggest that avoiding nutrient inadequacies whilst following a vegan diet can be challenging. In general, vegan diets in which intake of foods from several food groups (e.g. vegetables, fruits, legumes, cereals, nuts), soya and high-quality oils can be characterized as healthy and balanced. However, the low intakes of vitamins B_2, Niacin, B_{12}, D, iron, calcium and iodine, cannot be overlooked. Further action should be considered to prevent these potential deficiencies. Moreover, vegan diets are related to more favorable GI and lipid profiles and have been is associated with lower incidence of several cancers. Nevertheless, mortality among vegans does not seem to differ from individuals who follow other diets but further research is needed [149]. Further investigation in the field of vegan diets and the quality of the alternative products that are consumed is required.

Statement of authorship

DRB, AH, HL, AO participated in various stages of the writing of this manuscript. KW, JB and MC conducted the idea of the manuscript. AH, HL, JW, TD, KW, JB, MC reviewed each version of the manuscript. All authors approved the final version of the manuscript.

Funding disclosures

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of interest

The authors declare that they have no competing interests for the content of this paper. The writing group takes sole responsibility for the content of this article and the content of this article reflects the views of the authors only. JB, KW and JW are staff members of the WHO Regional Office for Europe and HR and AH are WHO consultants. The World Health Organization is not liable for any use that may be made of the information contained therein.

Acknowledgements

We would like to acknowledge Clare Farrand, Technical Officer for the WHO European Office for the Prevention and Control of Non-communicable Diseases, who generously contributed to the later stages of the editing of the manuscript. Additionally, we would like to thank Dr. Ioannis Doundoulakis who generously contributed in the early stages of the protocol.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clnu.2020.11.035.

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