Plant-Based Diets—Environmental Benefits but Better Awareness Needed to Prevent Future Micronutrient Shortcomings

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Abstract

Plant-based diets are accelerating in their popularity and yet their nutritional viability remains a matter of interest. In the present review, data has been extrapolated from available studies assessing micronutrient profiles amongst those following plant-based diets. A total of five systematic review and meta-analysis papers collating evidence from 95 separate studies and six observational studies collating evidence from 16,262 participants were evaluated. Systematic and meta-analytical evidence showed that vitamin B12, vitamin D, iron and zinc shortfalls were most common. Observational evidence showed that vitamin B12, vitamin D, selenium and iodine deficits were most widespread. Low intakes of zinc, niacin, riboflavin and potassium were also reported. These findings suggest that stronger nutrition communication strategies are needed to improve the micronutrient profile of these diets. Supplementation strategies together with food fortification where appropriate could also help to bridge dietary gaps. Bearing this in mind, current supplementation guidance should also be updated to reflect contemporary dietary shifts. Ongoing research is also required to better understand the nutritional ramifications of these diets both across the lifecycle and in relation to a broader spectrum of health outcomes.

Keywords: choline; definitions; iodine; life-cycle nutrition; micronutrients; Plant-based diets; selenium; vitamin B12, vitamin D; zinc

Introduction

The movement towards plant-based diets has garnered increased attention among healthcare and public sectors in recent years [1]. In 2019 the EAT-Lancet Commission published "Food in the Anthropocene" highlighting the need for food systems to support environmental sustainability and nurture human health with fundamental dietary changes, including a shift towards plant-based diets [2]. Such recommendations are highly commendable and, in fact, are not a new concept – rather an old-new trend in nutrition [3]. Many early human food cultures were plant-based along with the Greek philosopher Pythagoras who was considered the "father of ethical vegetarianism"-a trend which more or less disappeared from Europe during the Middle Ages but has since re-emerged – mainly for health, ecological and ethical reasons [4].

From an environment perspective, plant-based diets are deemed sustainable as they generally use fewer natural resources and are less taxing on the environment [5]. Global modelling analyses have shown that substituting animal-sourced foods with plant-based foods in high-income countries can reduce Greenhouse Gas Emissions (GHGEs) by up to 84% [6]. Other models similarly show that GHGEs of equicaloric diets are 29% less in vegetarian diets (calculated using Adventist Health Study-2 data) and 47-60% for vegetarian/vegan diets (calculated using European Prospective Investigation into Cancer; EPIC and Nutrition-Oxford data) when compared against non-vegetarian diets [7].

Many people appear to be transitioning to plant-based diets for their beneficial environmental effects [8]. Young people will be confronted with the effects of climate change in their lifetime and as decision-makers will play a pivotal role in shaping societal developments [9]. In terms of trend data, in 2019 the UK was regarded as the most popular country globally for veganism, followed by Australia and New Zealand [10]. In the UK alone, specific interest in veganism increased sevenfold in five years (between 2014 and 2019) and received four times more interest than vegetarian or gluten-free searches [11]. Interestingly, a survey of 329 vegans revealed three distinct motives for following such a diet, these being: (1) animal-related motives (89.7%), (2) personal wellbeing/health (69.3%) and (3) environment-related motives (46.8%) [12].

Health research evidence for plant-based diets has been building over the years. Evidence suggests that 'high-quality' plant-based diets can confer benefits to certain aspects of...
health, including cardiovascular and cardio-metabolic health [13-15], improved lipid profiles [16], lower risk of Type 2 diabetes [17] and of all-cause mortality in US adults [18]. Meta-analytical evidence has reported protective effects of vegetarian and vegan diets in relation to total cancer incidence, -8% and -15%, respectively [19]. From a nutritional stance, however, the potential effects of increasing plant-based foods at the expense of other food groups and its ramifications on micronutrient nutrient adequacy remains largely unknown [1].

One modelling study using US NHANES (National Health and Nutrition Examination Survey) data from n=17,387 individuals showed that increasing plant-foods led to more people failing to meet dietary targets for vitamin A, D and calcium, thus resulting in unintended dietary outcomes [1]. Similarly, in the Netherlands, work replacing 30 or 100% of meat and dairy consumption with plant-based alternatives confirmed that in the 100% scenario, 60% of adults had vitamin A intakes below the Estimated Average Requirement (EAR) and 10-31% had zinc, thiamin and vitamin B12 intakes below the EAR [20]. Iron intakes were sufficient but non-haem iron present in the diet had a lower bioavailability [20].

Clearly, reverting back to and promoting plant-based diets is a viable part of helping to achieve a sustainable future [5]. Recently, it has been questioned whether diets such as the EAT-Lancet really do reduce premature mortalities from noncommunicable diseases to the extent that was originally thought [21]. Other work suggests that transitioning to plant-based diets is less likely to affect health outcomes such as obesity [8]. Given the rapid uptake of such diets, the present review reflects on available evidence focusing on the micronutrient profiles of such diets.

**Methods**

**Definitions**

Definitions of plant-based diets can vary widely-some define plant-based diets in relation to the complete exclusion of animal or meat products. Others include moderate amounts of animal-sourced foods and align more closely with the definition of flexitarianism [15,22] The EAT-Lancet planetary health plate advises that: “the volume of approximately half a plate should be vegetables and fruits whilst the other half should consist of primarily whole grains, plant protein sources, unsaturated plant oils, and (optionally) modest amounts of animal sources of protein” [23] which represents a plant-based dietary model.

In contrast to popular belief plant-based diets do not necessarily have to be vegan or vegetarian [15]. The UK British Dietetic Association (BDA) [24] has adopted a robust definition that encompasses all sub-groups. It specifies that types of plant-based diets can include: lacto-ovo vegetarians, ovo-vegetarians or vegans and that other variations of plant-based diets also include: pescatarians and semi-vegetarians or flexitarians [24]. A summary of plant-based dietary definitions is shown in Table 1.

| British Dietetic Association (2020) [24] | “A plant-based diet is based on foods derived from plants, including vegetables, wholegrains, legumes, nuts, seeds and fruits, with few or no animal products”. |
| EAT-Lancet Commission (2019) [23] | “The volume of approximately half a plate should be vegetables and fruits whilst the other half should consist of primarily whole grains, plant protein sources, unsaturated plant oils, and (optionally) modest amounts of animal sources of protein.” |
| McManus (2018) Harvard Medical School [62] | “Plant-based or plant-forward eating patterns focus on foods primarily from plants. This includes not only fruits and vegetables, but also nuts, seeds, oils, whole grains, legumes, and beans. It doesn’t mean that you are vegetarian or vegan and never eat meat or dairy. Rather, you are proportionately choosing more of your foods from plant sources”. |
| Tuso et al. (2013) Definition for Physicians [63] | “A regimen that encourages whole, plant-based foods and discourages meats, dairy products, and eggs as well as all refined and processed foods.” |

**Table 1**: Definitions of plant-based diets.

**Study selection criteria**

Papers were restricted to systematic reviews and meta-analysis papers, multicentre studies, comparative studies and observational studies. All papers were published within the last 10 years (2010-2020) to reflect current food trends. Systematic review and meta-analysis papers were included if they monitored either micronutrient intakes or status. For multicentre, comparative and observational studies these included human studies conducted on individuals’ ≥2 years following plant-based diets and reported daily micronutrient intakes.

The UK BDA definition of plant-based diets was followed and applied as it encompasses all sub-groups; thus lacto-ovo vegetarians, ovo-vegetarians, vegans, pescatarians and semi-vegetarians/flexitarians were included. For these studies, publications were only included if they published data on ‘daily micronutrient intakes’ presented as a mean value. Publications were excluded if they only focused on, or recorded the intake of, one or two micronutrients. For inclusion, intakes of multiple (i.e. more than three micronutrients) needed to be recorded. Publications were excluded if they focused on micronutrient status rather than intakes.
**Search Strategy**

A systematic review of peer-reviewed literature published up to the 29th of February 2020 was performed. The search strategy was undertaken using the National Centre for Biotechnology Information (NCBI) search engine (PubMed). The following PubMed search algorithm was embedded: [plant-based [All Fields] OR vegan [All Fields] OR vegetarian [All Fields] OR lacto-ovo-vegetarian [All Fields]) OR ovo-vegetarian [All Fields]) OR semi-vegetarian [All Fields]) OR flexitarian [All Fields]) OR pescatarian [All Fields]) AND (micronutrient* [All Fields] OR vitamin intakes [All Fields] OR mineral intakes [All Fields]).

![Diagram](image)

**Figure 1: Algorithm for identifying trials**

Additionally, manual searches of reference lists of previous reviews and original research were carried out, to identify additional relevant articles that could have been missed in previous searches. Attempts were made to contact authors when only the abstract was available.

**Data collection and analysis**

Systematic review and meta-analysis publications, multicentre studies, comparative studies and observational cohorts were considered. Case reports and generic reviews were not included. Data was extracted and organised into methodological details (Table 2) and micronutrient intakes (Tables 3 and 4). The following methodological data was obtained: author(s), year, study period (as stated in the paper), study population, type of diet and main findings.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Micronutrient of focus</th>
<th>Life stage</th>
<th>Evidence-Base</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haider et al. (2018) [29]</td>
<td>Iron</td>
<td>Adults</td>
<td>27 cross-sectional and 3 intervention studies</td>
<td>Vegetarians are more likely to have lower iron stores compared with NVs.</td>
</tr>
<tr>
<td>Schürmann et al. (2017) [30]</td>
<td>Various</td>
<td>Children</td>
<td>16 studies</td>
<td>Low status of vitamin B12 was reported in one study and low status of vitamin D in two studies.</td>
</tr>
<tr>
<td>Piccoli et al. (2015) [31]</td>
<td>Various</td>
<td>Pregnancy</td>
<td>Nine studies focusing on dietary deficiencies</td>
<td>Vegan-vegetarian diets in pregnancy could be considered safe provided that attention is paid to vitamin and trace element requirements.</td>
</tr>
<tr>
<td>Foster et al. (2015) [27]</td>
<td>Zinc</td>
<td>Pregnancy</td>
<td>6 observational studies</td>
<td>Pregnant vegetarian women had lower zinc intakes than NV control populations and both has lower than recommended amounts.</td>
</tr>
<tr>
<td>Foster et al. (2013) [28]</td>
<td>Zinc</td>
<td>Adults including female sub-analysis</td>
<td>34 studies</td>
<td>Dietary zinc intakes and serum zinc concentrations were significantly lower ($P &lt; 0.001$ and $P = 0.001$) in populations that followed vegetarian diets compared with NVs. Females, vegetarians from developing countries and vegans were most at risk.</td>
</tr>
</tbody>
</table>

Table 2: Evidence from Systematic Review and Meta-analyses.
Key: NV, non-vegetarian

Data on micronutrients intakes was also extrapolated from relevant publications. This included suitably reported intakes for: Vitamin A (µg/day), Thiamin (mg/day), Riboflavin (mg/day), Niacin equivalent (mg/day), Vitamin B6 (mg/day), Vitamin B12 (µg/day), Folate (µg/day), Vitamin C (mg/day), Vitamin D (µg/day) and for the minerals: Iron (mg/d), Calcium (mg/day), Magnesium (mg/day), Potassium (mg/day), Zinc (mg/day), Copper (mg/day), Iodine (µg/day), Selenium (µg/day) and Phosphorus (mg/day). Micronutrients intakes extrapolated from studies were compared against UK dietary guidelines [25].

<table>
<thead>
<tr>
<th>Author(s), year</th>
<th>Type of study</th>
<th>Country &amp; Type of diet</th>
<th>Sample Size</th>
<th>Sample age</th>
<th>Gender</th>
<th>Sources of micronutrients</th>
<th>Main findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allès et al. (2017) [32]</td>
<td>Cross-sectional</td>
<td>French vegetarians and vegans</td>
<td>n=2370 vegetarians, n=789 vegans</td>
<td>Mean 48.7 years</td>
<td>n=2,610 females, n=549 males</td>
<td>Calculated from foods + drinks</td>
<td>Vegetarians had the most balanced diets whilst vegans exhibited a higher estimated prevalence of inadequacies for some nutrients, including vitamin B12.</td>
</tr>
<tr>
<td>Schüpbach et al. (2017) [33]</td>
<td>Observational</td>
<td>Swiss vegetarians and vegans</td>
<td>n=100 vegetarians, n=53 vegans</td>
<td>18-50 years</td>
<td>68% vegetarians were female and 60% vegans were female</td>
<td>Calculated from foods</td>
<td>The highest prevalence of deficiencies was 58% for B6 and 34% for niacin in the vegetarian group and 47% in the vegan group, for zinc.</td>
</tr>
<tr>
<td>Elorinne et al. (2016) [34]</td>
<td>Observational</td>
<td>Finnish long-term vegans</td>
<td>n=22</td>
<td>24-50 years</td>
<td>n=16 females, n=6 males</td>
<td>Calculated from foods + drinks (excluded dietary supplements)</td>
<td>Dietary intakes of vitamins B12 and D were lower (P&lt;0.001) in vegans than in non-vegetarians.</td>
</tr>
<tr>
<td>Sobiecki et al. (2016) [35]</td>
<td>Prospective cohort</td>
<td>UK fish eaters, vegetarians and vegans</td>
<td>n=4,531 fish eaters, n= 6,673 vegetarians, n=803 vegans</td>
<td>20-90 years</td>
<td>n=23,886 females, n=6365 mean</td>
<td>Calculated from foods + drinks</td>
<td>There was a high prevalence of vitamin B12 and iodine deficiency in vegans.</td>
</tr>
<tr>
<td>Kristensen et al. (2015) [36]</td>
<td>Observational</td>
<td>Danish vegans</td>
<td>n=70</td>
<td>18-61 years</td>
<td>n=37 females, n=33 males</td>
<td>Calculated from foods + drinks + dietary supplements</td>
<td>For vegans the intake of micronutrients (including supplements) did not reach the NNR for vitamin D, iodine and selenium. Among vegan women vitamin A intake also failed to reach the recommendations.</td>
</tr>
<tr>
<td>Farmer et al. (2014) [37]</td>
<td>Observational</td>
<td>US nondieting and dieting vegetarians</td>
<td>n=432 and n=419</td>
<td>≥19 years</td>
<td>Data collated</td>
<td>Food + dietary supplements</td>
<td>At any caloric amount, vegetarians should optimize intakes of vitamin B-12 and zinc. Vegetarians also need to increase intakes of vitamins A, C, calcium and magnesium.</td>
</tr>
</tbody>
</table>

Table 3: Study Methodologies
### Table 4: Daily Micronutrients Intakes – Vitamins

<table>
<thead>
<tr>
<th>Author(s), year</th>
<th>Country, Study population</th>
<th>Vitamin A (µg/day)</th>
<th>Thiamin (mg/day)</th>
<th>Riboflavin (mg/day)</th>
<th>Niacin equivalent (mg/day)</th>
<th>Vitamin B6 (mg/day)</th>
<th>Vitamin B12 (µg/day)</th>
<th>Folate (µg/day)</th>
<th>Vitamin C (mg/day)</th>
<th>Vitamin D (µg/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allès et al. (2017) [32] *</td>
<td>French vegetarians (n=2370)</td>
<td>1163</td>
<td>1.2</td>
<td>1.7</td>
<td>16.1</td>
<td>1.8</td>
<td>3.6</td>
<td>394</td>
<td>131</td>
<td>2.4</td>
</tr>
<tr>
<td>Allès et al. (2017) [32] *</td>
<td>French vegans (n=789)</td>
<td>1361</td>
<td>1.6</td>
<td>1.7</td>
<td>18.2</td>
<td>2.3</td>
<td>2.7</td>
<td>481</td>
<td>165</td>
<td>1.9</td>
</tr>
<tr>
<td>Schüpbach et al. (2017) [33]</td>
<td>Swiss vegetarians (n=100)</td>
<td>NR</td>
<td>1.3</td>
<td>1.5</td>
<td>12.5</td>
<td>1.9</td>
<td>1.6</td>
<td>368</td>
<td>158</td>
<td>1.2</td>
</tr>
<tr>
<td>Schüpbach et al. (2017) [33]</td>
<td>Swiss vegans (n=53)</td>
<td>NR</td>
<td>2.1</td>
<td>2.0</td>
<td>17.6</td>
<td>2.9</td>
<td>0.2</td>
<td>662</td>
<td>239</td>
<td>0.1</td>
</tr>
<tr>
<td>Elorinne et al. (2016) [34]</td>
<td>Finnish vegans (n=22)</td>
<td>NR</td>
<td>1.7</td>
<td>1.5</td>
<td>27.0</td>
<td>NR</td>
<td>0.9</td>
<td>586</td>
<td>181</td>
<td>5.0</td>
</tr>
<tr>
<td>Sobiecki et al. (2016) [35]</td>
<td>UK fish eaters males</td>
<td>NR</td>
<td>2.0</td>
<td>2.3</td>
<td>22.8</td>
<td>2.6</td>
<td>6.6</td>
<td>457</td>
<td>172</td>
<td>3.9</td>
</tr>
<tr>
<td>Sobiecki et al. (2016) [35]</td>
<td>UK fish eaters females</td>
<td>NR</td>
<td>1.9</td>
<td>2.2</td>
<td>20.9</td>
<td>2.4</td>
<td>6.3</td>
<td>439</td>
<td>173</td>
<td>3.5</td>
</tr>
<tr>
<td>Sobiecki et al. (2016) [35]</td>
<td>UK vegetarian males</td>
<td>NR</td>
<td>2.2</td>
<td>2.4</td>
<td>21.2</td>
<td>2.5</td>
<td>3.1</td>
<td>477</td>
<td>171</td>
<td>2.2</td>
</tr>
<tr>
<td>Sobiecki et al. (2016) [35]</td>
<td>UK vegetarian females</td>
<td>NR</td>
<td>1.9</td>
<td>2.2</td>
<td>18.4</td>
<td>2.3</td>
<td>3.0</td>
<td>438</td>
<td>172</td>
<td>1.8</td>
</tr>
<tr>
<td>Sobiecki et al. (2016) [35]</td>
<td>UK vegan males</td>
<td>NR</td>
<td>2.4</td>
<td>2.0</td>
<td>23.8</td>
<td>2.6</td>
<td>0.8</td>
<td>539</td>
<td>189</td>
<td>2.0</td>
</tr>
<tr>
<td>Sobiecki et al. (2016) [35]</td>
<td>UK vegan females</td>
<td>NR</td>
<td>2.2</td>
<td>1.7</td>
<td>20.4</td>
<td>2.3</td>
<td>0.7</td>
<td>480</td>
<td>187</td>
<td>1.6</td>
</tr>
<tr>
<td>Kristensen et al. (2015) [36]</td>
<td>Danish vegan males (n=33)</td>
<td>NR</td>
<td>2.1</td>
<td>1.2</td>
<td>21.3</td>
<td>2.5</td>
<td>0</td>
<td>628</td>
<td>221</td>
<td>0</td>
</tr>
<tr>
<td>Kristensen et al. (2015)[36]</td>
<td>Danish vegan females (n=37)</td>
<td>NR</td>
<td>1.5</td>
<td>1.0</td>
<td>17.5</td>
<td>1.9</td>
<td>0</td>
<td>578</td>
<td>221</td>
<td>0</td>
</tr>
<tr>
<td>Farmer et al. (2014) [37]</td>
<td>US nondieting vegetarians (n=432)</td>
<td>801</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>3.8</td>
<td>NR</td>
<td>127</td>
<td>NR</td>
</tr>
<tr>
<td>Farmer et al. (2014) [37]</td>
<td>US dieting vegetarians (n=419)</td>
<td>600</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>3.9</td>
<td>NR</td>
<td>91</td>
<td>NR</td>
</tr>
<tr>
<td>NRV** Males</td>
<td>-</td>
<td>700</td>
<td>1.0</td>
<td>1.3</td>
<td>16.5</td>
<td>1.4</td>
<td>1.5</td>
<td>200</td>
<td>40</td>
<td>10</td>
</tr>
<tr>
<td>NRV** Females</td>
<td>-</td>
<td>600</td>
<td>0.8</td>
<td>1.1</td>
<td>13.2</td>
<td>1.2</td>
<td>1.5</td>
<td>200</td>
<td>40</td>
<td>10</td>
</tr>
</tbody>
</table>
Key: *data adjusted for age, sex and total energy intake; **extrapolated for adults aged 19-64 years; NR, not reported. Those highlighted in grey fall below UK nutrition guidelines

<table>
<thead>
<tr>
<th>Author(s), year, country</th>
<th>Study population</th>
<th>Iron (mg/d)</th>
<th>Calcium (mg/day)</th>
<th>Magnesium (mg/day)</th>
<th>Potassium (mg/day)</th>
<th>Zinc (mg/d)</th>
<th>Copper (mg/day)</th>
<th>Iodine (µg/day)</th>
<th>Selenium (µg/day)</th>
<th>Phosphorus (mg/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allès et al. (2017) [32*]</td>
<td>French vegetarians (n=2370)</td>
<td>15.4</td>
<td>960</td>
<td>408</td>
<td><strong>3139</strong></td>
<td>9.9</td>
<td>2.0</td>
<td>223</td>
<td>65</td>
<td>1258</td>
</tr>
<tr>
<td>Allès et al. (2017) [32*]</td>
<td>French vegans (n=789)</td>
<td>18.6</td>
<td>760</td>
<td>495</td>
<td>3676</td>
<td>10.0</td>
<td>2.5</td>
<td>248</td>
<td>64</td>
<td>1250</td>
</tr>
<tr>
<td>Schüpbach et al. (2017) [33]</td>
<td>Swiss vegetarians (n=100)</td>
<td>14.7</td>
<td>1116</td>
<td>448</td>
<td><strong>3440</strong></td>
<td>10.2</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>1359</td>
</tr>
<tr>
<td>Schüpbach et al. (2017) [33]</td>
<td>Swiss vegans (n=53)</td>
<td>22.9</td>
<td>817</td>
<td>702</td>
<td>5375</td>
<td>11.5</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>1427</td>
</tr>
<tr>
<td>Elorinne et al. (2016) [34]</td>
<td>Finnish vegans (n=22)</td>
<td>21.0</td>
<td>1004</td>
<td>NR</td>
<td>NR</td>
<td>12.0</td>
<td>NR</td>
<td>NR</td>
<td>79</td>
<td>NR</td>
</tr>
<tr>
<td>Sobiecki et al. (2016) [35]</td>
<td>UK fish eaters males</td>
<td>17.8</td>
<td>1173</td>
<td>444</td>
<td>4242</td>
<td>10.7</td>
<td>1.7</td>
<td>197</td>
<td><strong>72</strong></td>
<td>NR</td>
</tr>
<tr>
<td>Sobiecki et al. (2016) [35]</td>
<td>UK fish eaters females</td>
<td>16.3</td>
<td>1115</td>
<td>414</td>
<td>4082</td>
<td>10.1</td>
<td>1.6</td>
<td>195</td>
<td>64</td>
<td>NR</td>
</tr>
<tr>
<td>Sobiecki et al. (2016) [35]</td>
<td>UK vegetarian males</td>
<td>18.3</td>
<td>1153</td>
<td>451</td>
<td>4133</td>
<td>10.9</td>
<td>1.8</td>
<td>141</td>
<td><strong>55</strong></td>
<td>NR</td>
</tr>
<tr>
<td>Sobiecki et al. (2016) [35]</td>
<td>UK vegetarian females</td>
<td>16.2</td>
<td>1099</td>
<td>407</td>
<td>3908</td>
<td>10.0</td>
<td>1.6</td>
<td>146</td>
<td><strong>45</strong></td>
<td>NR</td>
</tr>
<tr>
<td>Sobiecki et al. (2016) [35]</td>
<td>UK vegan males</td>
<td>19.9</td>
<td>862</td>
<td>505</td>
<td>4243</td>
<td>9.4</td>
<td>2.2</td>
<td>56</td>
<td>62</td>
<td>NR</td>
</tr>
<tr>
<td>Sobiecki et al. (2016) [35]</td>
<td>UK vegan females</td>
<td>17.6</td>
<td>839</td>
<td>452</td>
<td>3972</td>
<td>8.4</td>
<td>2.0</td>
<td>54</td>
<td>52</td>
<td>NR</td>
</tr>
<tr>
<td>Kristensen et al. (2015) [36]</td>
<td>Danish vegan females (n=37)</td>
<td>13.5</td>
<td>724</td>
<td>484</td>
<td>3602</td>
<td><strong>8.6</strong></td>
<td>NR</td>
<td>65</td>
<td>25</td>
<td>1249</td>
</tr>
<tr>
<td>Farmer et al. (2014) [37]</td>
<td>US nondieting vegetarians (n=432)</td>
<td>17.9</td>
<td>NR</td>
<td>349</td>
<td>NR</td>
<td>10.2</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>Farmer et al. (2014) [37]</td>
<td>US dieting vegetarians (n=419)</td>
<td>15.4</td>
<td>NR</td>
<td>283</td>
<td>NR</td>
<td>9.9</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
</tr>
</tbody>
</table>

| **NRV** - Males | | 8.7 | 700 | 300 | 3500 | 9.5 | 1.2 | 140 | 75 | 550 |
| **NRV** - Females | | 14.8(19-50y) 8.7 (50-64y) | 700 | 270 | 3500 | 7.0 | 1.2 | 140 | 60 | 550 |

Table 5: Daily Micronutrients Intakes-Minerals
Results

Sixty-one titles and abstracts were screened-58 publications identified through PubMed and three from literature reference lists. Of these, 50 publications were excluded. Twenty-seven did not focus specifically on the topic of plant-based diets. Eight publications were irrelevant (none systematic) reviews or book chapters. Six studies focused on micronutrient status rather than intakes, typically for just one or two nutrients. In four studies, other variations of diet other that plant-based diets were followed. Three studies were not conducted in the last 10 years, one focused on the nutritional profile of breast milk and another did not report dietary data as a mean daily intake. This resulted in 11 key publications being identified-five systematic review/meta-analysis papers and six separate observational studies which collated evidence from 16,262 participants.

Focusing on meta-analytical evidence, this is highly regarded from a scientific stance and placed at the top of the hierarchy of evidence [26]. Two meta-analysis articles focused on zinc profiles [27, 28]. A systematic review using data from six observational studies concluded that zinc intakes of pregnant vegetarians was significantly lower (about 1.53mg lower) compared with non-vegetarians [27]. An earlier review by the same author evaluated evidence from 34 studies finding that both serum and zinc intakes were significantly lower in those with habitual vegetarian diets compared with non-vegetarians, with females being particularly vulnerable [28].

A meta-analysis of 27 cross-sectional and 3 observational studies conducted by Haider et al. (2018) [29] found that serum ferritin levels were significantly lower in adult vegetarians versus non-vegetarian controls and that effects were more pronounced in men. In 2017 Schürmann and colleagues [30] pooled evidence from 16 studies with a median sample size of 35 study subjects focusing on vegetarianism in childhood. Of the nutrients, shortfalls in vitamins B12 and D were apparent but there was a bias in studies towards upper social classes indicating that this was possibly 'best case scenario' [30]. Piccoli et al. (2015) [31] reviewed findings from nine heterogeneous studies on vitamins and microelements, concluding that pregnant vegan-vegetarian women could be at risk of vitamin B12 and iron deficiencies.

Observational evidence studies were predominantly undertaken on vegetarian and vegan populations [32-36]. Sample sizes varied, with the smallest study being comprised of n=22 Finnish vegans [34] and the largest study consisting of 12,007 pescatarians, vegetarians and vegans [35]. Studies generally observed some benefits but equally certain micronutrient shortfalls when these diets were followed. Of the micronutrients, habitual vitamin D intakes fell below UK Government guidance of 10μg daily in all studies comprised of 16,262 participants [32-37]. Vitamin B12 intakes amongst vegans fell below dietary targets in four studies, for males and females alike (n=948) [33-36]. Selenium, zinc and iodine intakes were suboptimal and did not meet UK dietary guidance in two studies [35, 36] and potassium fell below guidelines in two separate studies focusing on vegetarians [32, 33]. Niacin and riboflavin shortfalls were apparent in other studies [33, 36].

Focusing on separate studies, the French NutriNet-Santé Study found that vegetarians had higher prevalence of inadequacy for thiamin (men and women), niacin (only in men <65 years of age), B6 (men <65 years of age and women), zinc, and potassium (for men and women <55 years of age) compared to other diets groups [32]. In the same study, vegans had the highest prevalence of shortfalls for total vitamin A, riboflavin (men and women <55 years of age), B12 (for all men, as well as women <55 years of age) and calcium (for women >55 years of age) [32].

In Switzerland, research conducted on 153 vegetarians and vegans showed that vitamin and mineral requirements could be fulfilled provided that a well-balanced diet which included supplements of fortified foods was provided [33]. The research showed that vegans tended to report lower intakes of calcium and had marginal intakes of vitamin D and B12 with the lower risk of deficiencies being attributed to supplement use, particularly for vitamin B12 [33]. Sobiecki et al. (2016) [35] undertook one of the largest studies to date comprised of 12,007 pescatarians, vegetarians and vegans using data from the EPIC Nutrition-Oxford study. Results were strongly suggestive of a high prevalence of certain dietary inadequacies for vegetarians, and particularly for vegans, which included vitamin B12, iodine and possible zinc and selenium [35]. Authors also emphasised the use of supplements and fortified foods alongside appropriate food choices [35]. In an earlier study, Farmer et al. (2014) [37] concluded that vegetarian diets could be used for weight management but care should be taken to optimise nutritional profiles especially vitamins B12 and zinc.

Elorinne et al. (2016) [34] focused specifically on the diet of 22 Finnish vegans, finding that their intakes of vitamin B12 and D were lower than vegetarians’. Serum biomarkers in this study also showed lower levels of 25-hydroxyvitamin D3, selenium and iodine, highlighting the need for targeted nutritional guidance [34]. Amongst Danish vegans, Kristensen et al. (2015) [36] observed significant variations compared with the lay population. Even when supplements were included, vitamin D, iodine and selenium intakes did not reach Nordic Nutrition Recommendations and vitamin A fell short of dietary targets amongst vegan females [36].

Discussion

The popularity of plant-based diets is escalating at a notable pace yet their nutritional viability is still largely under investigation. Evidence from systematic reviews and meta-analysis papers shows that vitamin B12 [30], vitamin D [30], zinc [27, 28] and iron shortfalls [29] are most common. Over the last 10 years, six observational studies (n=16,262 participants) have monitored dietary intakes amongst populations whose diets were pescatarian, vegetarian or vegan [32-37]. From these studies alone it can be seen that vitamin B12 [33, 35, 36], D [32-37], iodine [35, 36], zinc [35, 36] and selenium [35, 36] shortfalls were apparent.

It should, however, be considered that a larger body of evidence is needed to build on findings from these studies. Within this...
work, a broader spectrum of nutrients should be considered. For example, choline was not reported in any of the observational studies and is quite often overlooked [38]. Similarly, data on omega-3 fatty acid intakes from plant-based diets is also lacking. Additionally, ongoing work investigating sub-sections of the population e.g. according to age and sex is required to better understand their micronutrient profiles. Most of the studies also recruited subjects who were vegetarian, vegan or pescatarian rather than following a formal definition of a 'plant-based' diet. This highlights the lack of evidence relating specifically to 'plant-based' diets using definitions that are aligned with contemporary definitions, such as the EAT Lancet.

What constitutes a plant-based diet also needs more consideration. Just like any other, if improperly balanced, this type of diet can result in suboptimal intakes of certain nutrients. It has been reported that plant-based diets do not necessarily prevent chronic diseases [39]. For example, in a large US study equivalent to 4,833,042 person-years of follow-up, data from the Nurses’ Health Study and Health Professionals Follow-up Study showed that healthier plant-based food consumption (e.g. fruits, vegetables and whole grains) was linked to lower coronary heart disease (CHD) risk but, in contrast, less-healthy plant food consumption (e.g. sweets and refined grains) was related to higher CHD risk [40]. Other work using NHANES female adolescent data showed that when plant-based foods were increased by 100% there were reductions in zinc, calcium and vitamin D intakes [41]. This demonstrates that in some instances, unhealthful plant-based diets could have unintended nutritional ramifications.

Balanced plant-based diets and their micronutrient profiles also become increasingly important during key life-stages where nutritional requirements increase or immune status can change. Sebastiani et al. (2019) [42] evaluated the quality of vegetarian and vegan diets during pregnancy, finding that well-planned diets can be considered safe although a strong awareness about what constitutes a balanced diet is needed. Of the nutrients, vitamin B12, calcium, vitamin D, iron, iodine and omega-3 were most likely to be deficient in vegan or vegetarian pregnant mothers [42]. In a systematic review focusing on vegetarian children, intakes of vitamin C, folate and dietary fibre were favourable whilst vitamin B12 and D status tended to be lacking in some studies [30]. The prevalence of iron deficiency has also been found to be significantly higher amongst vegetarian children, despite having high vitamin C intakes [43].

Elsewhere, low iron status in vegetarian children has been linked to reduced immunoglobulin levels [44]. Amongst athletes and exercisers following vegan diets, vitamin B12, iron, zinc, calcium, vitamin D, iodine and long-chain n-3 fatty acids have been identified as nutrients to be monitored [45].

A number of confusions are also evident within the public domain when it comes to definitions and characteristics of plant-based diets. A recent UK Omnibus survey [46] (n=1,051 participants on varied diets) identified that 49% viewed vegan or vegetarian diets as being 'plant-based'. Forty-four per cent admitted that they never researched the nutritional ramifications of switching diets and 95 per cent had not sought advice from a General Practitioner, dietitian nor nutritionist about their diet. Thirty-four per cent were most likely to obtain any advice that they required from online sources. One in five were unaware of which nutrients vegan diets could be lacking in and 48 per cent of respondents were not taking a multivitamin or mineral supplement. One-third (31%) stated that they would like more guidance on what supplements to take, with 53% reporting that this should come from a registered nutritionist.

**Ways Forward**

Given the apparent gaps that appear to exist, updated fortification and supplementation strategies and related public health guidance would be worthy of consideration. In particular, these should continue to focus on vitamin D. Currently in the UK, a Reference Nutrient Intake of 10μg of Vitamin D daily is recommended for adults throughout the year in order to protect bone and muscle health [47]. These guidelines are currently targeted at everyone in the general UK population and no specific mentions are given as of yet to those following plant-based diets. Such an approach could be considered in the future as the evidence-base further builds. It should also be made aware that some vitamin D3 supplements are not appropriate for vegans whilst vitamin B2 and lichen-derived vitamin B3 are generally suitable [24].

Vitamin B12 shortfalls were also apparent in the present review [30, 32, 34, 35, 37]. Elsewhere in the EPIC-Oxford Cohort study comprised of 689 men (232 of which were vegan) half the vegan males were B12 deficient according to their serum levels [48]. This is not surprising given that foods of ruminant origin, i.e. dairy and meat products, are predominant sources of B12 [49]. Alongside dietary inadequacy of this nutrient, its absorption is also generally limited which can be attributed to genetic factors and/or acquired diseases, e.g. inflammatory bowel disease or iatrogenic conditions (caused by gastric acid suppression medications which impair B12 release from foods) [50]. Provisional evidence has linked low serum B12 levels to cognitive impairment and neurodegenerative disease [51]. Subsequently, for those following a plant-based diet, regular consumption of fortified breakfast cereals (ideally twice daily), non-dairy milks, yeast extracts or taking a supplement could help to optimise B12 status [24].

Iodine intakes were also in shortfall in several studies (n=12,077) [35, 36]. In pregnancy, iodine intakes without supplements have been reported to be 190μg/d - lower than that of the WHO’s 250μg/d recommendation [52]. Low iodine intake amongst women of childbearing age is concerning as this has been associated with maternal and foetal hypothyroidism and impaired neurological development of the foetus [53]. Bearing this in mind, greater awareness about the iodine profile of plant-based foods across this particular sector of the lifecycle would be worthwhile. The iodine content of plant foods can be highly variable as this depends on levels of iodine in the soil and groundwater which are low in many parts of the world [54]. Foods such as iodised salt and seaweed can provide iodine and iodine can also be found in supplements, typically in the forms of potassium iodide or iodate which should not exceed adult daily requirements of 150μg [55]. Finally, the bioavailability of micronutrients from plant-based foods needs to be better understood. It has long been known that bioactive substances present in plant-foods can alter mineral bioavailability and vitamin requirements [56, 57]. For example, high intakes of phytate-containing legumes and
wholegrains have been attributed to reduced iron and zinc absorption [58]. Subsequently, the European Food Safety Authority has established zinc requirements based on four levels of phytate intake [59, 60]. This highlights the need for growing awareness about such issues, along with the need for phytate food composition data.59 Interestingly, a re-analysis of the iron content of plant-based food showed that there has been a fall in natural dietary iron content which has been negated and possibly surpassed by iron from fortificants—though the long-term ramifications of this are unclear [61].

Conclusions

Plant-based diets are becoming increasingly widespread in that any individual is more likely than previously to choose a plant-based diet in his/her own lifetime. Undoubtedly, these have an important role to play from an environmental and health stance but their nutritional viability is less conclusive. Present research indicates that such diets, if improperly balanced, may lead to vulnerabilities in vitamin B12 and D intakes, with other shortfalls including iodine, iron, zinc, selenium and omega-3 fatty acids being reported.

This is of particular concern and relevance at key life stages such as childhood, pregnancy and lactation. Therefore, consideration should be given to reinforcing plant-based diets at these life stages with the use of a daily multivitamin and mineral supplement or fortified food sources. Ongoing research is now needed to better observe, measure and evaluate dietary profiles and status. Alongside this, updated supplementation guidance is also warranted.

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Competing Interests Statement

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