University of Southampton

Faculty of Environment and Life Sciences

School of Biological Sciences

Defining Solutions for the Improvement of Food and Nutrition Security in the UK: Parsnips as a Case Study for Improving Folate Status through Dietary Intervention

by

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Thesis for the degree of Doctor of Philosophy

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Abstract

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Achieving food and nutrient security remains a pressing challenge in the UK, with inadequate dietary quality and widespread micronutrient deficiencies contributing to poor health outcomes. In response, this thesis investigates the potential of parsnips (*Pastinaca sativa* L.) as a case study crop for addressing these challenges. Parsnips were selected as a domestically produced, underutilised, yet micronutrient-dense root vegetable with scope to support healthier and more sustainable diets. Within this context, folate (vitamin B9) was identified as a nutrient of particular interest: it is naturally present in parsnips and simultaneously represents a major public health concern, with consistently low intakes and high deficiency rates across the UK population, especially among adolescents. While forthcoming legislation to mandate folic acid fortification of flour will help alleviate deficiency, fortification alone cannot provide a long-term or holistic solution. This research therefore examines the extent to which parsnips could serve as a complementary dietary source of folate, exploring their nutritional potential from field to fork and their integration into everyday diets through school meal provision as a practical intervention model.

A mixed methods approach combined analysis of nationally representative intake and biomarker data, laboratory studies of parsnip folate content, and modelling of school meal provision. National survey data highlighted that 74.4% of adolescent females had folate intakes below the RNI threshold. Laboratory analyses revealed statistically significant 14.3% difference in total folate content across parsnip varieties and identified 5-methyltetrahydrofolate and tetrahydrofolate as the predominant folate vitamers. Storage trials showed parsnip folate content was maintained over four weeks, while cooking experiments demonstrated that roasting and microwaving increased folate concentration by 67.2% and 96.4%, respectively, whereas boiling caused losses of 18.5%. Nutritional analysis revealed substantial variation in folate provision across school meals in Southampton, UK. A reformulation case study showed that substituting boiled parsnip for boiled potato in Bangers and Mash could increase folate provision by 134.8% for a cost increase of 15.8% per portion.

The findings demonstrate that parsnips are a robust dietary source of folate, retaining nutrient value through storage and cooking methods, and that their integration into institutional food systems could meaningfully improve folate intake. More broadly, this work highlights the potential for UK-grown, nutrient-dense crops to strengthen domestic food systems. By linking crop science, nutrition, and public health, the thesis provides novel evidence of how diet-based interventions can enhance micronutrient security. Future work should expand beyond folate to consider other micronutrients and crops, but the case of parsnips demonstrates the feasibility and value of leveraging traditional, locally appropriate foods in sustainable nutrition strategies.

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List of Accompanying Materials

Some of the work in this thesis was presented at the FENS 2023 conference in Belgrade, Serbia. The opportunity to present at the conference was judged by the submission of an abstract. Successful abstracts were submitted for publication in the Proceedings of the Nutrition Society Journal. The published abstract is submitted alongside this thesis and is also available online at https://doi.org/10.3390/proceedings2023091386.

Research Thesis: Declaration of Authorship

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I declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. None of this work has been published before submission

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Definitions and Abbreviations

BMI ..... Body Mass Index

CoFID ..... The Composition of Food Integrated Dataset

DRV ..... Dietary Reference Value

EAR..... Estimated Average Requirement

EGRAC..... Erythrocyte Glutathione Reductase Activity Coefficient

ETKAC..... Erythrocyte Transketolase Activity Coefficient

FAO ..... Food and Agriculture Organization

FSA..... Food Standards Agency

GBP ..... Great British Pounds

HPLC ..... High-Performance Liquid Chromatography

LRNI ..... Lower Reference Nutrient Intake

NDNS ..... The National Diet and Nutrition Survey Rolling Programme

NTD ..... Neural Tube Defect

PGA ..... Folic acid

PHE ..... Public Health England

RNI ..... Reference Nutrient Intake

SMP ..... School meal provider

THF..... Tetrahydrofolate

USD ..... United States Dollar

5-CH_3-THF 5-methyltetrahydrofolate

5-CHO-THF..... 5-formyltetrahydrofolate

5,10-CH^+-THF..... 5,10-methenyltetrahydrofolate

10-CHO-PGA ..... 10-formylfolic acid

Chapter 1 General Introduction

"Let food be thy medicine, and medicine be thy food" - Hippocrates

1.1 Global Food Security

In November 1996, political leaders of 112 countries gathered in Rome to attend the World Food Summit (FAO, 2002). At this summit, a major, time-bound, goal to address global hunger and malnutrition was put into writing, with the corresponding Rome Declaration on World Food Security outlining that:

> "We, the Heads of State and Government, or our representatives, gathered at the World Food Summit... reaffirm the right of everyone to have access to safe and nutritious food, consistent with the right to adequate food and the fundamental right of everyone to be free from hunger. We pledge our political will and our common and national commitment to achieving food security for all and to an ongoing effort to eradicate hunger in all countries, with an immediate view to reducing the number of undernourished people to half their present level no later than 2015." (FAO, 1996)

The current definition of food security comes from this commitment, and is described as the conditions under which 'all people, at all times, have physical and economic access to sufficient safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life' (FAO, 1996). Although it is now long past 2015 and the goals set at the 1996 World Food Summit remain unmet (FAO et al., 2024), this definition of food security is still widely used, as it encompasses not just the need for sufficient calories, but also the cultural, societal and economic aspects of food, nutrition, and health. Furthermore, this definition includes details of the 'pillars of food security' – food availability, food access, food utilisation, and food sustainability/stability (World Bank Group, 2024). These pillars highlight the multifaceted nature of food security, and therefore, the multifaceted solutions needed to enable global food security to be achieved (Johnstone and Lonnie, 2024).

1.2 Food Security in the UK

The United Kingdom (UK) is the sixth largest global economy (Silver, 2025; The World Bank, 2025), with a GDP of over $3.6 trillion (Silver, 2025; The World Bank, 2025) and the 13th highest Human Development Index ranking in the world (United Nations Development Programme, 2025). Despite this prosperity, the FAO categorised 2.3 million people, or 3.3%, of the UK

population as severely food insecure, averaged over data between 2022 and 2024 (FAO *et al.*, 2025), with only Ukraine, Romania, Republic of Moldova, Hungary, Albania, and North Macedonia performing worse in Europe (FAO *et al.*, 2025). Furthermore, recent global challenges – such as the coronavirus pandemic and cost of living crisis – have made this statistic even worse (Food Standards Agency, 2022; Shinwell *et al.*, 2022; Stone *et al.*, 2024); data from the Food Foundation suggest that as many as 7.3 million households in the UK, or 13.9% of households, experienced food insecurity in January 2025 (Food Foundation, 2025). Overall, the state of food security in the UK is poor in comparison to other countries in Europe, despite its high prosperity and wealth (Yau *et al.*, 2020). To decrease levels of food insecurity, it is essential to understand the causes and consequences of poor food security in the UK in greater detail. There is also a need for holistic solutions that improve food security whilst aligning with broader governmental priorities, including economic growth, environmental sustainability, and wider public health (Department for Levelling Up, Housing and Communities, 2022; Shinwell *et al.*, 2022).

The 2020 Agriculture Act mandates that the UK Government submit a report of statistical data on the state of food security in the UK to Parliament at least every three years (Department for Environment, Food & Rural Affairs, 2024b). The latest of these reports was published in 2024, and presented data across five themes: global food availability, UK food supply sources, food supply chain resilience, food security at a household level, and food safety and consumer confidence (Department for Environment, Food & Rural Affairs, 2024b). Whilst the report covers trade, food production, and sustainability in detail, it makes little mention of the UK consumers themselves. This is a notable omission, as the diverse and changing demographics of the UK population influence both nutritional requirements and food preferences (Stone *et al.*, 2024), each of which form part of the working definition of food security (FAO, 1996). Therefore, the report disconnects issues of food availability and sustainability from food access and utilisation, and considers food supply separately to human health and nutrition. In this thesis, all research undertaken is considered in the wider demographic context of the UK. In this way, issues of food access, nutrition, and health are united with explorations of food availability and sustainability, providing a holistic understanding of food security in the UK.

1.3 Food, nutrition, and health

Most people in the UK do not eat a healthy diet (Rayner and Scarborough, 2005; Roberts *et al.*, 2018; Steel *et al.*, 2018; Mason *et al.*, 2019; Public Health England, 2020; Scheelbeek *et al.*, 2020; Food Standards Agency, 2022), and up to 13% of all deaths in the UK have been attributed to diet-related ill health (Rayner and Scarborough, 2005; Food Standards Agency, 2022).

Furthermore, the quality of diet in the UK is declining over time: over the last 20 years, there has been a trend of decreasing consumption of minerals and vitamins, whilst consumption of high fat, salt, and sugar foods has increased (Public Health England, 2020; Jones *et al.*, 2023; Johnstone and Lonnie, 2024). Whilst the causes of these trends are not fully understood, several contributing factors have been proposed, including the increasing price of healthy food options, reduced time and resources to prepare healthy foods, higher levels of fast food and pre-prepared food consumption, and even changing working patterns, which may all be contributing to worsening dietary habits for UK consumers (Yau *et al.*, 2020; Food Standards Agency, 2022; Jones *et al.*, 2023; Carrillo-Alvarez *et al.*, 2025).

Furthermore, socioeconomic status is a factor that creates clear inequalities in the consumption of healthy food across the UK (Yau *et al.*, 2020; The Department for Environment & Rural Affairs, 2021a; Chapman and Wentworth, 2024; Johnstone and Lonnie, 2024; Carrillo-Alvarez *et al.*, 2025). In part, this may stem from higher rates of food insecurity in more deprived socioeconomic groups (The Department for Environment & Rural Affairs, 2021b; Shinwell *et al.*, 2022; Jones *et al.*, 2023; Carrillo-Alvarez *et al.*, 2025). However, differences in the food environment may also play a role (Hawkesworth *et al.*, 2017; Maguire *et al.*, 2017; Burgoine *et al.*, 2018; Johnstone and Lonnie, 2024).

The term 'food environment' describes the 'collective physical, economic, policy and sociocultural surroundings, opportunities and conditions that influence people's food and beverage choices and nutritional status' (Swinburn *et al.*, 2013). A good food environment is dependent on good food security as the availability and accessibility of food is key for allowing people to make healthy dietary choices. In addition, the food environment considers the impact of factors such as food promotion, advertising, and food safety, on consumer behaviour and, therefore, diets (HPLE, 2017). These factors may significantly impact dietary quality (Johnstone and Lonnie, 2024). For example, the most socioeconomically deprived areas of the UK have double the number of fast-food outlets per capita compared to the least deprived areas (The Department for Environment & Rural Affairs, 2021a), and junk food advertisements appear six times more frequently per kilometre of road (Bite Back, 2025). It is likely, therefore, that people in the UK's most deprived communities are under more pressure to consume unhealthy foods, and consequently, may be more likely to choose unhealthy diets, even when they could afford and access healthier options (Maguire *et al.*, 2017; Burgoine *et al.*, 2018; Yau *et al.*, 2020; Johnstone and Lonnie, 2024). While this thesis focuses primarily on food security, improving the food environment will also be treated as a twin objective, particularly in Chapter 2 and Chapter 5, where the findings may benefit the wider UK population, not just those experiencing food insecurity.

Access to a nutritionally adequate, balanced, and diverse diet is a cornerstone of human health (Miller, Spiro and Stanner, 2016; Kandel, 2019; Cena and Calder, 2020; Springmann *et al.*, 2020; English *et al.*, 2024). The macronutrients and micronutrients derived from food are essential not only for the structural and metabolic integrity of the body (Bloom *et al.*, 2018; Robinson, Granic and Sayer, 2019; Beck *et al.*, 2021; Bianchi *et al.*, 2024; Schalla *et al.*, 2024), but also for supporting immune function (Chandra, 1997; Childs, Calder and Miles, 2019; Gombart, Pierre and Maggini, 2020; Munteanu and Schwartz, 2022), preventing non-communicable diseases (Afshin *et al.*, 2019; Grosso, 2019; Ruthsatz and Candeias, 2020; Alamnia, Sargent and Kelly, 2023), promoting a healthy gut microbiome (Singh *et al.*, 2017; Leeming *et al.*, 2019; Zhang, 2022; Rinninella *et al.*, 2023; Ross *et al.*, 2024), and promoting overall psychological and physiological wellbeing (O'Neil *et al.*, 2014; Afshin *et al.*, 2019; Springmann *et al.*, 2020; Yau *et al.*, 2020; Rucklidge *et al.*, 2025). In fact, higher dietary quality has been found to predict lower risk of all-cause mortality, independent of genetic background or genetic risk of disease (Afshin *et al.*, 2019; Scheelbeek *et al.*, 2020; Livingstone *et al.*, 2021; Chapman and Wentworth, 2024; Carrillo-Alvarez *et al.*, 2025). These relationships highlight the fundamental role of nutrition in determining health trajectories and underscore the critical need to ensure and promote healthy diets, by improving both food security and the wider food environment.

1.4 Focus on micronutrients

Micronutrients are components of the diet that are essential for the functioning of the human body (Shenkin, 2006; Shergill-Bonner, 2017; Kumar *et al.*, 2024; WHO, no date). They include both organic substances, known as vitamins, and inorganic substances, known as minerals (Shenkin, 2006; Shergill-Bonner, 2017; Kumar *et al.*, 2024; WHO, no date). They are required in much smaller amounts than macronutrients, with only milli or even micro grams needed daily (Shenkin, 2006; Public Health England, 2016; Shergill-Bonner, 2017). Despite being needed in such small quantities, micronutrients are vital for numerous biochemical processes, including DNA synthesis, gene expression, enzyme mediated metabolism, and antioxidant activity (Shenkin, 2006; Shergill-Bonner, 2017; Cena and Calder, 2020; Kumar *et al.*, 2024; Espinosa-Salas and Gonzalez-Arias, 2025). Around one-third of the global population suffers from deficiency in at least one micronutrient (HPLE, 2017; Han *et al.*, 2022; Sheoran *et al.*, 2022). Although there are 30 micronutrients known to be essential to human health (Shergill-Bonner, 2017), deficiencies in iron, vitamin A, iodine, folate, and zinc are the most common globally (HPLE, 2017; Han *et al.*, 2022). A brief overview of the functions, deficiency symptoms, and dietary sources of these key micronutrients is shown in Table 1-1.

Table 1-1 Overview of micronutrients of key public health concern

Micronutrient (alternative names)	Type of micronutrient	Key roles	Dietary sources
Folate (Vitamin B9)	Vitamin	DNA synthesis; gene expression; red blood cell production; prevention of neural tube defects	Offal, lentils, spinach, broccoli, yeast, fortified bread, fortified breakfast cereals, beetroot, parsnips
Iodine	Mineral	Thyroid hormone synthesis	Milk, eggs, shrimp, cod, tuna, seaweed, iodised salt
Iron	Mineral	Enzyme mediated reactions; haemoglobin synthesis; DNA, amino acid, neurotransmitter, collagen, and hormone synthesis; antioxidant activity; immune function	Beef, oysters, beans, lentils, spinach, eggs, raisins, fortified cereals, tomatoes
Vitamin A (Retinol)	Vitamin	Cell growth and development; vision; immune function	Beef liver, eggs, butter, fortified cereal, fortified milk, sweet potato, carrots, spinach, broccoli, butternut squash
Zinc	Mineral	Enzyme mediated reactions; haemoglobin production; antioxidant activity; immune function	Beef, oysters, crab meat, yoghurt, milk, cashews, chickpeas, peanuts, cheese

Table adapted from (Linus Pauling Institute, 2024)

For a diet to be considered healthy, it must: 1) provide sufficient calories, protein, fat, and fibre to support growth and development of the body - preventing hunger, wasting, and starvation; and 2) supply adequate amounts of all essential micronutrients needed for normal bodily function (Stipanuk and Caudill, 2018; Cena and Calder, 2020; Sheoran *et al.*, 2022; Espinosa-Salas and Gonzalez-Arias, 2025). A diet that meets the first criterion but not the second cannot be described as healthy, as it will not support the functions required for an active and fulfilling life (Sheoran *et al.*, 2022).

Historically, food security has been understood primarily in terms of the first criterion—preventing hunger and starvation. This focus is understandable, as meeting the second criterion is unlikely if the first is not fulfilled. However, in the UK, insufficient diet quantity affects fewer people than poor diet quality; in fact, more individuals in the UK suffer from overweight and obesity than from wasting and starvation (Johnstone and Lonnie, 2024; Malnutrition Task Force, 2024; Stiebahl, 2025). It could therefore be argued that a deeper understanding of the

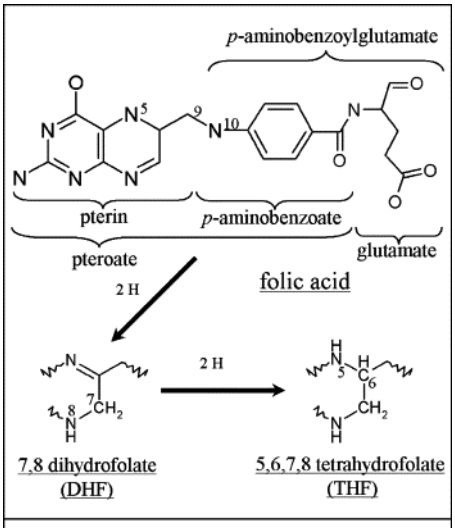
micronutrient content of diets may offer a more meaningful assessment of food insecurity in the UK than focussing on calories and food quantity alone. By examining the availability and adequacy of food-derived micronutrients, this thesis aims to provide a more detailed understanding of food security in the UK, offering greater insight into the health and wellbeing benefits associated with sufficient micronutrient intakes.

1.5 Folate – sources, uptake, and metabolism

As outlined above, folate is a micronutrient of significant public health importance. For this reason, and others discussed in detail in Chapter 2, folate will be a primary focus of this thesis. While the full rationale is presented in Chapter 2, an overview of folate as a key metabolite and micronutrient is provided here in preparation for discussion in later chapters.

1.5.1 Overview

The term folate refers to all forms of the vitamin B9, including folic acid, a purely synthetic form, and the over 150 folate vitamers found in nature (Quinlivan, Hanson and Gregory, 2006; Rébeillé *et al.*, 2006; Saini, Nile and Keum, 2016; Gmelch *et al.*, 2020). All folates share a common three-part structure: a pterin ring, a *p*-aminobenzoate moiety, and one or more glutamate residues (Figure 1-1). They vary in the number of glutamate residues and in the redox state of the pterin ring and *p*-aminobenzoate moiety (Figure 1-1), causing differences in stability and biological function (Delchier *et al.*, 2016; Gmelch *et al.*, 2020; Wusigale and Liang, 2020; Siatka *et al.*, 2025). Although all higher organisms require folate for primary metabolism, no animals can synthesise folate *de novo*, instead relying on the consumption and assimilation of folates from their diets (Delchier *et al.*, 2016; Gorelova *et al.*, 2017; Siatka *et al.*, 2025).



one-carbon unit	trivial name	abbreviation
N^5–**CH_3**	5-methyl-THF	5-CH3-THF
N^5–**CHO**	5-formyl-THF	5-CHO-THF
N^5–**CH=NH**	5-formimino-THF	5-NH=CH-THF
OHC–N^{10}	10-formyl-THF	10-CHO-THF
N^5=**CH**=N^{10}	5,10-methenyl-THF	5,10-CH=THF
N^5–**CH_2**–N^{10}	5,10-methylene-THF	5,10-CH2-THF

Figure 1-1 Conservation and variation in the structure of folates. Figure source: (Quinlivan, Hanson and Gregory, 2006)

1.5.2 Function

Folate is essential for red blood cell production, DNA synthesis, the synthesis of certain amino acids, and the regulation of gene expression through methylation, whilst also acting as a cofactor in a range of biological reactions (Lynn B Bailey *et al.*, 2015; Saini, Nile and Keum, 2016, 2016; Wusigale and Liang, 2020; Jones *et al.*, 2023; Siatka *et al.*, 2025). To achieve these variable functions, folates undergo transformation between a variety of redox states, both spontaneously, and via enzyme mediated reactions (Figure 1-2). For example, methionine synthase converts 5-methyltetrahydrofolate to tetrahydrofolate, enabling the regeneration of methionine from homocysteine – a key step in DNA methylation – whilst the spontaneous reduction of 10-formyltetrahydrofolate to tetrahydrofolate produces purines for DNA synthesis (Peters *et al.*, 2013; Lynn B Bailey *et al.*, 2015; Siatka *et al.*, 2025) (Figure 1-2).

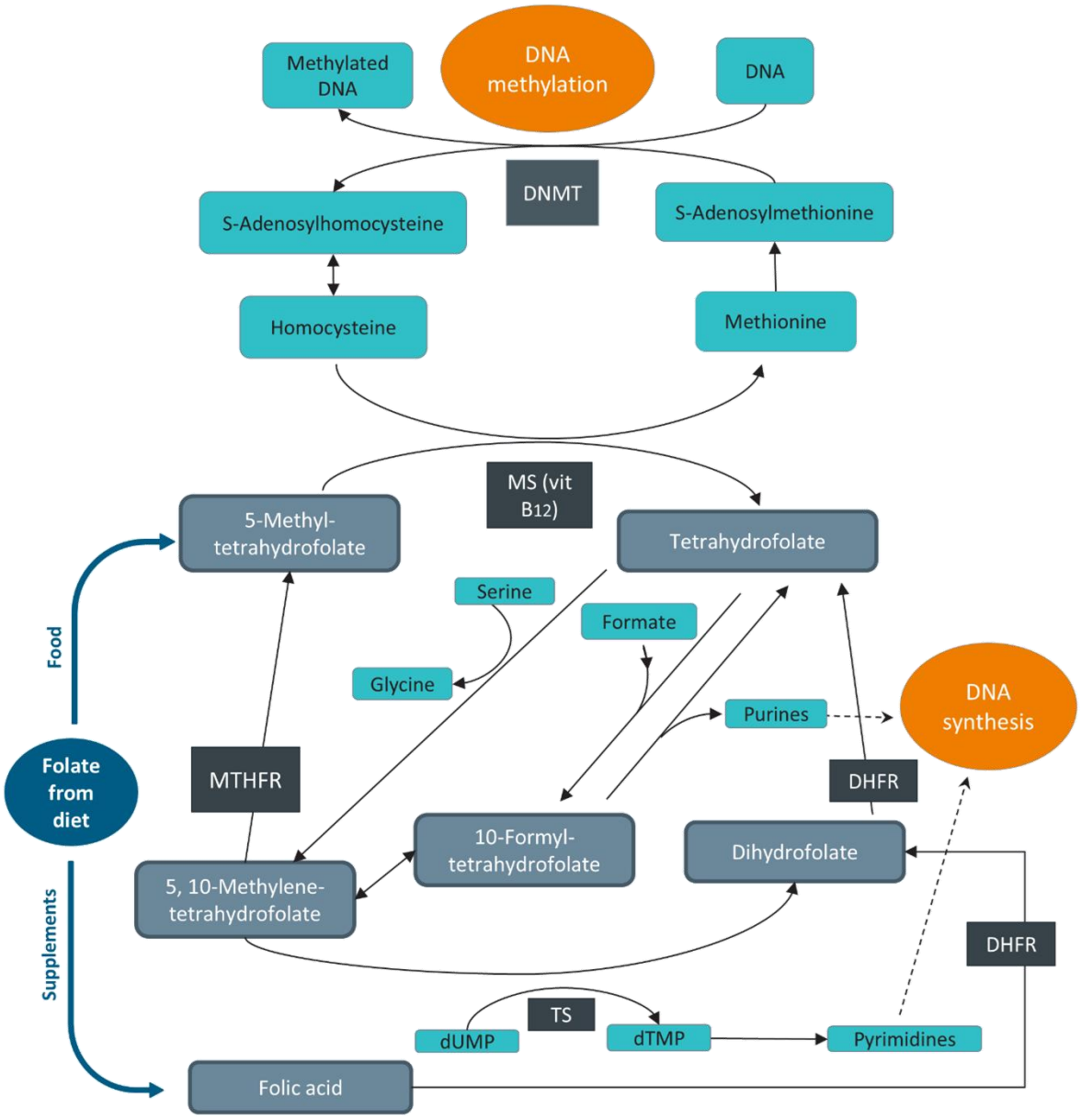


Figure 1-2 Schematic of folate metabolism in humans. Dark grey rectangles: Enzymes. Light grey rectangles: folate vitamers. Turquoise rectangles: non-folate products of metabolism. Orange ovals: metabolic outcomes. Blue oval: sources of folate. Enzyme name abbreviations: TS – thymidine synthase; DHFR – dihydrofolate reductase; MTHFR – methylene-tetrahydrofolate reductase; MS – methionine synthase; DNMT – DNA methyltransferase. Figure adapted from (Peters *et al.*, 2013)

Due to its central role in metabolism, folate deficiency can lead to life-threatening conditions. The severity and range of symptoms experienced, however, depend on the extent and duration of deficiency, as well as the individual's biological context (Bailey, 1994; Linus Pauling Institute, 2014; Bjørke-Monsen and Ueland, 2023; Xu *et al.*, 2023; Baddam, Khan and Jialal, 2025; Fallah *et al.*, 2025) . Even at sub-clinical levels, folate deficiency is associated with adverse effects including mouth ulcers, premature hair greying, and poor memory (Linus Pauling Institute, 2014;

Baddam, Khan and Jialal, 2025) (Figure 1-3). Abnormal body folate levels are also associated with a range of pathologies, including increased risk of colorectal, pancreatic, prostate, and breast cancers (Kim, 2018; Moazzen *et al.*, 2018; Chen *et al.*, 2023), cardiovascular diseases (Otsu, Ae and Kuwabara, 2023; Xu *et al.*, 2023), mood disorders including depression (Liwinski and Lang, 2023), and impaired cognitive function (Reynolds, 2002; Ramos *et al.*, 2005; Zhang *et al.*, 2021; Rotstein *et al.*, 2022), although for most diseases the exact nature of the relationship between body folate levels and disease remains unclear (Bjørke-Monsen and Ueland, 2023). An in-depth review of evidence of the roles of folate in health and disease may be found elsewhere (Bo *et al.*, 2020; Baddam, Khan and Jialal, 2025; Fallah *et al.*, 2025).

There is strong evidence that folate deficiency in pregnant mothers increases the risk of neural tube birth defects (NTDs) in their children (Wald and Sneddon, 1991; Scientific Advisory Committee on Nutrition, 2006, 2017; Wald, Morris and Blakemore, 2018; Bo *et al.*, 2020; Wald, 2022; Baddam, Khan and Jialal, 2025; Fallah *et al.*, 2025). In 1991, a landmark Medical Research Council (MRC) funded study found that 8 out of 10 NTD cases across a diverse population of pregnant mothers could be attributed to lack of folate, with the trial stopped early due to the strength of the findings (Wald and Sneddon, 1991; Wald, 2022). Some researchers now recommend a daily dose of 4-5 mg of folic acid for all women who could become pregnant, 20 times the standard recommended intake in the UK of 200 µg/day (Wald, 2022), although, official government guidance in the UK is for all women who are or may become pregnant to take a daily 400 µg folic acid supplement until the 12th week of pregnancy (Scientific Advisory Committee on Nutrition, 2006, 2017; Public Health England, 2016). However, there is some evidence that overconsumption of folate may too be linked to adverse health outcomes (Fardous and Heydari, 2023). This is predominantly associated with synthetic folate, or folic acid, and not the natural folate derivatives found in food (Scientific Advisory Committee on Nutrition, 2017; Fardous and Heydari, 2023; Fallah *et al.*, 2025).

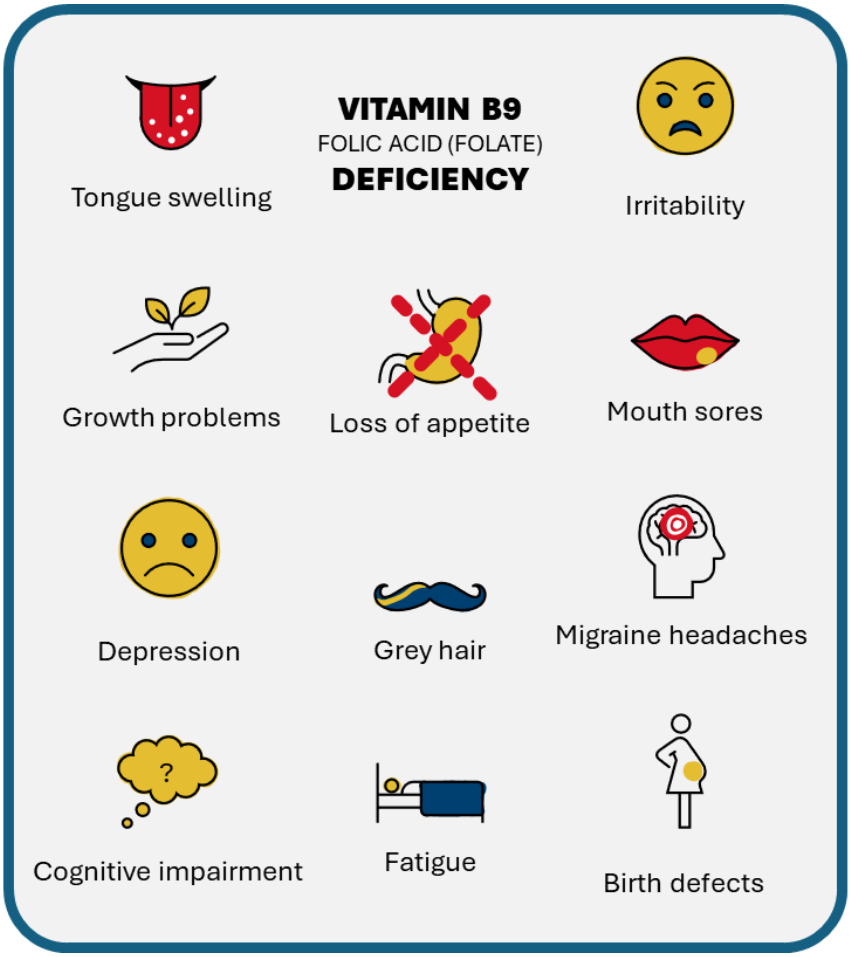


Figure 1-3 Symptoms of folate deficiency. Adapted from (Your Choice Primary Care, 2014; George, 2019)

1.5.3 Sources

The name 'folate' is derived from 'foliar', in recognition of the early purification of folate extracts from leafy green vegetables (Rosenberg, 2012). Folate is present in a wide range of foods, including both plant and animal sources (Gorelova *et al.*, 2017; Public Health England, 2021; Siatka *et al.*, 2025). It is abundant in green vegetables, as noted above, but also in offal, beans, and certain root vegetables like beetroots and parsnips (Public Health England, 2021) (Figure 1-4). Some foods are additionally fortified with folic acid (Crider, Bailey and Berry, 2011; Scientific Advisory Committee on Nutrition, 2017). Key examples include white bread flour, for which mandatory fortification has been implemented across more than 80 countries including the USA, Canada, and Australia (Wald, Morris and Blakemore, 2018), and breakfast cereals (Crider, Bailey and Berry, 2011).

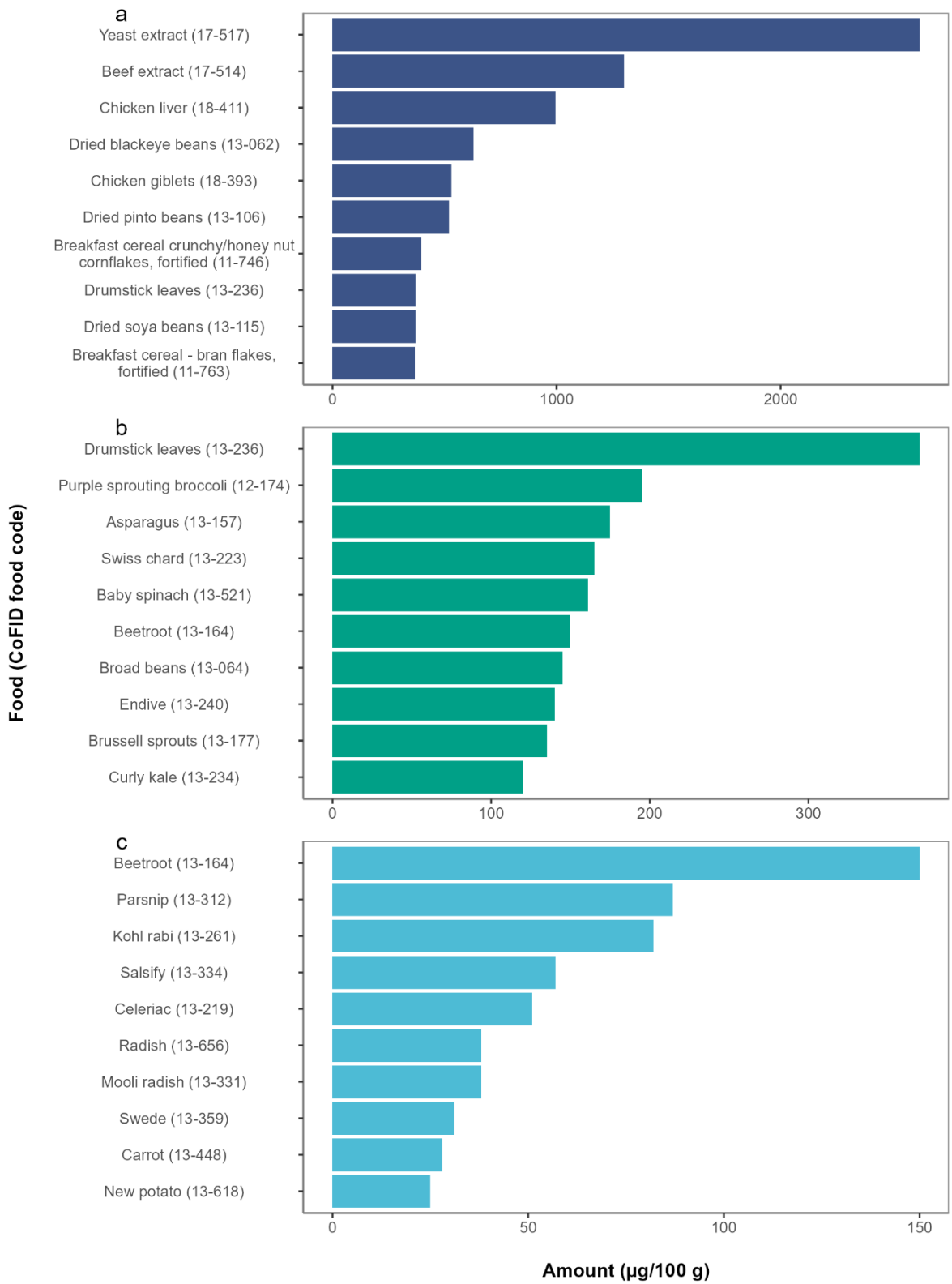


Figure 1-4 Top food sources of folate for a) all foods, b) fresh vegetables, and c) root vegetables and tubers. Only raw, non-composite (ingredient rather than recipe) items are listed to avoid duplication. Fresh vegetables category excludes herbs and spices. All data sourced from (Public Health England, 2021).

1.6 Folate Security in the UK

Although cereals are not naturally rich in folate, they are commonly fortified with folic acid, and the large quantities consumed mean that cereals and cereal based products are the largest contributors to dietary folate intakes for UK consumers (Public Health England, 2020) (Figure 1-5).

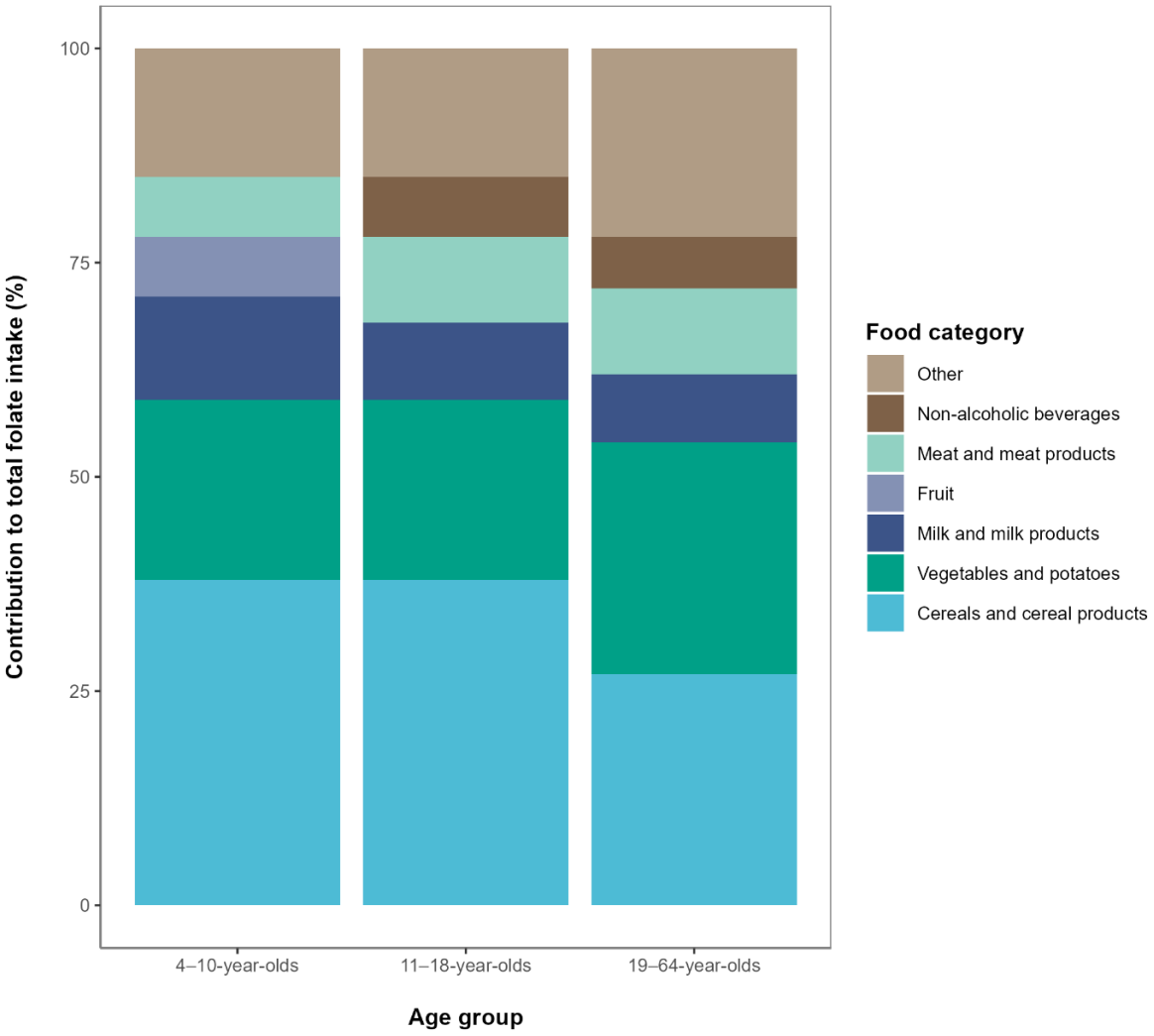


Figure 1-5 Top food contributors to folate intakes in the UK. Figure produced using data from (Public Health England, 2020).

Folate status in the UK is relatively well monitored through the National Diet and Nutrition Survey Rolling Programme (NDNS) (University of Cambridge, MRC Epidemiology Unit, NatCen Social Research, 2023). The NDNS collects data on folate intake and biomarkers of folate status, along with other nutritional indicators, over rolling two- or three-year intervals. These data have shown not only that a large proportion of the UK population has poor folate status, but that this situation is worsening over time (Jones *et al.*, 2023). In 2019, it was reported that 9 out of 10 females of reproductive age had red blood cell folate levels associated with an increased risk of pregnancy affected by neural tube defects (Jones *et al.*, 2023). This prevalence is higher

than that which led to the introduction of mandatory folic acid fortification of white bread flour in the USA in the 1990s (Pfeiffer *et al.*, 2019; Jones *et al.*, 2023), and has strengthened recent proposals for similar measures in the UK.

The folate status of the UK population is a matter of concern for the government. In response, legislation has been passed to implement mandatory fortification of bread flour with folic acid from December 2026 (Department of Health and Social Care *et al.*, 2024). This measure is expected to prevent around 200 cases of neural tube defects each year, improve maternal health, save the NHS approximately £20 million over 10 years, and boost the economy by more than £90 million in the same period (Department of Health and Social Care *et al.*, 2024).

1.7 Interventions to improve folate intakes

Various methods have been suggested to improve folate status, which can be broadly divided into supplement-based, fortification-based, biofortification-based, and dietary approaches. The following section critically evaluates these methodologies, outlining some major strengths and drawbacks of each.

1.7.1 Supplement-based approaches for improving folate status

Supplement-based approaches encourage the daily consumption of tablets containing a high dose of folic acid (Ismail, Eljazzar and Ganji, 2023; Khan and Jialal, 2023). These can be implemented in both proactive and reactive contexts. For example, all women of childbearing age in the UK are advised to take a 400 µg folic acid supplement daily to proactively reduce the risk of NTDs should they become pregnant (Department of Health, 2000; BBC News, 2015; Scientific Advisory Committee on Nutrition, 2017). Reactively, when low folate status is detected via a blood test, a daily folic acid supplement may be prescribed to rapidly increase the folate intake of the affected individual (Green and Datta Mitra, 2017; Khan and Jialal, 2023).

Supplementation has been shown to be effective for improving body folate levels and reducing health risks linked to folate deficiency. Clinical trials show that supplementing pregnant women with folic acid in early pregnancy reduces the incidence of NTDs (Wald and Sneddon, 1991; Czeizel *et al.*, 2013; De-Regil *et al.*, 2015; Naderi and House, 2018; Wald, Morris and Blakemore, 2018; Brown and Wright, 2020; Wald, 2022; Wald *et al.*, 2025). For deficiency treatment, prescribing 1-5 mg oral folic acid daily has been shown to improve serum folate concentration and alleviate symptoms of folate deficiency (Green and Datta Mitra, 2017; Khan and Jialal, 2023). These findings indicate strong potential for supplement-based interventions to improve folate status when implemented effectively.

A key limitation of supplementation-based approaches, however, is the need for individuals to actively engage with distribution systems. Women of childbearing age have been advised to take folic acid supplements since 1992 in the UK (Department of Health, 2000; BBC News, 2015; Scientific Advisory Committee on Nutrition, 2017). However, in 2019 less than a quarter of pregnant women consulted in antenatal clinics reported taking folic acid supplements prior to conception (Schoenaker *et al.*, 2023). Furthermore, 45% of pregnancies in the UK are unplanned (Public Health England, 2018). For these unplanned pregnancies, that are often detected at later stages than planned pregnancies, supplementation with folic acid occurs too late for the full protective effects of folic acid on NTD prevention to be realised (Czeizel *et al.*, 2013; NHS England, 2022).

Treatment of deficiency through prescribed supplements also depends on public motivation—whether to seek medical advice and a prescription, or to purchase supplements independently (Czeizel *et al.*, 2013; Ismail, Eljazzar and Ganji, 2023). This requirement for active engagement can limit population-level impact, especially in marginalised or disadvantaged communities (Ismail, Eljazzar and Ganji, 2023). It has been shown that the people most likely to take supplements often already engage in healthy lifestyles, including making healthier food choices (Conner *et al.*, 2003; Harrison *et al.*, 2004; McNaughton *et al.*, 2005; Dickinson and MacKay, 2014). In practice, therefore, supplement-based approaches may fail to reach those at most risk of low folate intakes (Ismail, Eljazzar and Ganji, 2023).

1.7.2 Fortification-based approaches for improving folate status

Folate fortification describes the practice of adding significant amounts of folic acid to commonly consumed foods (Dwyer *et al.*, 2015; Cardoso *et al.*, 2019; Olson *et al.*, 2021). This folic acid is then reduced into metabolically active dihydrofolate by dihydrofolate reductase in the body, at which point the folate can enter active metabolism and increase body folate levels (Figure 1-2).

Food fortification is known to be an effective strategy for targeting malnutrition (Crider, Bailey and Berry, 2011; Cardoso *et al.*, 2019; Olson *et al.*, 2021; Ismail, Eljazzar and Ganji, 2023). Unlike supplementation, it does not require individuals to interact with the healthcare system or change their food behaviours, thus increasing societal reach and lowering costs for consumers to improve folate intake (Castillo-Lancellotti, Tur and Uauy, 2013; Czeizel *et al.*, 2013; Olson *et al.*, 2021; Ismail, Eljazzar and Ganji, 2023; Kaim and Goluch, 2023). Although some concerns have been raised about the cost of implementation and surveillance of fortification programmes (Cardoso *et al.*, 2019; Ismail, Eljazzar and Ganji, 2023), in general, mandatory fortification has

been shown to be a cost effective intervention for improving folate nutrition (Grosse *et al.*, 2005; Czeizel *et al.*, 2013; Rodrigues, da Silva and Santos, 2021; Ismail, Eljazzar and Ganji, 2023).

The UK has fortified flour with calcium, iron, thiamin, and niacin since the Bread and Flour Regulations of 1998 (UK Government, 1998; Uk Flour Millers, no date). From December 2026, folic acid will also be included in mandatory fortification legislation (Department of Health and Social Care *et al.*, 2024). Countries that have already introduced mandatory fortification of flour with folic acid provide evidence that this campaign is likely to improve folate status in the UK, particularly when using rates of NTDs as a measure of effectiveness (Castillo-Lancellotti, Tur and Uauy, 2013; Cardoso *et al.*, 2019; Ismail, Eljazzar and Ganji, 2023; Quinn *et al.*, 2024).

The UK has been slower than many countries to introduce mandatory folic acid fortification, partly due to concerns about excessive folic acid intake which may occur as an unintended consequence of fortification (Scientific Advisory Committee on Nutrition, 2017; Wald, Morris and Blakemore, 2018; Wald, 2022; Ismail, Eljazzar and Ganji, 2023). Historically, high circulating folic acid has been linked to cancer development and progression (Baggott *et al.*, 1992; Kim, 2004; Ulrich and Potter, 2006; Mason *et al.*, 2007; Osterhues, Holzgreve and Michels, 2009; Czeizel *et al.*, 2013), and the possible masking of vitamin B12 deficiency, which can cause irreversible neurological damage if left untreated (Molloy *et al.*, 2009; Reynolds, 2016; Naderi and House, 2018). The long-term safety of very high intakes of folic acid also remains unclear (Ulrich and Potter, 2006; Reynolds, 2016). However, the evidence for harm is mixed, and evidence from existing international fortification programmes suggests that in practice the health risks associated with excessive folic acid intakes from fortification initiatives are likely to be minimal (Czeizel *et al.*, 2013; Vollset *et al.*, 2013; Wald, 2022).

1.7.3 Biofortification-based approaches for improving folate status

Biofortification describes the process by which the nutritional density of a food crop is increased through conventional plant breeding, improved agronomic practices and/or modern biotechnology, without sacrificing any desirable crop traits (Nestel *et al.*, 2006; Bekaert *et al.*, 2008; Strobbe and Van Der Straeten, 2017; Talsma and Pachón, 2017). Biofortification for enhanced folate content has been achieved in tomatoes ((Díaz de la Garza *et al.*, 2004; Díaz de la Garza, Gregory and Hanson, 2007), rice (Storozhenko *et al.*, 2007; Bekaert *et al.*, 2008; Abilgos Ramos, 2010; Dong *et al.*, 2014; Blancquaert *et al.*, 2015), maize (Naqvi *et al.*, 2009), lettuce (Nunes, Kalkmann and Aragão, 2009), Mexican common bean (Ramírez Rivera *et al.*, 2016) and potato (Blancquaert *et al.*, 2013; De Lepeleire *et al.*, 2017). A full review of the current status and future challenges of folate biofortification is available elsewhere (Strobbe and Van Der Straeten, 2017).

Biofortification avoids safety concerns linked to synthetic folic acid, as high natural folate intakes have no known adverse effects (Strobbe and Van Der Straeten, 2017; Fardous and Heydari, 2023; Siatka *et al.*, 2025). Therefore, biofortification approaches are not subject to the same health concerns, outlined above, as traditional fortification. Additionally, biofortification approaches offer sustainability advantages: once developed, biofortified crops require little ongoing investment compared to continuous fortification (Nestel *et al.*, 2006; Castillo-Lancellotti, Tur and Uauy, 2013; Sheoran *et al.*, 2022).

However, biofortified crops are a relatively recent innovation (Sheoran *et al.*, 2022), and significant effectiveness and regulatory challenges remain (Ashraf, 2025). For example, folate content may vary dramatically within and between biofortified crop varieties (Storozhenko *et al.*, 2007; Blancquaert *et al.*, 2015; Ramírez Rivera *et al.*, 2016; De Lepeleire *et al.*, 2017). Therefore, it is unclear how consistently these crops could be used to support folate intake (van Ginkel and Cherfas, 2023). Furthermore, in many biofortified crops, yield penalties have been incurred with increased micronutrient content (van Ginkel and Cherfas, 2023), making biofortified crop unattractive to growers. Additionally, many, but not all, biofortification approaches rely on genetic modification to improve folate levels in the target crop (Storozhenko *et al.*, 2007; Blancquaert *et al.*, 2015; Ramírez Rivera *et al.*, 2016; De Lepeleire *et al.*, 2017), which is heavily restricted in the UK (UK Government, 2023). As such, biofortification is not yet ready for immediate application in modern food systems, but represents a promising investment opportunity to make the crops of the future more nutrient dense.

1.7.4 Diet-based approaches for improving folate status

Some foods are naturally richer in folate than others (Figure 1-4). Diet-based interventions encourage consumption of folate rich foods or promote dietary diversity to increase the likelihood of sufficient folate intake from the diet (Nair, Augustine and Konapur, 2016; Chaudhary, Saraswathy and Sarwal, 2022; Ashraf, 2025). These interventions can utilise a variety of methods (Nair, Augustine and Konapur, 2016), including social-marketing techniques (Nayak *et al.*, 2001), the homestead food production model by Hellen Keller International (Talukder *et al.*, 2010), and women's empowerment and production diversity (Malapit *et al.*, 2013). To elicit widespread change, diet-based interventions should be initiated in food system leverage points – places in a system where a small change could lead to a large shift in behaviour or nutrition (Meadows and Wright, 2011; West *et al.*, 2014; Dorninger *et al.*, 2020). A key example is school meal programmes, where changes to the food offerings in school cafeterias can simultaneously affect the nutrition of large numbers of children simultaneously (Parnham *et al.*, 2024). In the UK in particular, country-wide standardisation of school meal offerings presents a key opportunity for diet-based interventions to be implemented (Golley,

Pearce and Nelson, 2011; Yang *et al.*, 2022; Haney *et al.*, 2023; Johnson, 2024; Parnham *et al.*, 2024), explored in detail in Chapter 5.

Consuming a varied diet that is rich in micronutrient dense foods has documented health benefits that go beyond improved micronutrient status (Nair, Augustine and Konapur, 2016; Afshin *et al.*, 2019; Cena and Calder, 2020; Carrillo-Alvarez *et al.*, 2025). In fact, a minimum dietary diversity score has recently been implemented into the United Nations Sustainable Development Goal targets, illustrating its known importance for health and wellbeing (Rigillo, 2025). When considering folate status, it has been acknowledged that 'a varied diet containing folate-rich foods is the optimal approach in combating folate deficiency' (Strobbe and Van Der Straeten, 2017). Furthermore, diet-based approaches may circumvent some of the regulatory, public acceptance, cost, and dosage issues raised in relation to other types of interventions for improving folate status.

However, there have been few experimental studies evaluating the effectiveness of diet-based approaches for improving micronutrient status, and none on improving folate status (Nair, Augustine and Konapur, 2016). Existing studies are mostly from low- and middle-income countries; a recent review of dietary diversity and micronutrient adequacy in children under five years of age found not a single paper on the relationship between these variables in a European context (Molani-Gol, Kheirouri and Alizadeh, 2023). This small evidence base makes it difficult to meaningfully engage policymakers with diet-based approaches (Nair, Augustine and Konapur, 2016). Moreover, these interventions often require consumers to change their dietary habits. There are many barriers to achieving consumer habit change (Malézieux *et al.*, 2024; Rickerby and Green, 2024), not least of which is contending with a food environment that may promote and reinforce unhealthy eating patterns (Pineda *et al.*, 2024), as discussed in Section 1.3. Altogether, this suggests that more research is needed to understand how to implement diet-based approaches to improve folate status in the UK.

1.7.5 Complementing mandatory fortification in the UK from December 2026

In practice, it is likely that multifaceted solutions will be needed to improve the long-term folate security of the UK population (Chaudhary, Saraswathy and Sarwal, 2022; Bechoff *et al.*, 2023; Malézieux *et al.*, 2024; Ashraf, 2025). In particular, approaches that may be complementary to mandatory fortification of flour from December 2026 should be explored, as although fortification may improve folate status in the short term, it may not sustainably improve folate security or wider food security and public health in the long term (Cardoso *et al.*, 2019; Chaudhary, Saraswathy and Sarwal, 2022).

As outlined in Section 1.1, there are four pillars of food security, availability, accessibility, utilisation, and sustainability. Fortification programmes improve the availability and accessibility of folate by adding folic acid to a cheap, widely available, food product, in this case, white bread flour (Kaim and Goluch, 2023; Falsafi *et al.*, 2025). However, this does not guarantee that utilisation will be improved. Particularly in very poor communities, it has been noted that not everyone consumes large amounts of white bread flour (Imhoff-Kunsch *et al.*, 2007). Additionally, relying on very few foods for folate provision leaves folate security vulnerable to disruption in supply chains, political upheaval, and otherwise threatens the sustainability of folate security.

Beyond folate security, a range of concerns have been raised about the overreliance on fortification to reach nutrition goals. One such concern is that policymakers may be diverted away from alternative strategies, such as supporting healthy and diverse diets, by the promise of a simple, single solution for improving folate intakes (Cardoso *et al.*, 2019; Bechoff *et al.*, 2023). Additionally, it has been noted that overreliance on fortified foods could lead to decreases in dietary diversity over time (Bechoff *et al.*, 2023; Ashraf, 2025), as the root causes of poor nutrient status, most commonly oversimplified, limited diets and insufficient nutritional awareness/education, are not addressed (Ashraf, 2025).

1.7.5.1 The UK Context

The range of strategies available for improving folate status outside of fortification are extensive, and selecting one or more for detailed investigation is necessary to explore them in depth within this thesis. A defining feature of this work is the examination of folate provision in the UK context. Therefore, some of the specific socio-political characteristics of the UK could help narrow down the choice of potential interventions.

Since the COVID-19 pandemic, and the onset of the Russia-Ukraine war, global trade has become increasingly unstable, highlighting the UK's dependence on imports to meet its population's nutritional needs (Macdiarmid *et al.*, 2018; Poppy, Baverstock-Poppy and Baverstock, 2022; Dyson *et al.*, 2023). This dependence poses risks for food and nutrition security (Macdiarmid *et al.*, 2018; Poppy, Baverstock-Poppy and Baverstock, 2022; Dyson *et al.*, 2023). Consequently, questions have arisen about whether the UK could do more to support nutrient intake through domestically produced food, with corresponding interest in locally grown crops.

The instability of global trade has also contributed to price volatility and a cost-of-living crisis, reducing disposable income for food purchases (Williams and Dienes, 2022; Meadows *et al.*,

2024; Stone *et al.*, 2024). This has emphasised the need for affordable, nutrient-rich food options that can support nutrition and public health despite rising prices.

In addition, the role of school food systems in supporting the health and nutrition of the UK population, particularly that of young people, has come under greater scrutiny since the COVID-19 pandemic (Parnham *et al.*, 2020; McIntyre *et al.*, 2022; Yang *et al.*, 2022). There has been increasing public pressure for the government to expand the free school meal programme, at least in part to offset the added financial burden on households in the cost-of-living crisis.

Together, these pressures indicate the need for locally produced, low-cost crops with high or potentially high folate content, which could be incorporated into existing nutrition programmes such as school meals. For these reasons, and others explored in the following chapters, this thesis will investigate the potential of parsnips as a diet-centred intervention to improve folate status in the UK. It will also assess the extent to which school meals already contribute to folate intakes, identifying opportunities for improvement. Finally, these two strands – parsnips and school meals – will be brought together to present a detailed case study of how non-fortification initiatives could strengthen folate security in the UK.

1.8 Parsnips – history, production, and consumption

The UK has a long history of producing a diverse range of hardy and relatively inexpensive winter vegetables that are dense in micronutrients (Laws, 2006). Parsnip (*Pastinaca sativa* L.*)*, is a starchy root vegetable that has been grown and consumed in the UK since the 1st century AD (Hendrick, 1919; Laws, 2006; Chappell and Dunford, 2021; AG Pearce Ltd, no date). Having been introduced by Roman settlers, parsnips became a staple in the diet of Anglo-Saxon farmers, and were later taken by British Colonialists and settlers to the New World during the Age of Exploration (Laws, 2006; A&G Lamattina & Sons Ptd Ltd, 2017). Beyond their use as a staple crop, parsnips served as a common sweetener before cultivated sugar cane and sugar beet became widely available (Harris, no date), and were used in the UK as a substitute for rationed bananas during World War II (Carlson, 2023).

Parsnips are a biennial crop, producing an edible root in their first year of growth, which is then used as an energy source for flowering and seed production in the second year (Chappell and Dunford, 2021). Most commercial parsnip varieties are ‘F1 hybrids’ (Selvakumar and Kalia, 2025), produced by crossing two distinct parental varieties. The first commercially available F1 hybrid parsnip seed was developed by Peter Dawson at Tozer Seeds Ltd in the 1970s, following his discovery that male sterile plants could greatly improve the efficiency of hybrid seed production (Selvakumar and Kalia, 2025). This process led to the creation of ‘Gladiator’, the first

hybrid parsnip, which was licensed and introduced commercially in 1982 (Tozer Seeds Ltd, 2017; Selvakumar and Kalia, 2025). Today, Tozer Seeds' 'Javelin' variety is the leading parsnip variety in the UK market (Tozer Seeds, personal communication, 2022).

Tozer Seeds Ltd is the largest producer of parsnip seed in the UK, holding a 44% share of the £6.2 million global market (Tozer Seeds, personal communication, 2021). As an industry co-supervisor for this thesis, Tozer Seeds Ltd provided parsnip seed, allowed sample collection from their existing field trials, hosted thesis-specific field trials, and contributed expertise for phenotypic trait evaluation in Chapter 3, as well as supporting some PhD programme costs. This collaboration has been central to ensuring both the accuracy and the broader economic relevance of this research.

Parsnips remain under-researched (Wang *et al.*, 2022; Selvakumar and Kalia, 2025). Although the parsnip genome has been sequenced, it is not publicly available (Chappell and Dunford, 2021; Selvakumar and Kalia, 2025). The National Centre for Biotechnology Innovation (NCBI) contains just 311 nucleotide sequences related to parsnips, and only three DNA repositories worldwide hold *P. sativa* L. samples (Selvakumar and Kalia, 2025).

Parsnips belong to the *Apiaceae* family of flowering plant, containing 434 genera and nearly 3780 species (Wang *et al.*, 2022). The family contains many important culinary and medicinal plants, including carrot (*Daucus carota*), coriander (*Coriandrum sativum*), celery (*Apium graveolens var. dulce*), celeriac (*Apium graveolens var. rapaceum*), parsley (*Petroselinum crispum*), fennel (*Foeniculum vulgare*), and cumin (*Cuminum cyminum*) (Wang *et al.*, 2022). It also includes highly poisonous plants, such as poison hemlock (*Conium maculatum*) and fool's parsley (*Aethusa cynapium*) (Wang *et al.*, 2022), both of which contain the toxin coniine (Hotti *et al.*, 2015; James, Ralphs and Nielsen, 2019; Wang *et al.*, 2022).

By far the most economically important of the *Apiaceae* is the carrot (*Daucus carota*), which is classified within the same subfamily, *Apioideae*, as parsnips (Downie, Katz-Downie and Watson, 2000; Wang *et al.*, 2022). As the most economically significant member, carrot is also the most extensively studied (Wang *et al.*, 2022). In addition to being relatively closely related, carrots and parsnips are also used in the human diet in similar ways, with the enlarged taproot being the most commonly eaten tissue (Motegaonkar *et al.*, 2024). However, there are significant differences in methods of cooking and storage before consumption, in part due to the differences in starch, and other nutrient, content between the two vegetables (Brandt, 2015; Ilić *et al.*, 2016; Motegaonkar *et al.*, 2024). The similarities between the two vegetables also extend to their requirements as root crops: they grow in similar conditions and can be harvested with the same machinery, so are often grown together or in rotation by UK growers (Tozer Seeds Ltd, personal communication, 2023). Consequently, in later chapters of this thesis, evidence

from carrot research may be referenced as an indicator of likely effects in parsnip, particularly when little or no direct research on parsnip exists.

1.8.1 Production and consumption in the UK

According to the 2023 Horticultural Production statistics (Department for Environment, Food & Rural Affairs, 2024a), 63,000 tonnes of parsnips were produced in the UK in 2023, a 10% decrease from 2022 (Figure 1-6). Planted area (2383 hectares), yield (25.6 tonnes/hectare), and total sales value (£29 million) all fell over the same period (Figure 1-6). By contrast, the Fresh Produce Journal 'Big 50 Products 2023' report describes a 20.5% increase in total sales value to £43.6 million in 2023, despite a smaller production decline of 1.9% (Searle *et al.*, 2023). Both sources agree, however, that production volume decreased from 2022 to 2023.

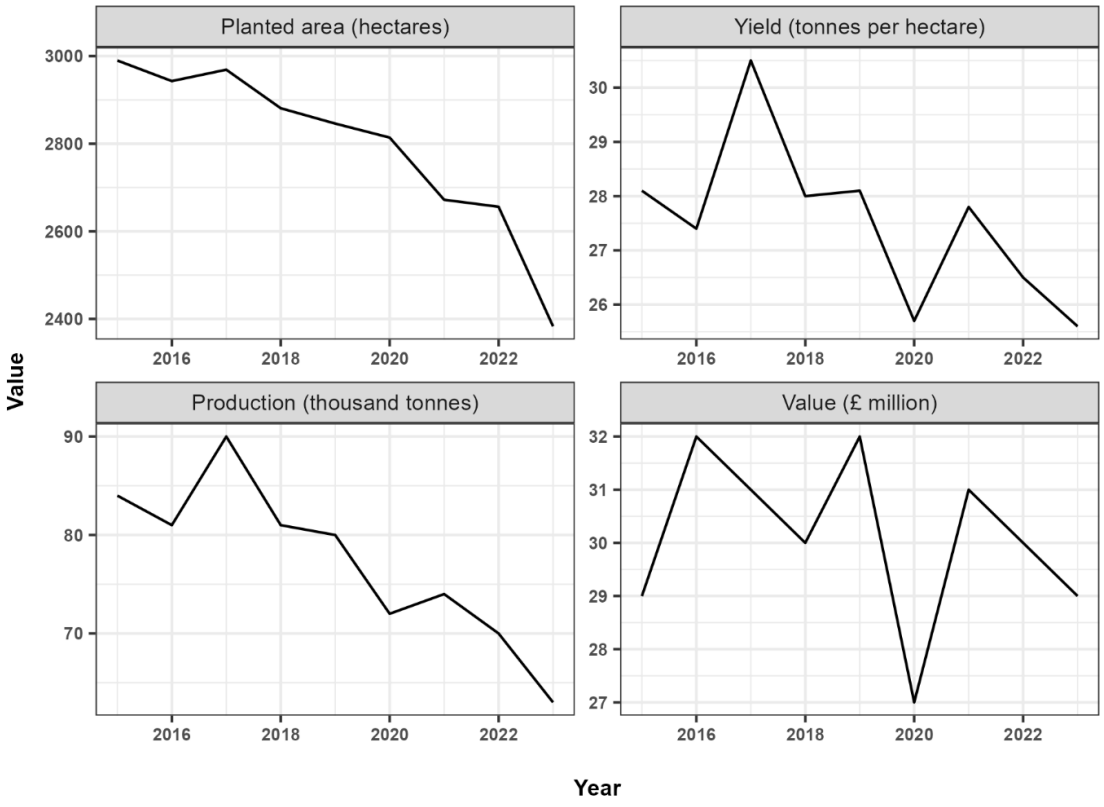


Figure 1-6 Line graphs showing production statistics for parsnips in the UK. Visualisation produced using data from (Department for Environment, Food & Rural Affairs, 2024a)

Global statistics for production can be obtained from the FAOSTAT balance sheets. Parsnips are not individually specified but are contained within a wider bracket of item "01599.10: Edible roots and tubers with high starch or inulin content, n.e.c., fresh". In 2023, an estimated 9630951.9 tonnes of these commodities were produced globally, with a yield of 13822.2 kg/hectare (Figure 1-7).

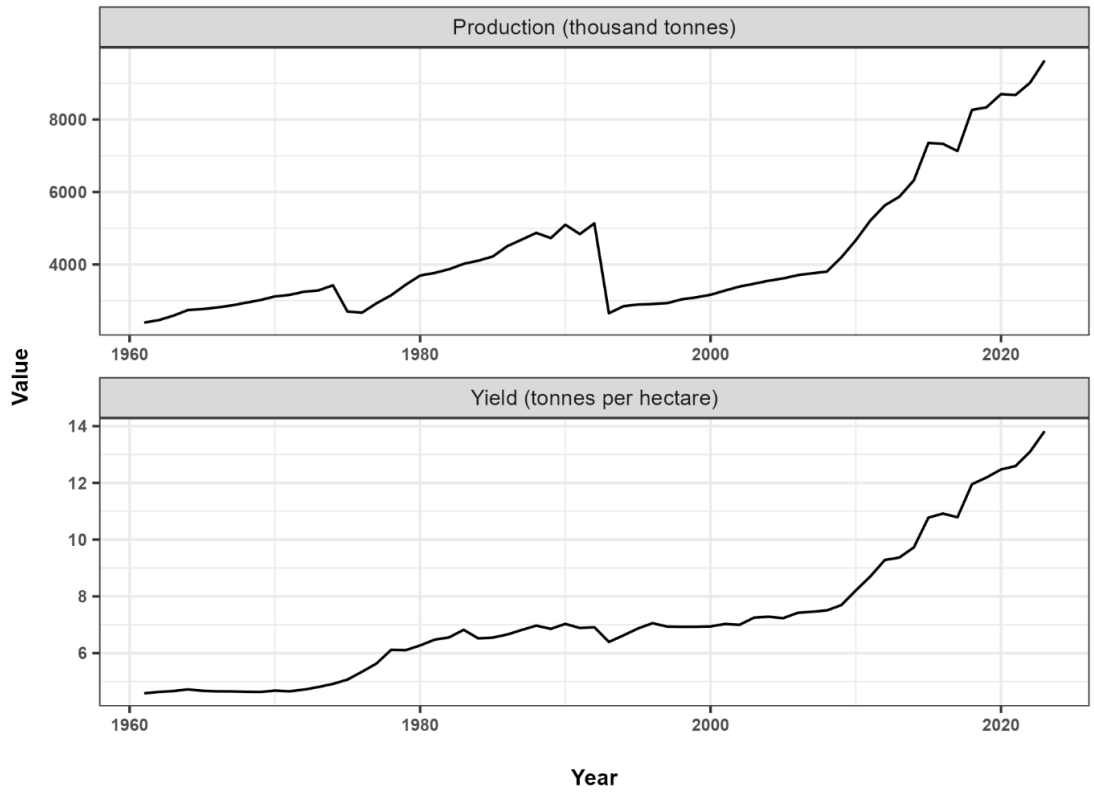


Figure 1-7 Line graphs showing production of item "01599.10: Edible roots and tubers with high starch or inulin content, n.e.c., fresh" over time.Visualisation produced using data from (FAO, 2025).

Import and export values for parsnips are not individually reported for the UK. In the international Harmonised System (HS) from the World Customs Organisation, parsnips are classified within the code 070690 for root vegetables, which also includes beetroot, salsify, celeriac, radishes and similar edible root vegetables (Tridge, 2025). The export value of this group from the UK is USD 7.01 million, with a total export volume of 10.74 thousand metric tonnes (Tridge, 2025). Import value of the same group was USD 29.24 million, with a total import volume of 22.91 thousand metric tonnes (Tridge, 2025). Parsnips are included in the 'all other fresh vegetables' category in the DEFRA Horticultural Production Statistics, for which the export value in 2023 was estimated at £16 million and 22.9 thousand tons (Department for Environment, Food & Rural Affairs, 2024a). The import value of 'all other fresh vegetables' was estimated at £329.9 million and 184.4 thousand tonnes for the same period (Department for Environment, Food & Rural Affairs, 2024a). However, it is unclear what proportion of both sets of statistics can be attributed to parsnips.

1.8.2 Nutrition and food characteristics

Although all tissues of cultivated parsnips are edible, the most commonly consumed is its large white tap root (Castro, Bergenståhl and Tornberg, 2012), which is sweet and starchy, and most

commonly eaten roasted, or in soups and stews (Chappell and Dunford, 2021). Although UK grown parsnips may be harvested fresh from July (early crop) to March (late crop) (McPherson, no date), they have a high tolerance to refrigerated storage which allows them to be available year round (Boswell, 1923). In the UK, purchases of parsnips peak around Christmas and at Easter and peak production is directed towards availability at these key times (Figure 1-8).

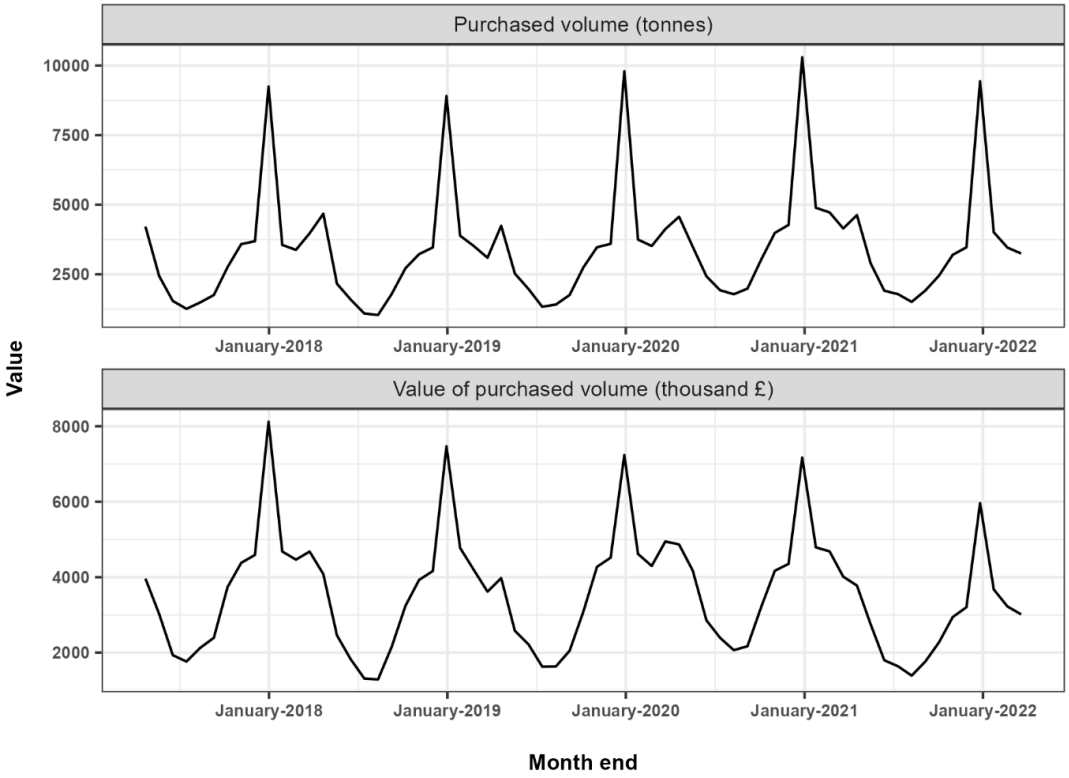


Figure 1-8 Line graph showing parsnip purchases in the UK over time. Visualisation produced using data from (Fisher, 2025).

Parsnips are a highly nutritious root vegetable (Chappell and Dunford, 2021) (Table 1-2). For example, relative to carrot parsnips contain substantially more fibre (120%), vitamin C (850%), thiamine (177%) and folate (1088%) (Public Health England, 2021). Data on the nutritional composition of parsnips from across twelve open access national level composition of food databases were collated, averaged, and translated into the percentage daily requirement for an adult, shown in Table 1-2. These averages provide a useful overview of the nutrient content of parsnips. Parsnips have been assessed in multiple different nutrient composition databases that have used different methods, varieties, and sources of samples. By collating differences across reported values, it is possible to account for potential sources of variation that can affect measured nutrient content such as growing conditions, experimental protocol variation, or varietal differences (Strandler and Jastrebova, 2011; Hefni, Shalaby and Witthöft, 2015, 2015; Riaz *et al.*, 2019; Li *et al.*, 2025). However, the relative impact of each of these factors remains unclear from the nutritional composition database values. This thesis generates novel insights by directly investigating the impact of variety selection and growing practice on the nutrient

composition of parsnips (Chapter 3) and the effects of post-harvest processing on nutrient content in parsnips (Chapter 4).

Parsnips also contain a range of other bioactive compounds such as polyacetylenes and essential oils (Kenari *et al.*, 2021), which can affect both flavour and nutritional qualities. Their leaves may contain furanocoumarins - tricyclic derivatives of the phenylpropanoid pathway (Chappell and Dunford, 2021) – which are thought to be protective to the plant (Berenbaum, Zangerl and Nitao, 1984, 1986), but can be harmful to humans (Osman, Chittiboyina and Khan, 2013; Melough, Cho and Chun, 2018). Furanocoumarin content varies between plants and is influenced by storage, processing, and maturity (Ostertag *et al.*, 2002; Melough, Cho and Chun, 2018). However, domesticated parsnips generally have lower levels than wild progenitors due to human selection against bitter or toxic compounds, and the roots of most cultivated varieties contain negligible amounts (Chappell and Dunford, 2021).

Table 1-2 Nutritional composition of parsnips

Nutrient category	**Nutrient**	**Number of data points**	**Average amount/100 g of parsnip**	**Coefficient of variation (%)**	**% DRV for an adult/100 g of parsnip**
Macronutrients	Energy (kcal)	12	65.88	7.64	2.93*
	Total Carbohydrates (g)	11	13.55	21.18	4.52*
	Total Fats (g)	12	0.59	43.52	0.68*
	Dietary fibre (g)	12	4.49	22.69	14.97*
	Total protein (g)	12	1.55	19.09	3.11*
	Water (g)	10	80.30	1.12	3.21**
	Ash (g)	7	0.99	9.10	ND
Carbohydrates	Available Carbohydrates (g)	7	11.23	7.81	4.08**
	Starch (g)	5	5.66	9.32	ND
	Total sugars (g)	10	5.98	37.18	19.93*
	Sucrose (g)	5	3.93	20.39	ND
	Glucose (g)	4	0.78	16.24	ND
	Fructose (g)	4	0.65	36.62	ND
Fats	Total fatty acids (g)	5	0.46	62.63	ND
Minerals	Sodium (mg)	11	5.67	54.90	0.24*
	Potassium (mg)	11	460.73	16.08	13.16*

	Calcium (mg)	11	40.95	21.36	5.85*
	Magnesium (mg)	11	24.32	19.34	8.53*
	Phosphorus (mg)	11	70.14	18.29	12.75*
	Iron (mg)	11	0.57	25.98	3.84*
	Zinc (mg)	11	0.82	115.16	9.88*
	Copper (mg)	8	0.11	35.42	9.44*
	Manganese (mg)	5	0.47	14.68	20.35**
	Iodine (µg)	8	1.15	133.89	0.82*
	Selenium (µg)	10	1.99	148.51	2.95*
	Chromium (µg)	2	1.00	0	1.90**
	Nickel (µg)	2	20.00	0	ND
Vitamins	Vitamin A (µg RAE)	9	1.99	87.46	0.31*
	Vitamin E (µg ATE)	9	1.19	49.03	7.91**
	Vitamin K (µg)	6	7.53	154.15	6.27**
	Thiamin/Vitamin B1 (mg)	11	0.12	47.27	13.23*
	Riboflavin/Vitamin B2 (mg)	11	0.08	65.32	6.82*
	Niacin/Vitamin B3 (mg)	10	1.60	52.10	10.75*
	Pantothenic acid/Vitamin B5 (mg)	7	0.55	9.39	10.91**
	Folates/Vitamin B9 (µg)	11	72.55	18.76	34.75*
	Vitamin C (mg)	11	15.40	23.89	37.74*

Nutrient unit abbreviations: kcal – kilocalories; g – grams; mg – milligrams; µg – micrograms; µg RAE – micrograms of retinoic acid equivalents; µg ATE – micrograms of alpha-tocopherol equivalents. ND represents where no data was provided on daily requirements in the UK government nutritional tables or FDA recommended list, so no percentage could be calculated. DV – dietary reference value, * - % calculated from the UK government recommendations for adults 19-65. ** - % calculated from FDA recommendations. Data were collated from (Slovak Food Composition Data Bank, 2008; National Food Institute, 2019; National Institute for Health and Welfare, 2019; USDA, 2019; Anses, 2020; Prague: Institute of Agricultural Economics and Information, 2020; Federal Food Safety and Veterinary Office FSVO, 2021; GOV.UK, 2021; National Institute for Health Development, 2021; Norwegian Food Safety Authority, 2021; RIVM, 2021; The Swedish Food Agency, 2021)

A notable characteristic of parsnips is their increased sweetness after exposure to low temperatures—a trait reflected in the widespread belief in the UK that parsnips are best harvested after a frost (CALU, 2007). Research shows that starch levels drop significantly when

parsnips experience temperatures below 5°C for eight weeks before harvest, and almost completely deplete after 24 weeks of cold storage (Bufler and Horneburg, 2013). Ilić et al. (2016) further demonstrated that pre-storage treatments, including storage at 0 °C with 98% relative humidity combined with a sodium chloride wash, can extend shelf life while maintaining sugar content.

Given the effects of refrigeration on carbohydrate metabolism outlined above, it could be hypothesised that there may be effects of refrigeration on other nutritional characteristics of parsnips. There is also evidence from other crops that exposure to refrigerated storage conditions may impact nutrient retention in harvested crop tissues. For example, in kale just 16% of the original vitamin C content remained after 3 weeks storage at 4°C (Wibowo *et al.*, 2019). Contrastingly, vitamin C and vitamin K in cabbage and leeks were both robust to storage over 6 weeks at 4°C (Vancoillie *et al.*, 2024). Vitamin B1 and vitamin C content both decrease over 18 days storage at 8°C in green beans (Sánchez-Mata, Cámara and Díez-Marqués, 2003). In potatoes, smaller concentrations of potassium and magnesium were detected in potatoes stored in the fridge, cupboard, and ideal storage conditions after 2 weeks (Payne *et al.*, 2023). After 5 weeks, concentrations of potassium were greater in all samples compared to the original unstored samples, likely reflecting dehydration of the potato tissue over longer storage durations (Payne *et al.*, 2023). In choy sum, folate content was unchanged after 3 weeks of storage at 4°C (O'Hare *et al.*, 2012), but in watercress folate losses of 37% were observed after 7 days storage at 4°C (Pinela *et al.*, 2019). This thesis will build on existing evidence from other crops to explore the impact of refrigerated storage on micronutrient content in parsnips (Chapter 4).

In addition to exposure to low temperatures during cultivation and storage, parsnips are also often exposed to high temperatures during cooking prior to consumption (Oddbox, 2022). The effects of cooking on micronutrient content in foods are complex and often vary between different foodstuffs (Fabbri and Crosby, 2016; Lee *et al.*, 2017). This may be due to differences in the structural matrix of foods, or the unique chemical profiles of foods interacting with micronutrients with protective or destructive effects during cooking processes (Fabbri and Crosby, 2016; Lee *et al.*, 2017). For example, potatoes boiled for 20 minutes lose over 50% of their vitamin C content, but vitamin K content increases by over 40% per 100g cooked tissue (Lee *et al.*, 2017). Furthermore, if the same potato samples are blanched for 5 minutes or microwaved for 3 minutes, only 20% of the vitamin C content is lost but vitamin K content is unaffected (Lee *et al.*, 2017). Boiling, steaming, blanching, and microwaving all decreased the vitamin C content and the vitamin K content of carrots (Lee *et al.*, 2017). Given the nuance of different responses of micronutrients to cooking in individual foods, it is difficult to predict how the micronutrient content of parsnips may be being affected by cooking. This thesis will seek to

address this evidence gap by exploring the effects of common domestic cooking methods on the folate content of parsnips (Chapter 4).

1.9 Conclusions

The evidence presented in this chapter highlights that, despite the UK's relative economic prosperity, significant challenges remain in ensuring adequate food security, particularly with respect to micronutrient sufficiency. Folate has emerged as a micronutrient of particular public health concern, with deficiencies linked to a range of adverse health outcomes, including neural tube defects, anaemia, and impaired cognitive function. Although the forthcoming mandatory fortification of bread flour with folic acid is expected to improve folate status at the population level, it is unlikely to represent a complete or sustainable solution. Fortification strategies alone cannot guarantee equitable improvements in utilisation or address the broader issues of dietary diversity, resilience of supply chains, and the long-term sustainability of nutrient provision.

Within this context, the potential for complementary, non-fortification approaches warrants investigation. Locally produced, nutrient-dense crops offer an opportunity to strengthen domestic food systems, reduce vulnerability to global supply disruptions, and contribute to public health objectives. Parsnips, a crop with a long history of cultivation and consumption in the UK, are naturally rich in folate and possess favourable agronomic and storage characteristics. However, there is currently a lack of detailed data on varietal differences in folate content, the stability of folate during storage, and the effects of common cooking practices on folate retention.

Furthermore, institutional food systems such as school meals represent a practical and potentially high-impact vehicle for delivering folate-rich foods to children and adolescents, while also supporting broader goals of improving dietary quality and reducing health inequalities. Understanding the current contribution of school meals to folate intake, and the potential to enhance this through the inclusion of locally produced high-folate parsnip varieties, could inform integrated strategies that address both nutritional and socioeconomic priorities.

By situating the investigation of folate security within the wider framework of UK food security and public health, this thesis seeks to generate novel evidence on the potential role of parsnips and school meals as part of a multifaceted, sustainable approach to improving micronutrient provision. The subsequent chapters will examine these themes in detail, drawing together insights from crop science, nutrition, and public health to inform targeted, context-specific interventions.

1.9.1 Thesis aims and objectives

This thesis will first examine the micronutrient status of the UK population to identify vulnerable groups and areas of especially poor nutritional status. These insights provide the broader context for subsequent chapters. Within this framework, folate is identified as a key micronutrient of concern. The overall hypothesis of this thesis is that parsnips - a locally produced, folate-rich crop - could serve as a practical and sustainable complement to mandatory fortification strategies for improving folate security in the UK. In addition, the role of school meals in shaping folate intake is investigated, with particular attention to how dietary choices influence folate provision, and the potential impacts on folate intakes of greater incorporation of parsnips into school meals is explored.

The aims outlined above will be achieved through the following objectives:

1. Assess the current micronutrient status of the UK population using nationally representative dietary intake and biomarker data (Chapter 2).
2. Quantify folate content across a range of commercially relevant parsnip varieties (Chapter 3).
3. Examine relationships between varietal characteristics and folate content to inform breeding and selection strategies in parsnips (Chapter 3).
4. Investigate the effects of different storage conditions and durations on folate content in parsnip roots (Chapter 4).
5. Determine the impact of common domestic and commercial cooking methods on folate content (Chapter 4).
6. Identify handling and preparation practices that maximise folate retention from harvest to consumption (Chapter 4).
7. Analyse the contribution of current UK school meals to dietary folate intakes in children and adolescents (Chapter 5).
8. Model the potential impact of incorporating high-folate parsnip varieties into school menus (Chapter 5).

Chapter 2 Investigating Micronutrient Deficits in the UK Population, with Emphasis on Nutrients Present in Parsnips

2.1 Introduction

Micronutrients are components of the human diet, required in milligram or microgram quantities each day, that are essential for normal physiological function (Shenkin, 2006; Public Health England, 2016; Shergill-Bonner, 2017; Kumar *et al.*, 2024; WHO, no date). The term micronutrient encompasses both organic molecules (vitamins) and inorganic ions (minerals) which participate in diverse metabolic processes (Chapter 1 Section 1.4). Deficiency in specific micronutrients causes various disease pathologies, including scurvy (vitamin C deficiency) (Dresen *et al.*, 2023), neural tube defect affected births (folate deficiency) (Czeizel *et al.*, 2013), pellagra (niacin/vitamin B3 deficiency) (Penberthy and Kirkland, 2020), and beriberi (thiamin/vitamin B1 deficiency) (Polegato *et al.*, 2019). Suboptimal status may also lead to non-specific symptoms such as fatigue, malaise, impaired memory, and delayed wound healing (Linus Pauling Institute, 2014; Kaganov *et al.*, 2015; Siatka *et al.*, 2025). Ensuring adequate micronutrient intake is therefore central to achieving public health goals.

Inadequate micronutrient status is most often linked to poor diet, although certain disease states may also contribute by increasing requirements or impairing the absorption of micronutrients (Shenkin, 2006; Shergill-Bonner, 2017; Brownson *et al.*, 2024; WHO, no date). While insufficiency is commonly associated with regions of low food availability, it can also occur in high-income countries when access to nutrient-rich foods is constrained (Bennett and Gibney, 2024; Johnstone and Lonnie, 2024). For example, economic barriers and food environments that encourage consumption of nutrient-poor foods may reduce the intake of more nutrient-dense alternatives (Bennett and Gibney, 2024; Johnstone and Lonnie, 2024). In the UK, both affordability and dietary environments are recognised as contributors to micronutrient insufficiency (Kaganov *et al.*, 2015; Miller, Spiro and Stanner, 2016; Johnstone and Lonnie, 2024; Stiebahl, 2025).

Robust monitoring systems are crucial for identifying population groups who are at risk of micronutrient deficiencies. The National Diet and Nutrition Survey Rolling Programme (NDNS) has operated in the UK since 2008, providing nationally representative data on diet, nutrition, and health (Public Health England, 2020; University of Cambridge, MRC Epidemiology Unit,

NatCen Social Research, 2023), whilst also collecting broader information on the wellbeing, socioeconomic, and wider characteristics of the volunteer participants. The NDNS collects data on micronutrient status through measures of micronutrient intake and biomarker analysis (Miller, Spiro and Stanner, 2016; Shergill-Bonner, 2017; Public Health England, 2020; University of Cambridge, MRC Epidemiology Unit, NatCen Social Research, 2023).

Micronutrient intake analyses are based on dietary recall methods, captured via food frequency questionnaires, 24 hour dietary recalls, or a range of other methods, which collect information on the foods consumed by an individual (Henríquez-Sánchez *et al.*, 2009; Bailey, 2021). These foods are then matched to nutrient databases to estimate the quantities of micronutrients consumed (Henríquez-Sánchez *et al.*, 2009; Bailey, 2021). Intake data can be compared to dietary reference values, such as the reference nutrient intake (RNI) or lower reference nutrient intake (LRNI), to determine if consumption is adequate relative to assumed bodily needs (Department of Health, 1991).

The RNI describes the amount of a micronutrient that is sufficient to meet the requirements of 97.5% of the population (Department of Health, 1991; Shergill-Bonner, 2017). Thresholds for these values for a range of age groups are maintained by Public Health England (PHE), with routine updates for micronutrients deemed to be of particular public health importance or current relevance (Public Health England, 2016). The LRNI represents the amount of a micronutrient that is only sufficient for the 2.5% of the population with especially low requirements (Department of Health, 1991). Intakes below this threshold are very likely to lead to deficiencies (Department of Health, 1991).

Biomarker analyses, in contrast, measure the quantity of a micronutrient, or an indicator of a micronutrient, in biological samples such as blood or urine (Bates, Thurnham and Nelson, 1997; Lamers, 2019). These values are then compared with thresholds specific to each micronutrient to directly assess deficiency (Bates, Thurnham and Nelson, 1997; Lamers, 2019). Thresholds are based on the rate of base metabolism relative to intake, and are often consistent across age and sex groups (Bates, Thurnham and Nelson, 1997; Bates *et al.*, 2014; Public Health England, 2020). Together, intake and biomarker-based approaches provide complementary insights into population level micronutrient status.

The most recent NDNS overview report at the time of analysis was published in 2020 using data collected in 2018/2019, prior to the disruptions of the COVID-19 pandemic, the Ukraine-Russia war, and the subsequent cost-of-living crisis (Public Health England, 2020; Ogundijo, Tas and Onarinde, 2021; Rivington *et al.*, 2021; Thomas *et al.*, 2022; Williams and Dienes, 2022; Lin *et al.*, 2023; Meadows *et al.*, 2024). This report focused on foods and nutrients “selected for their nutritional and public health relevance to current dietary concerns in the UK” (Public Health

England, 2020), including sugar-sweetened beverages, free sugar, saturated fat, fibre, red blood cell (RBC) folate, serum folate, and vitamin D (Public Health England, 2020). Additional Microsoft Excel workbooks contained collated, summarised statistical tables on a further 12 food groups, 12 macronutrient groups, 11 micronutrients, and 13 blood and urinary analytes, although these data were not discussed in the report (Public Health England, 2020). Notably, some micronutrients, such as vitamin C, vitamins B1 and B3, phosphorus, and copper, were not included in the report or in the published summary tables, despite nutritional data being collected. The reasons for this exclusion are unclear but may reflect assumptions of sufficiency or lower perceived relevance to public health priorities such as obesity. However, no published works have confirmed whether sufficiency of these micronutrients is assured in the UK population.

Parsnips are a source of several micronutrients which are recognised as important for public health (Chapter 1 Section 1.8.2), including folate, which was included as a priority nutrient in the 2020 PHE report (Public Health England, 2020). They also contain significant quantities of nutrients that were not discussed in the PHE report, including potassium, magnesium, vitamin C, vitamins B1 and B3, phosphorus, and copper (Chapter 1 Section 1.8.2). To evaluate the potential role of parsnips in supporting dietary sufficiency, it is necessary to assess the status of these micronutrients in the UK population and identify groups at greatest risk of inadequacy. Additionally, the identification of population groups for whom nutrient deficits are most pronounced would also allow the better targeting of parsnip-based interventions towards those most in need.

This chapter examines the sufficiency of a range of micronutrients known to be found in parsnips, extending the range of micronutrients considered in previous research, using both intake and biomarker data from the NDNS. By analysing and visualising these data, the chapter seeks to identify population groups most at risk of micronutrient deficiency and highlight potential public health benefits of parsnip-based dietary interventions.

2.1.1 Chapter aims and objectives

The hypothesis of Chapter 2 is that there are insufficient intakes or poor biomarker status in the UK population for at least one of the micronutrients present in significant quantities in parsnips. The primary aim of Chapter 2 is to explore the micronutrient status of the UK population for the micronutrients present in large quantities in parsnips, using both intake data and biomarker data from the NDNS. This will be achieved by answering the following objectives:

1) Evaluate NDNS dietary intake data for the ten most abundant micronutrients in parsnips, highlighting those micronutrients with poor intake levels in the UK population.

2) Explore all available biomarker data for the ten most abundant micronutrients present in parsnips to identify those micronutrients with a high prevalence of deficiency in the UK population.
3) Identify population groups likely to be at high risk of poor micronutrient status across the ten most abundant micronutrients found in parsnips.
4) Cross-reference the intake and biomarker data to identify one or more key micronutrients with poor intakes and biomarkers for which parsnip could be used as a targeted diet-based intervention.

2.2 Material and methods

2.2.1 Data selection

2.2.1.1 Micronutrients of interest

The nutritional profile of parsnips, as published across a range of National Nutrient Composition Databases, was explored in Chapter 1 Section 1.8.2. The micronutrients on this list were ranked in relation to the percentage of the UK Adult Reference Nutrient Intake (RNI) provided by a 100 g portion of raw parsnip, and compared to the micronutrients for which Public Health England (PHE) has published RNI recommendations (Table 2-1). Micronutrients present in parsnip that are without a published RNI – manganese, vitamin B5, and vitamin E – were excluded from further analysis. The top 10 remaining nutrients, based on RNI provision, were selected for inclusion in the study (Table 2-1).

2.2.1.2 Micronutrient intake and biomarker data

The NDNS data from survey years 1 to 11, covering the period from 2008 to 2019, were accessed under a safeguarded data licensing agreement from the UK Data Service web portal (URL: https://beta.ukdataservice.ac.uk/datacatalogue/studies/study?id=6533) (University of Cambridge, MRC Epidemiology Unit, NatCen Social Research, 2023). Data from combined years 9 –11 were used in this study, as this was the most recently published dataset at the time of analysis. Information on age, sex, micronutrient intakes, biomarker status, and relevant weighting and stratification variables were extracted from the larger dataset. The selected variables are listed in Table 2-2. For micronutrient intake data, the effects of supplementation on nutrient intakes were excluded by selecting the variables where micronutrients from supplements were not counted into total intakes. The biomarker data do not distinguish between supplement and non-supplement users. Where data were recorded across different

data files, the 'seriali' variable was used to combine datasets, ensuring that measurements were assigned to the correct individuals.

Table 2-1 Prioritised micronutrients for further investigation based on presence in parsnip and RNI guidance availability

Micronutrient	% of RNI for an average 19 year+ person in 100 g raw parsnip	Intake data available?	Biomarker data available?	RNI available?	ID
Vitamin C	38	Yes	Yes	Yes	1
Folate/Vitamin B9	35	Yes	Yes	Yes	2
Manganese	20	Yes	No	No	-
Niacin/Vitamin B3	15	Yes	No	Yes	3
Thiamin/Vitamin B1	13	Yes	Yes	Yes	4
Potassium	13	Yes	No	Yes	5
Phosphorus	13	Yes	No	Yes	6
Vitamin B5/Pantothenic acid	11	Yes	No	No	-
Zinc	10	Yes	Yes	Yes	7
Copper	9	Yes	No	Yes	8
Magnesium	9	Yes	No	Yes	9
Vitamin E	8	Yes	No	No	-
Riboflavin/Vitamin B2	7	Yes	Yes	Yes	10

Micronutrients highlighted in red had no Public Health England Reference Nutrient Intake value, so were excluded from further analysis

Table 2-2 Variables included in the filtered NDNS Years 9-11 dataset

Variable	Description	Source dataset
seriali	Individual serial number	NDNS_Yr9-11a_indiv
astrata4	Stratification level	NDNS_Yr9-11a_indiv
AgeR	Age (years)	NDNS_Yr9-11a_indiv
Sex	Sex	NDNS_Yr9-11a_indiv
wti_Y911	Weighting for individual and diary-all ages, combined year 9-11	NDNS_Yr9-11a_indiv
wtb_Y911	Weighting for blood – all ages, combined year 9-11	NDNS_Yr9-11a_indiv
VitaminCmg	Vitamin C (mg) diet only	NDNS_Yr9-11a_DayLevelDietaryData_Nutrients
Folateμg	Folate (μg) diet only	NDNS_Yr9-11a_DayLevelDietaryData_Nutrients
Niacinequivalentmg	Niacin equivalent (mg) diet only	NDNS_Yr9-11a_DayLevelDietaryData_Nutrients

Thiaminmg	Thiamin (mg) diet only	NDNS_Yr9-11a_DayLevelDietaryData_Nutrients
Potassiummg	Potassium (mg) diet only	NDNS_Yr9-11a_DayLevelDietaryData_Nutrients
Phosphorusmg	Phosphorus (mg) diet only	NDNS_Yr9-11a_DayLevelDietaryData_Nutrients
Zincmg	Zinc (mg) diet only	NDNS_Yr9-11a_DayLevelDietaryData_Nutrients
Coppermg	Copper (mg) diet only	NDNS_Yr9-11a_DayLevelDietaryData_Nutrients
Magnesiummg	Magnesium (mg) diet only	NDNS_Yr9-11a_DayLevelDietaryData_Nutrients
Riboflavinmg	Riboflavin (mg) diet only	NDNS_Yr9-11a_DayLevelDietaryData_Nutrients
VitC	Plasma Vitamin C (µmol/L)	NDNS_Yr9-11a_indiv
RCFolate	Red Cell Folate (nmol/L)	NDNS_Yr9-11a_indiv
VitB1	Vitamin B1 Status (ETKAC)	NDNS_Yr9-11a_indiv
Zn	Plasma zinc (µmol/L)	NDNS_Yr9-11a_indiv
VitB2	Vitamin B2 Status (EGRAC)	NDNS_Yr9-11a_indiv

The weighted intake and biomarker data were compared to statistics from the Office for National Statistics Census Data 2021 (URL: https://www.ons.gov.uk/census) and the NHS Health Survey for England Data 2021 (URL: https://www.gov.uk/government/statistics/health-survey-for-england-2021) to observe the impact of weighting on the overall characteristics of the survey population.

2.2.2 Micronutrient intake and biomarker thresholds

Values for RNI thresholds were obtained from the UK Government Dietary Recommendations (Public Health England, 2016). Values for LRNI thresholds were taken from the earlier Committee on Medical Aspects of Food and Nutrition Policy (COMA) Dietary Reference Values for Nutrition (Department of Health, 1991). Intake thresholds for each age were stratified into Male and Female categories within the age groupings of 1 – 3-year-old, 4 – 10-year-old, 11 – 18-year-old, 19 – 65-year-old, and over – 65-year-old, with the mean threshold value re-calculated for each group. These age groups were chosen to coincide with thresholds used in wider NDNS publications and UK government public health guidance and reporting. The RNI and LRNI thresholds used throughout this chapter are shown in Table 2-3 and Table 2-4.

There is no universally accepted set of biomarkers for indicating nutritional deficiency, nor is there consensus on the threshold below which each biomarker indicates deficiency. The literature was reviewed for publications citing deficiency thresholds and a set of thresholds was compiled based on the cited evidence (Table 2-5). Where multiple biomarkers were available, the biomarker that is known to best reflect long term nutrient status was selected. Specifically,

red blood cell (RBC) folate, rather than plasma folate, was selected as the biomarker for folate status in this study. The complete information from publications used to establish these thresholds is provided in Appendix A.

Table 2-3 RNI thresholds across age group and sex

	Population group									
	1 – 3-year-old		**4 – 10-year-old**		**11 – 18-year-old**		**19 – 65-year-old**		**Over – 65-year-old**	
Micronutrient	**Female**	**Male**	**Female**	**Male**	**Female**	**Male**	**Female**	**Male**	**Female**	**Male**
Vitamin C (mg/day)	30	30	30	30	38	38	40	40	40	40
Folate (µg/day)	70	70	129	129	200	200	200	200	200	200
Niacin / Vitamin B3 (mg/day)	6.0	6.5	10.3	11.1	13.2	16.5	13.2	16.5	12.6	15.5
Thiamin / Vitamin B1 (mg/day)	0.4	0.4	0.7	0.7	0.8	1.0	0.8	1.0	0.8	0.9
Potassium (mg/day)	800	800	1614	1614	3300	3300	3500	3500	3500	3500
Phosphorus (mg/day)	270	270	407	407	625	775	550	550	550	550
Zinc (mg/day)	5.0	5.0	6.8	6.8	8.0	9.3	7.0	9.5	7.0	9.5
Copper (mg/day)	0.4	0.4	0.7	0.7	0.9	0.9	1.2	1.2	1.2	1.2
Magnesium (mg/day)	85	85	166	166	290	290	270	300	270	300
Riboflavin / Vitamin B2 (mg/day)	0.6	0.6	0.9	0.9	1.1	1.3	1.1	1.3	1.1	1.3

Thresholds produced using data from the following source: (Department of Health, 1991; Public Health England, 2016)

Table 2-4 LRNI thresholds across age group and sex

	Population group									
	1 – 3-year-old		4 – 10-year-old		11 – 18-year-old		19 – 65-year-old		Over – 65-year-old	
Micronutrient	**Female**	**Male**	**Female**	**Male**	**Female**	**Male**	**Female**	**Male**	**Female**	**Male**
Vitamin C (mg/day)	8	8	8	8	10	10	10	10	10	10
Folate (µg/day)	35	35	64	64	100	100	100	100	100	100
Niacin / Vitamin B3 (mg/day)	4.0	4.3	6.9	7.4	8.8	11.0	8.8	11.0	8.4	10.3
Thiamin / Vitamin B1 (mg/day)	0.2	0.2	0.4	0.4	0.5	0.6	0.5	0.6	0.4	0.5
Potassium (mg/day)	450	450	800	800	1800	1800	2000	2000	2000	2000
Phosphorus (mg/day)	155	155	235	235	370	400	310	310	310	310
Zinc (mg/day)	3.0	3.0	4.0	4.0	4.7	5.4	4	5.5	4	5.5
Copper (mg/day)	-	-	-	-	-	-	-	-	-	-
Magnesium (mg/day)	50	50	96	96	185	185	150	190	150	190
Riboflavin / Vitamin B2 (mg/day)	0.3	0.3	0.5	0.5	0.8	0.8	0.8	0.8	0.8	0.8

Thresholds produced using data from the following source: (Department of Health, 1991)

Table 2-5 Biomarker thresholds for deficiency for previously identified key micronutrients

Nutrient	Source Tissue	Biomarker	Deficiency threshold	References
Vitamin C	Plasma	-	11.35 µmol/L	(Gibson, 1990; Jacob, Pianalto and Agee, 1992; Simon, 1992; Wright *et al.*, 1995; Levine *et al.*, 1996; Loria *et al.*, 1998; Johnston and Corte, 1999; Institute of Medicine (US) Panel on Dietary Antioxidants and Related Compounds, 2000; Riemersma *et al.*, 2000; Simon, Hudes and Tice, 2001; Rousseau *et al.*, 2004; Rowe and Carr, 2020, 2020; Johnson, 2022d; Kraemer, 2022)
Folate (Vitamin B9)	Red Blood Cells	-	305 nmol/L	(Shin *et al.*, 1976; Bagley and Selhub, 1998; Institute of Medicine (US) Standing Committee on the Scientific Evaluation of Dietary Reference Intakes and its Panel on Folate, Other B Vitamins, and Choline, 1998; Pfeiffer *et al.*, 2009; Lynn B Bailey *et al.*, 2015; Bailey, 2021; Johnson, 2022a; Jones *et al.*, 2023; University of Cambridge, MRC Epidemiology Unit, NatCen Social Research, 2023)
Thiamin (Vitamin B1)	Whole blood	Erythrocyte Transketolase Activity Coefficient (ETKAC) activity	>1.25	(de Carvalho *et al.*, 1996; Bates, Thurnham and Nelson, 1997; Institute of Medicine (US) Standing Committee on the Scientific Evaluation of Dietary Reference Intakes and its Panel on Folate, Other B Vitamins, and Choline, 1998; Gibson, 2021; Jones *et al.*, 2021a)
Zinc	Plasma	-	9.00 µmol/L	(Smith and Garg, 2017; University of Cambridge, MRC Epidemiology Unit, NatCen Social Research, 2023)
Riboflavin (Vitamin B2)	Whole blood	Erythrocyte Glutathione Reductase Activity Coefficient (EGRAC) activity	>1.30	(Gibson, 1990, 2021; Sadowski, 1992; McCormick and Greene, 1994; Wright *et al.*, 1995; Institute of Medicine (US) Standing Committee on the Scientific Evaluation of Dietary Reference Intakes and its Panel on Folate, Other B Vitamins, and Choline, 1998; Hill *et al.*, 2009; University of Cambridge, MRC Epidemiology Unit, NatCen Social Research, 2023)

2.2.3 Data cleaning and wrangling

To allow comparisons with the intake thresholds, individuals' intake and biomarker data were stratified into the following age groups: 1 – 3-year-old, 4 – 10-year-old, 11 – 18-year-old, 19 – 65-year-old, and over – 65-year-old, with all age groups separated into Male and Female subcategories.

Exploratory analysis revealed a small number of data points that fell far outside the expected range of intake or biomarker values, even when accounting for extreme intakes or biomarker levels. When plotted, these data points resulted in the compression of the violin plot for the remaining data points, making it difficult to visualise the distribution of the remaining points. Individuals with intakes or biomarker levels greater than five times the mean value for their population group were, therefore, excluded from subsequent plots. This threshold was chosen to minimise the number of points removed from the dataset, whilst still allowing clear visualisation of the population distribution. Seven data points were removed from the intake dataset, and three points were removed from the biomarker dataset.

2.2.4 Data analysis

Data processing, analysis, and visualisation were performed in R (R Core Team, 2024), via RStudio version 2025.05.1 (Posit team, 2025). The 'srvyr' package version 1.3.0 (Ellis and Schneider, 2024) was used to incorporate weighting and stratification variables into dataset statistical summaries, in line with the complex survey design and the guidance provided alongside the NDNS data (URL: https://beta.ukdataservice.ac.uk/datacatalogue/studies/study?id=6533). This enabled the calculation of nationally representative weighted mean values for each micronutrient and population group. These means were overlayed onto violin plots of the individual data points for each group, constructed using the 'ggplot2' package version 3.5.1 (Wickham, 2016), to visualise the underlying distribution of data points. The 'gtsummary' package version 2.3.0 (Sjoberg *et al.*, 2021)was used to produce population summary statistics for the weighted intake and biomarker datasets.

2.3 Results

2.3.1 Cohort Characteristics

A summary of the overall characteristics of the surveyed population is shown in Table 2-6. In general, weighting brought the sample population characteristics closer to the wider UK Census

population, especially the variables of median age, sex, and region (Table 2-6). Other variables, such as smoking status, ethnicity, and mean BMI remained different to the reference population even after weighting (Table 2-6). Biomarker data were available for 1395 individuals, whilst intake data were available for all 3558 individuals (Table 2-6).

Table 2-6 Population characteristics of the surveyed population, weighted populations, and reference (UK) population

	Sample Population	**Weighted Population Intakes**	**Weighted Population Biomarkers**	**Reference (UK) population**
Number of individuals / n	3558	3558	1395	59.6 mil[1]
Median age / yrs (se)	23 (0.4)	40 (1.0)	40 (1.3)	39.6[1]
Mean BMI / kg/m^2 (se)	23.0 (0.1)	23.3 (0.2)	24.0 (0.3)	27.5 (0.12)[2]
Age group / n (%)				
1 – 3 years	306 (8.6)	109 (3.1)	-	1.9 mil (3.3) [1]
4 – 10 years	725 (20.4)	314 (8.8)	122 (8.7)	4.9 mil (8.3) [1]
11 – 18 years	683 (19.2)	322 (9.0)	133 (9.5)	5.6 mil (9.3) [1]
19 – 64 years	1392 (39.1)	2156 (60.6)	872 (62.5)	35.5 mil (59.5) [1]
65+ years	452 (12.7)	657 (18.5)	232 (16.6)	11.1 mil (18.6) [1]
Sex / n (%)				
Male	1636 (46.0)	1754 (49.3)	671 (48.1)	29.2 mil (49.0) [1]
Female	1922 (54.0)	1804 (50.7)	724 (51.9)	30.4 mil[1] (51.0) [1]
Household income tertile / n (%)				
Lowest	1043 (29.3)	906 (25.5)	356 (25.5)	-
Middle	1015 (28.5)	977 (27.5)	376 (27.0)	-
Highest	1017 (28.6)	1090 (30.6)	451 (32.3)	-
Smoking status / n (%)				
Never	376 (34.4)	536 (47.8)	226 (47.2)	3813 (65.8)[2]
Ex Smoker	127 (11.6)	198 (17.7)	83 (17.3)	1304 (22.5)[2]
Smoker	111 (10.1)	153 (13.7)	72 (15.0)	679 (11.7)[2]
Ethnicity / n (%)				
White	3118 (87.6)	3068 (86)	1200 (86)	48.7 mil[1] (81.7)
Mixed ethnic group	63 (1.8)	47 (1.3)	23 (1.6)	1.7 mil[1] (2.9)
Black or Black British	93 (2.6)	104 (2.9)	32 (2.3)	2.4 mil[1] (4.0)
Asian or Asian British	231 (6.5)	284 (8.0)	116 (8.3)	5.5 mil[1] (9.3)

Any other group	46 (1.3)	53 (1.5)	25 (1.8)	1.2 mil[1] (2.1)
Region / n (%)				
North East	148 (4.2)	143 (4.0)	48 (3.4)	2.6 mil[1] (3.9)
North West	346 (9.7)	391 (11.0)	161 (11.5)	7.4 mil[1] (11.1)
Yorkshire & The Humber	243 (6.8)	294 (8.3)	121 (8.7)	5.5 mil[1] (8.2)
East Midlands	225 (6.3)	257 (7.2)	99 (7.1)	4.9 mil[1] (7.3)
West Midlands	286 (8.0)	316 (8.9)	114 (8.2)	6.0 mil[1] (8.9)
East of England	288 (8.1)	332 (9.3)	141 (10.1)	6.3 mil[1] (9.5)
London	296 (8.3)	474 (13.3)	187 (13.4)	8.8 mil[1] (13.1)
South East	404 (11.4)	490 (13.8)	200 (14.3)	9.3 mil[1] (13.9)
South West	256 (7.2)	300 (8.4)	125 (8.9)	5.7 mil[1] (8.5)
Wales	273 (7.7)	169 (4.7)	68 (4.9)	3.1 mil[1] (4.6)
Scotland	235 (6.6)	293 (8.2)	120 (8.6)	5.5 mil[1] (8.2)
Northern Ireland	558 (15.7)	101 (2.8)	11 (0.8)	1.9 mil[1] (2.8)

[1]Office for National Statistic Census Data 2021. [2]NHS Health Survey for England 2021. Abbreviations: mil = millions. Sample population – the raw data from individuals sampled in the NDNS cohort years 9 to 11. Weighted population intakes – the data from the NDNS cohort years 9 to 11 weighted using the 'wti_Y911' variable from the NDNS dataset. Weighted Population Biomarkers – the data from the NDNS cohort years 9 to 11 weighted using the 'wtb_Y911' variable from the NDNS dataset. Reference (UK) population – Characteristics of the UK population obtained from ONS Census data 2021 and the NHS Health Survey for England 2021

2.3.2 Vitamin C

All population groups had mean vitamin C intakes that exceeded the RNI (Figure 2-1). There was a statistically significant difference between the vitamin C intakes of different population groups ($H(9) = 28.4$, $p = 0.001$). The highest mean intake was in the 19–64-year-old Male group (87.2 mg/day), while the lowest was in the 1–3-year-old Male group (64.0 mg/day) (Figure 2-1). Males and females had similar intakes in all age groups, and the overall mean intake increased with age (Figure 2-1).

The 11–18-year-old Male and over-65-year-old Female groups had the largest percentage of individuals below the RNI (22.3%), while the 4–10-year-old Male group had the smallest (7.1%) (Figure 2-1). The 19–64-year-old Female group had the largest proportion below the LRNI (1.2%), while the 1–3-year-old Male and Female groups, and the 4–10-year-old Male group, had no individuals with intakes below the LRNI (Figure 2-1).

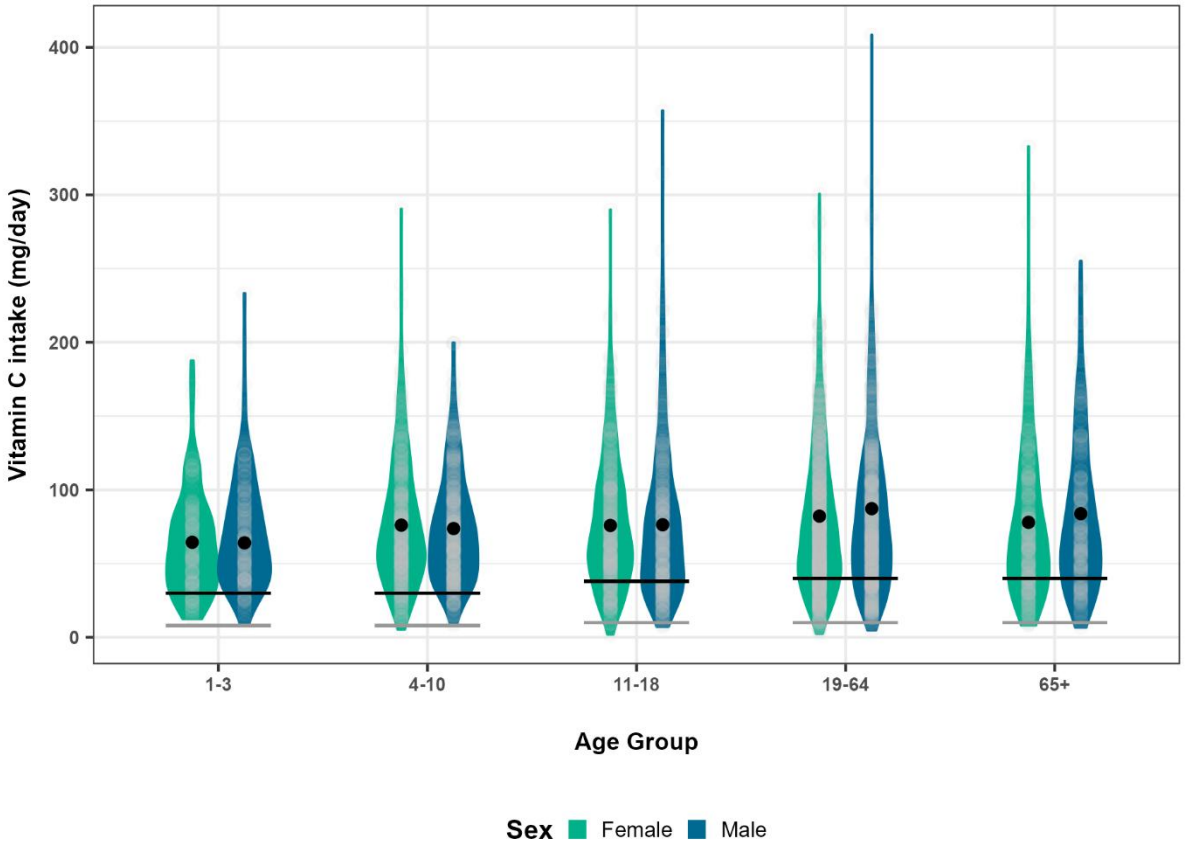


Figure 2-1 Violin plot of the vitamin C intakes of individuals in the NDNS dataset Years 9-11 (mg/d). Black point – weighted mean for population group. Black line – RNI for population group. Grey line – LRNI for population group.

All population groups had mean serum vitamin C levels that exceeded the deficiency threshold (Figure 2-2). There was a statistically significant difference between the serum vitamin C levels of the different population groups ($H(7) = 123.7$, $p < 0.001$). The lowest mean serum vitamin C level was in the over-65-year-old Male group (48.5 µmol/L), and the highest was in the 4 –10-year-old Female group (73.6 µmol/L) (Figure 2-2). Mean serum vitamin C levels decreased with age and were consistently lower in Males across all age groups (Figure 2-2).

The percentage of the population below the deficiency threshold was higher in adults compared with children and adolescents (Figure 2-2). The highest proportion was in the over-65-year-old Female group (7.52%), whilst the 11 –18-year-old Female and 4 – 10-year-old Male groups had no part of the population below the deficiency threshold (Figure 2-2).

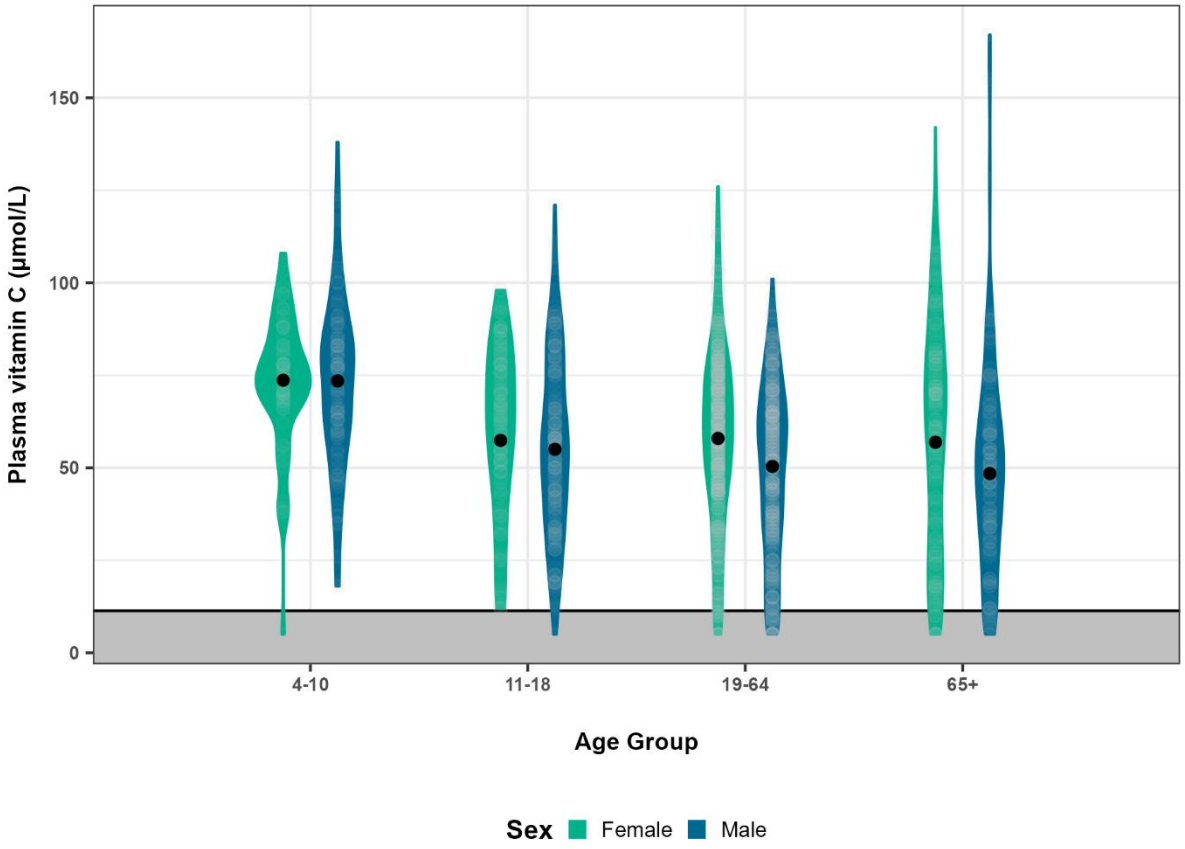


Figure 2-2 Violin plot of the plasma vitamin C levels of individuals in the NDNS dataset Years 9-11 (µmol/L). Black point – weighted mean for population group. Black line – threshold for deficiency. Grey rectangle – biomarker levels implying deficiency.

2.3.3 Folate (Vitamin B9)

All population groups had mean folate intakes above the RNI, except the 11 – 18-year-old Female group (Figure 2-3). There was a statistically significant difference between the folate intakes of different population groups ($H(9) = 1144.9$, $p < 0.001$). The highest mean intake was in the 19 – 64-year-old Male group (265 µg/day), and the lowest was in the 1 – 3-year-old Female group (128 µg/day) (Figure 2-3). Intakes were lower in Females than in Males across all age groups (Figure 2-3).

The percentage below the RNI threshold was consistently higher for Females (Figure 2-3). The 11 – 18-year-old Female group had the highest proportion below the RNI (74.4%), whilst the 1 – 3-year-old Male group had the lowest (2.4%) (Figure 2-3). The 11 – 18-year-old Female group also had the largest part of the population below the LRNI (10.4%) (Figure 2-3). All groups had some individuals below the LRNI, except the 1 – 3-year-old Male and Female groups (0.0%) (Figure 2-3).

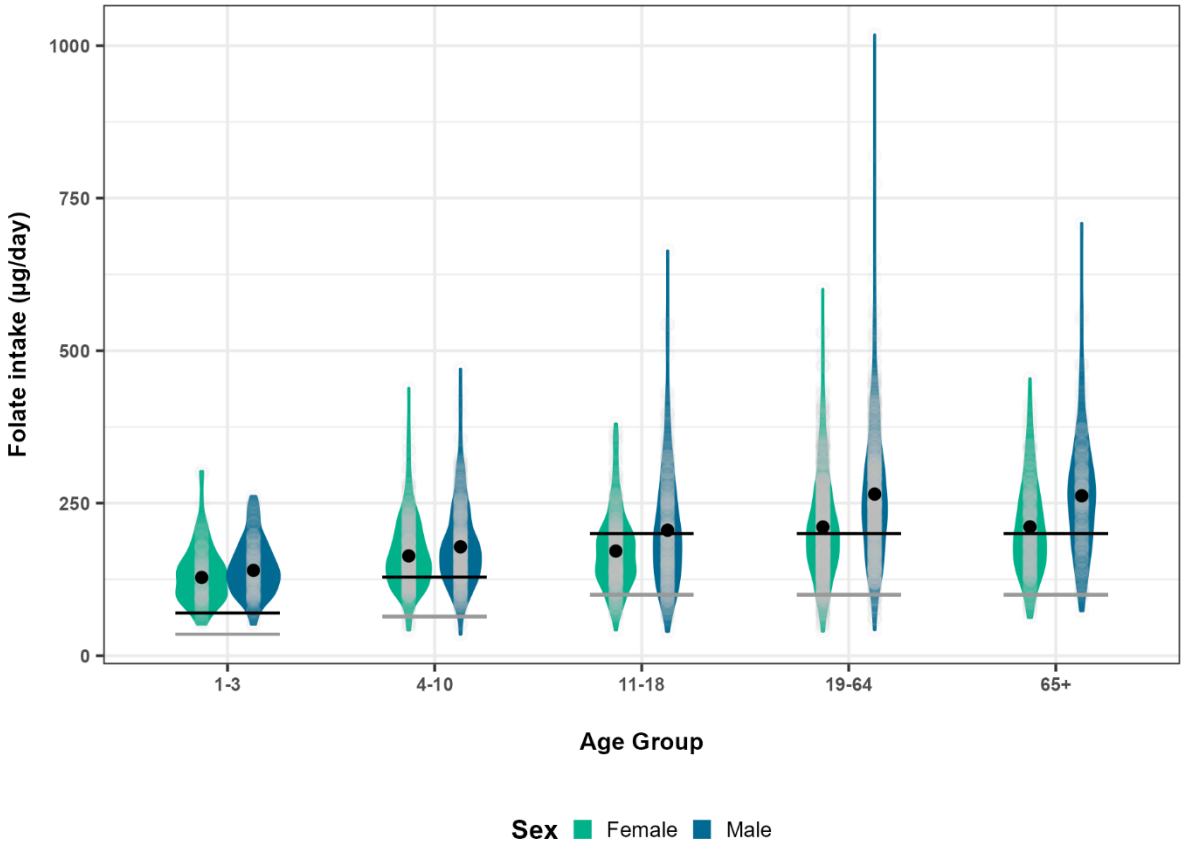


Figure 2-3 Violin plot of the folate intakes of individuals in the NDNS dataset Years 9-11 (µg/day). Black point – weighted mean for population group. Black line – RNI for population group. Grey line – LRNI for population group.

All groups had mean RBC folate levels above the deficiency threshold (Figure 2-4). There was a statistically significant difference between the RBC folate levels of the different population groups ($H(7) = 83.7$, $p < 0.001$). The lowest mean was in the 11 – 18-year-old Female group (413 nmol/L), and the highest was in the over-65-year-old Male group (648 nmol/L) (Figure 2-4). RBC folate levels were lower in Females than Males in all population groups apart from the 19 – 64-year-old groups (Figure 2-4). Deficiency prevalence ranged from 2.28% in 4–10-year-old Females to 17.1% in 11–18-year-old Males (Figure 2-4).

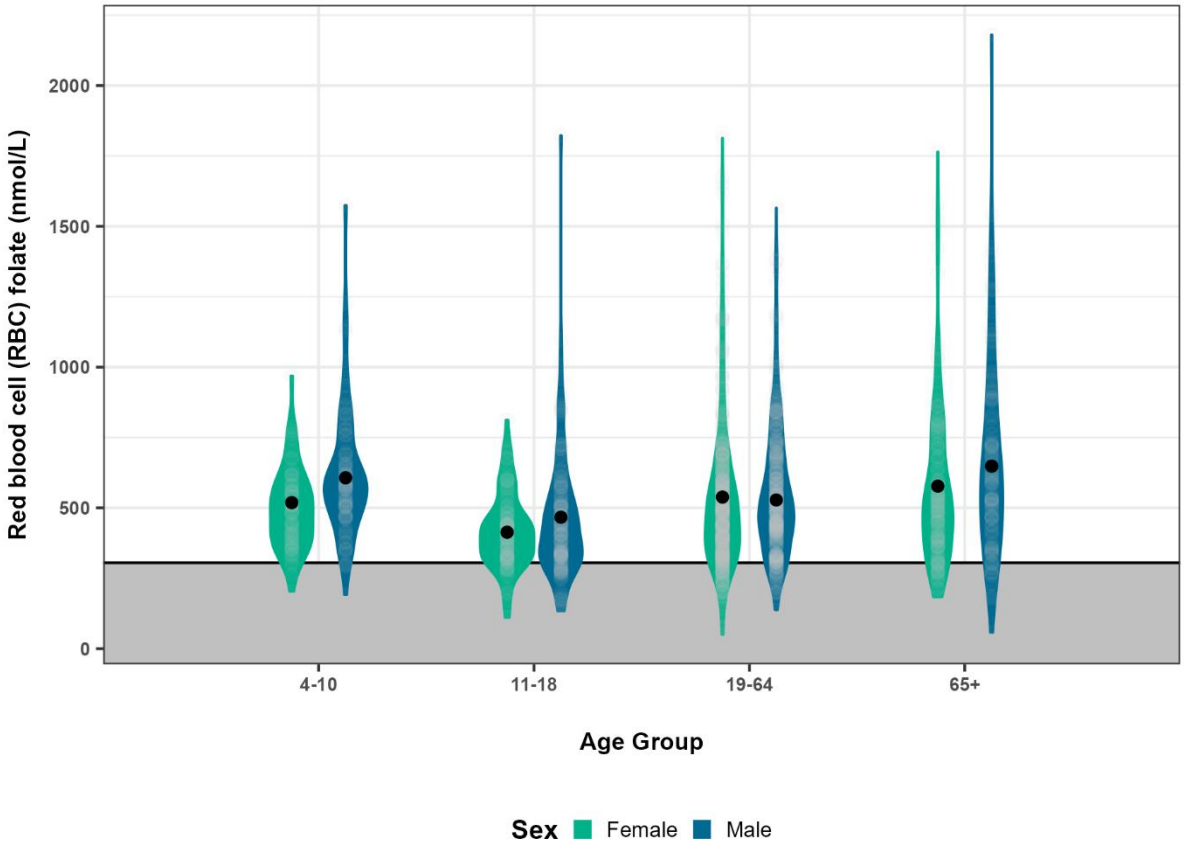


Figure 2-4 Violin plot showing the red blood cell (RBC) folate levels of individuals in the NDNS dataset Years 9-11 (nmol/L). Black point – weighted mean for population group. Black line – threshold for deficiency. Grey rectangle – biomarker levels implying deficiency.

2.3.4 Niacin (Vitamin B3)

Only dietary intake data were available in relation to niacin. All groups had mean niacin intakes that exceeded the RNI (Figure 2-5). There was a statistically significant difference between the niacin intakes of different population groups ($H(9) = 2459.8$, $p < 0.001$). The highest mean intake was in the 19 – 64-year-old Male group (40.6 mg/day), and the lowest was in the 1 – 3-year-old Female group (16.5 mg/day) (Figure 2-5). Intakes were lower for Females than Males in all age groups (Figure 2-5).

The proportion of the population below the RNI ranged from 2.25% in the 11 – 18-year-old Male group, to 0% in the 1 – 3-year-old Male and Female groups (Figure 2-5). The 11 – 18-year-old Male (0.66%), 19 – 64-year-old Male (0.31%), 19 – 64-year-old Female (0.35%) and over-65-year-old Male (1.16%) had populations below the LRNI (Figure 2-5). Overall, intakes were high relative to the LRNI and RNI thresholds (Figure 2-5).

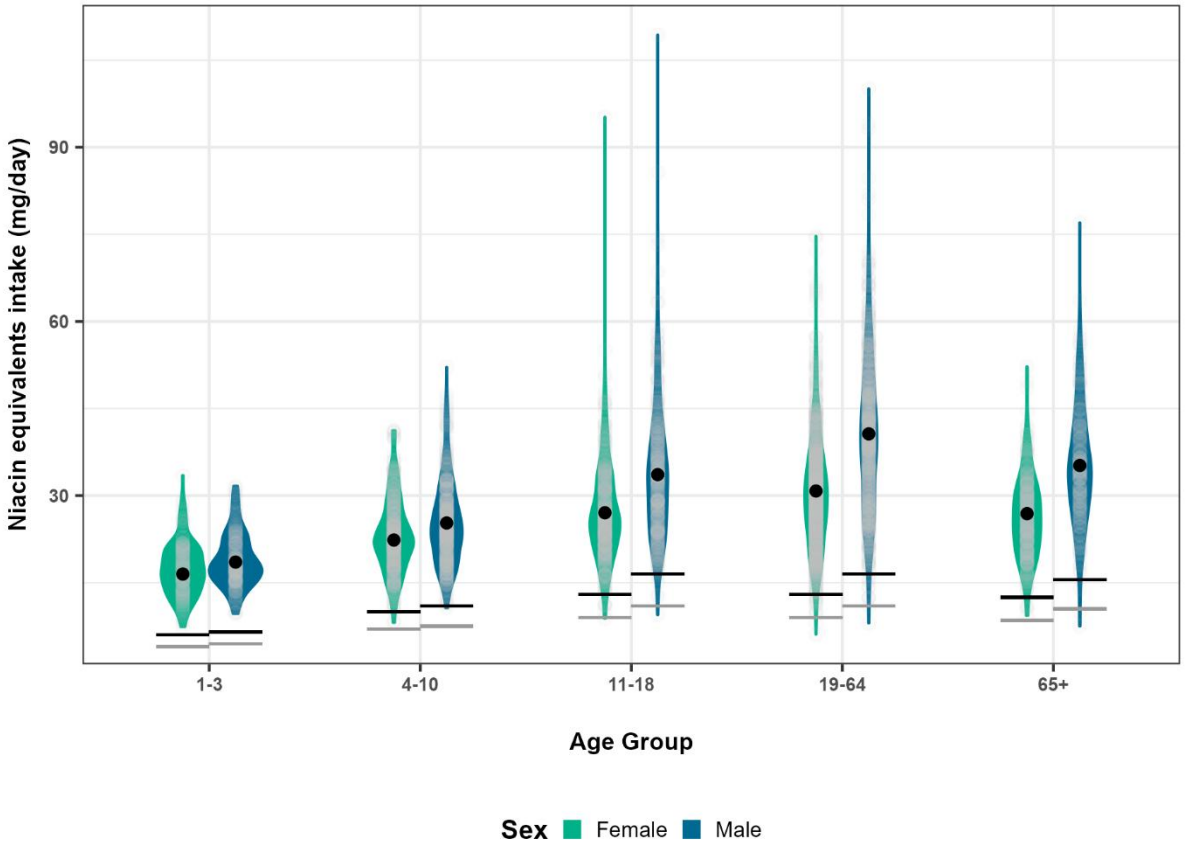


Figure 2-5 Violin plot of the niacin equivalent intakes of individuals in the NDNS dataset Years 9-11 (mg/day). Black point – weighted mean for population group. Black line – RNI for population group. Grey line – LRNI for population group.

2.3.5 Thiamin (Vitamin B1)

All groups had mean thiamin intakes above the RNI (Figure 2-6). There was a statistically significant difference between the thiamin intakes of different population groups ($H(9) = 761.1$, $p < 0.001$). The highest mean intake was in the 19 – 64-year-old Male group (1.68 mg/day), and the lowest in the 1 – 3-year-old female group (0.88 mg/day) (Figure 2-6). Males had higher intake than Females in all age groups (Figure 2-6).

The 11 – 18-year-old Male group had the largest population below the RNI (19.0%), whilst 1 – 3-year-old Males were the only group with no part of the population below the RNI (Figure 2-6). The 11 – 18-year-old Male group also had the largest proportion below the LRNI (2.49%). The 1 – 3-year-old Male and 1 – 3-year-old Female groups, along with the 4 – 10-year-old Female group, all had no individuals below the LRNI (Figure 2-6).

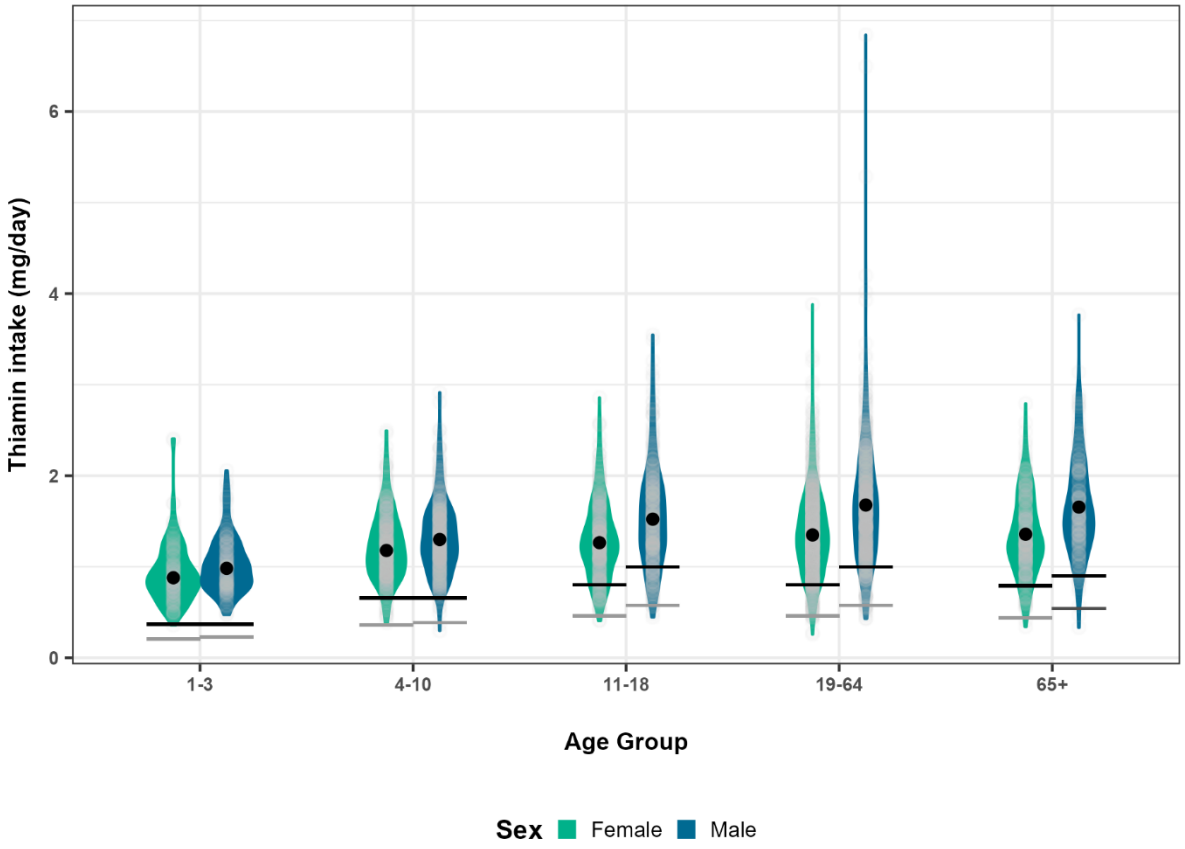


Figure 2-6 Violin plot of the thiamin intakes of individuals in the NDNS dataset Years 9-11 (mg/day). Black point – weighted mean for population group. Black line – RNI for population group. Grey line – LRNI for population group.

The biomarker for thiamin is the Erythrocyte Transketolase Activity Coefficient (ETKAC), for which higher values indicate lower body thiamin levels. All groups had mean ETKAC values below the deficiency threshold, indicative of sufficiency (Figure 2-7). There was a statistically significant difference between the ETKAC values of the different population groups ($H(7) = 46.8$, $p < 0.001$). The lowest mean values were in the 4–10-year-old Male (1.09) and Female groups (1.09), while the highest was in the 19–64-year-old Male group (1.13) (Figure 2-7).

The highest proportion of individuals above the ETKAC deficiency threshold was in the 11–18-year-old Female group (5.96%) (Figure 2-7). Additionally, the groups of 11 – 18-year-old Male (3.18%), 19 – 64-year-old Male (2.47%), 19 – 64-year-old Female (0.55%) and over-65-year-old Female (1.20) all had individuals with ETKAC levels indicating deficiency (Figure 2-7).

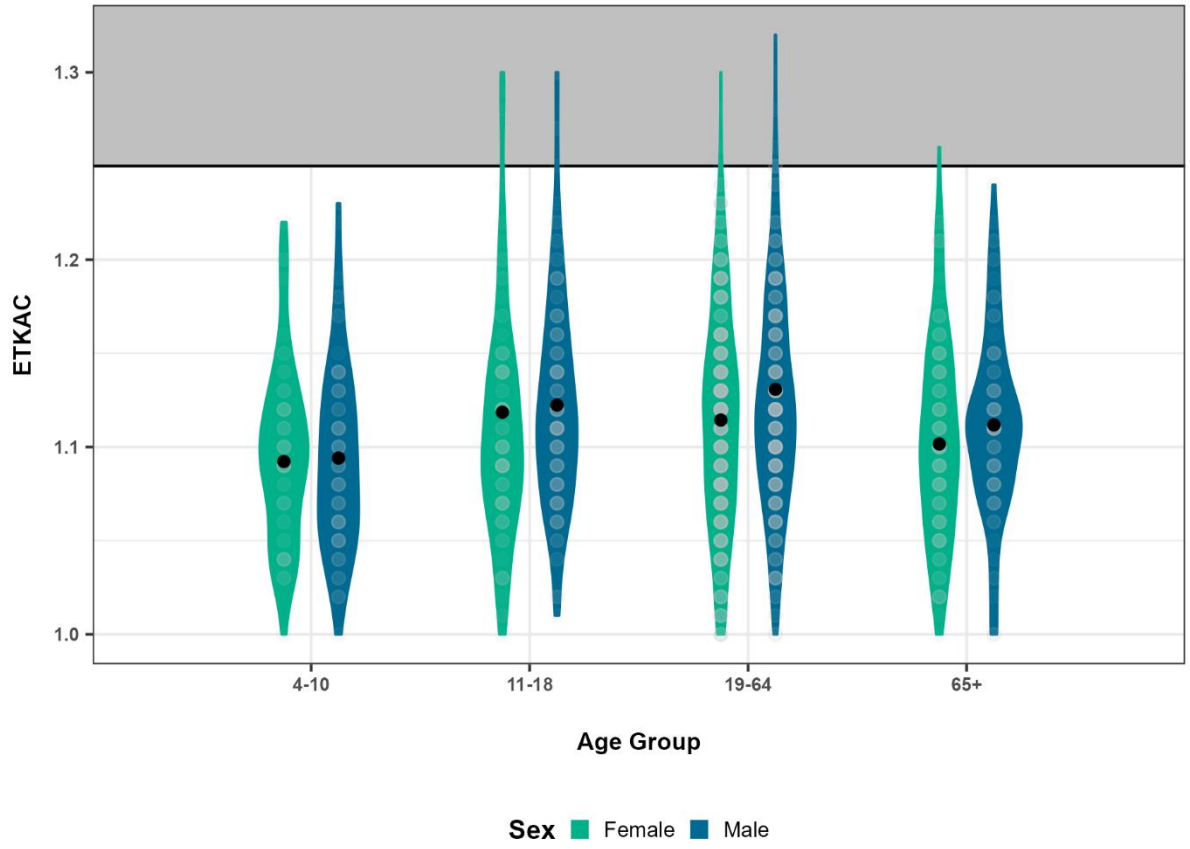


Figure 2-7 Violin plot of the ETKAC values of individuals in the NDNS dataset Years 9-11. Black point – weighted mean for population group. Black line – threshold for deficiency. Grey rectangle – biomarker levels implying deficiency.

2.3.6 Potassium

Only dietary intake data were available for potassium. All groups over the age of 10-years-old had mean potassium intakes below the RNI (Figure 2-8). There was a statistically significant difference between the potassium intakes of different population groups ($H(9) = 1523.7$, $p < 0.001$). The highest mean intake was in the 19 – 64-year-old Male group (3109 mg/day), and the lowest was in 1 – 3-year-old Female group (1566 mg/day) (Figure 2-8). Intakes were consistently lower in Females than in Males across all age groups (Figure 2-8).

All groups had some individuals below the RNI threshold (Figure 2-8). The 11 – 18-year-old Female group had the highest proportion below the RNI (96.6%), whilst the 1 – 3-year-old Male group had the lowest (1.92%) (Figure 2-8). The 11 – 18-year-old Female group also had the highest proportion below the LRNI (37.2%). No individuals in the 1 – 3-year-old groups had intakes below the LRNI (Figure 2-8). All population groups over the age of 10 included individuals below the LRNI threshold, ranging from 0.26% (4 – 10-year-old Male) to 37.2% (11 – 18-year-old Female) of the population (Figure 2-8).

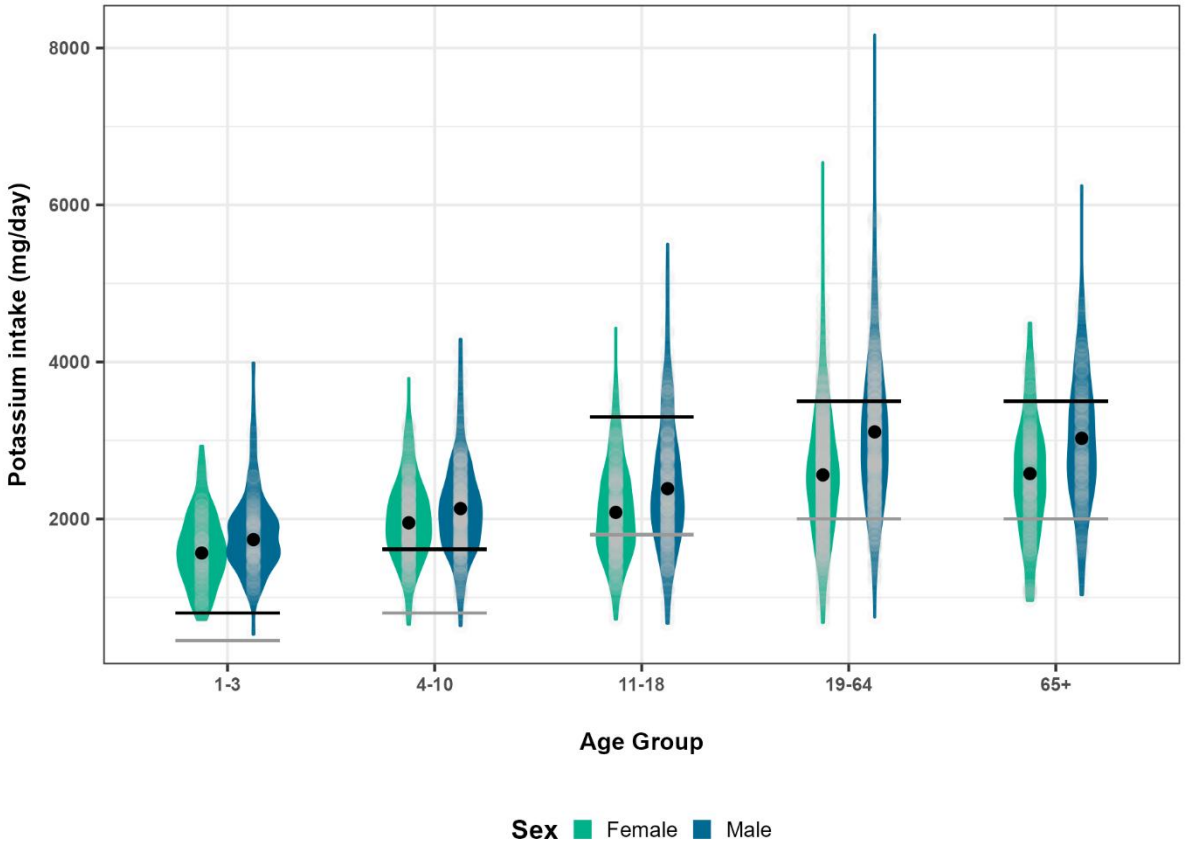


Figure 2-8 Violin plot of the potassium intakes of individuals in the NDNS dataset Years 9-11 (mg/day). Black point – weighted mean for population group. Black line – RNI for population group. Grey line – LRNI for population group.

2.3.7 Phosphorus

Only dietary intake data were available for phosphorus. All groups had mean phosphorus intakes that exceeded the RNI (Figure 2-9). There was a statistically significant difference between the phosphorus intakes of different population groups ($H(9) = 1018.9$, $p < 0.001$). The highest mean intake was in the 19–64-year-old Male group (1375 mg/day), and the lowest was in the 1–3-year-old Female group (757 mg/day) (Figure 2-9).

The 11–18-year-old Male group had the largest proportion below the RNI (14.6%), whilst both Male and Females in the 1 – 3-year-old age bracket had no individuals below RNI (0.0%) (Figure 2-9). Only the 11 – 18-year-old Female (0.48%) and 19 – 64-year-old Female (0.25%) groups included any individuals below the LRNI (Figure 2-9).

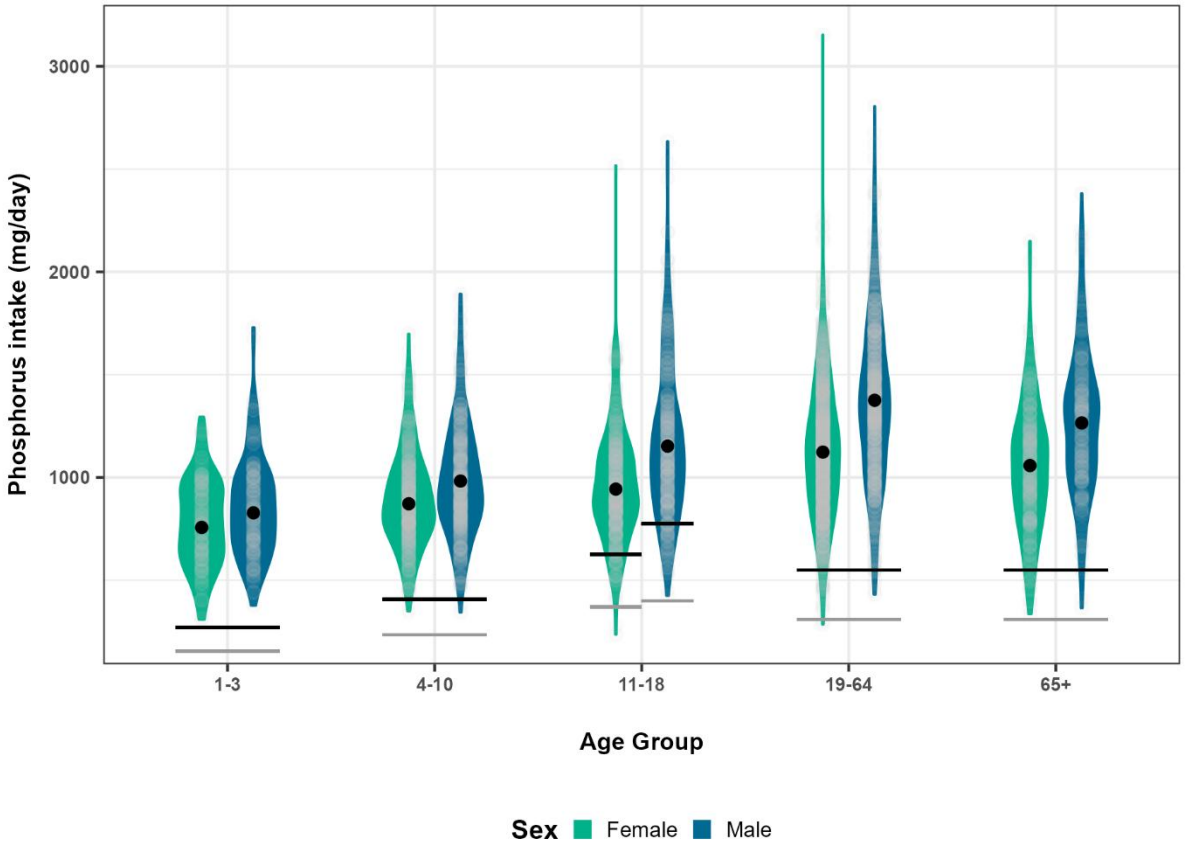


Figure 2-9 Violin plot of the phosphorus intakes of individuals in the NDNS dataset Years 9-11 (mg/day). Black point – weighted mean for population group. Black line – RNI for population group. Grey line – LRNI for population group.

2.3.8 Zinc

Most groups had mean zinc intakes below than the RNI (Figure 2-10). Exceptions were the 19-to-64-year-old Male (9.54 mg/day), 19-to-64-year-old Female (7.64 mg/day) and over-65-year-old Female (7.11 mg/day) groups (Figure 2-10). There was a statistically significant difference between the zinc intakes of different population groups ($H(9) = 1238.0$, $p < 0.001$). The highest mean intake was in the 19 – 64-year-old Male group, while the lowest was in the 1 – 3-year-old Female group (4.63 mg/day) (Figure 2-10). Males had higher intakes than Females in all age groups (Figure 2-10).

The percentage of individuals below the RNI was greater than 40% In all groups (Figure 2-10). The 11 – 18-year-old Female group had the highest proportion (80%), while the 19 – 64-year-old Female group had the lowest (42.8%) (Figure 2-10). The 11 – 18-year-old Male group had the highest proportion below the LRNI (20.0%), whilst the over-65-year-old Female group had the lowest (4.09%) (Figure 2-10). All population groups had at least 4% of the population with intakes below the LRNI (Figure 2-10).

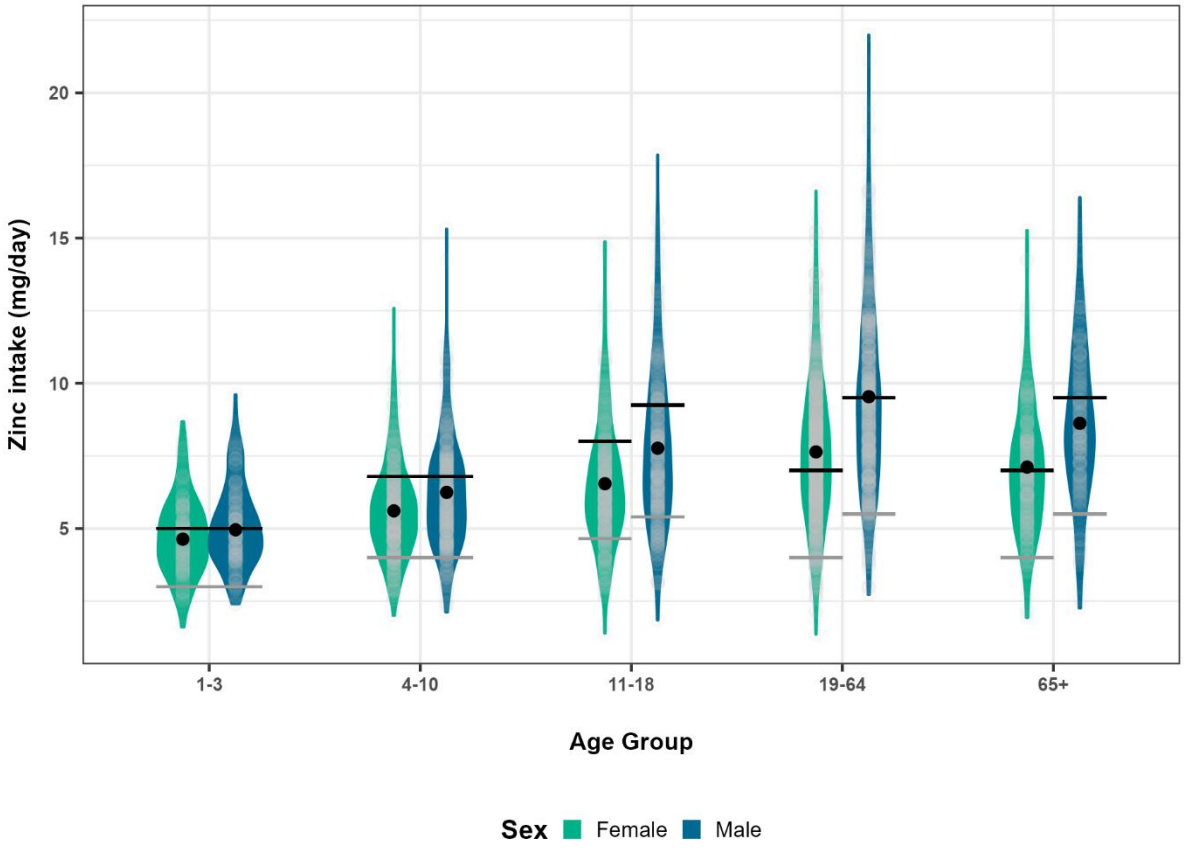


Figure 2-10 Violin plot of the zinc intakes of individuals in the NDNS dataset Years 9-11 (mg/day). Black point – weighted mean for population group. Black line – RNI for population group. Grey line – LRNI for population group.

All groups had mean plasma zinc levels above the deficiency threshold (Figure 2-11). There was a statistically significant difference between the plasma zinc levels of the different population groups ($H(7) = 112.9$, $p < 0.001$). The lowest mean plasma zinc level was in the 19 – 64-year-old Female population group (12.8 µmol/L), whilst the groups of 4 – 10-year-old Male (14.2 µmol/L) and 11 – 18-year-old Male (14.2 µmol/L) had the highest (Figure 2-11). Plasma zinc levels were consistently lower in Females relative to Males in the same age group (Figure 2-11). The highest prevalence of deficiency was in the over-65-year-old Male group (2.35%), whilst no individuals below the age of 18-years-old had plasma zinc levels below the deficiency threshold (Figure 2-11).

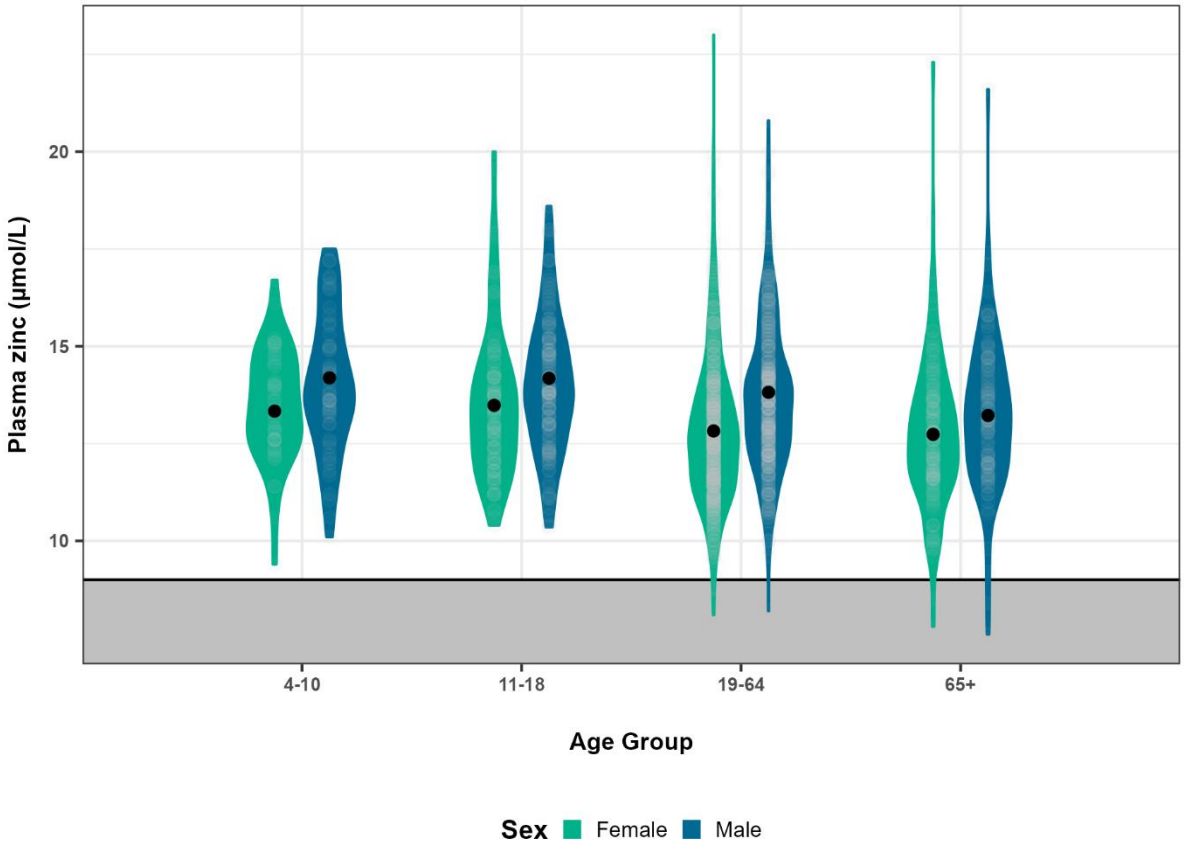


Figure 2-11 Violin plot of the plasma zinc levels of individuals in the NDNS dataset Years 9-11 (µmol/L). Black point – weighted mean for population group. Black line – threshold for deficiency. Grey rectangle – biomarker levels implying deficiency.

2.3.9 Copper

Only dietary intake data were available for copper. Most groups had mean intakes of copper that exceeded the RNI (Figure 2-12), with the exception of the 19 – 64-year-old Female and over-65-year-old Female groups (Figure 2-12). There was a statistically significant difference between the copper intakes of different population groups ($H(9) = 1649.1$, $p < 0.001$). The 19 – 64-year-old Male group had the highest mean intake of copper (1.34 mg/day), whilst the 1 – 3-year-old Female group had the lowest (0.551 mg/day) (Figure 2-12). Across all age groups, Males had higher intakes than Females (Figure 2-12).

The over-65-year-old Female group had the largest percentage of the population with below the RNI (71.0%), whilst the 1 – 3-year-old Male group had the smallest (18.3%) (Figure 2-12). The proportion below the RNI increased with age and was higher in Female than Male groups in all age groups (Figure 2-12). No LRNI values were available for copper.

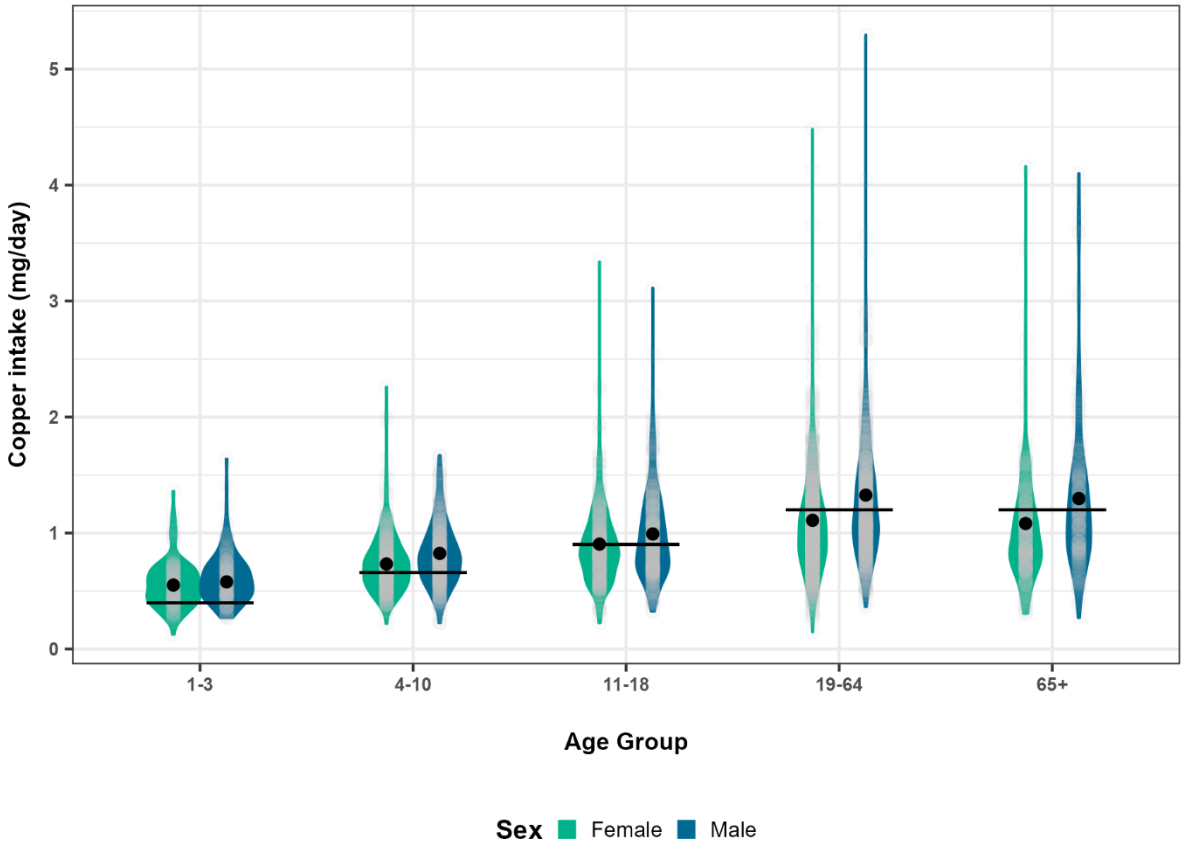


Figure 2-12 Violin plot of the copper intakes of individuals in the NDNS dataset Years 9-11 (mg/day). Black point – weighted mean for population group. Black line – RNI for population group.

2.3.10 Magnesium

Only dietary intake data were available for magnesium. Of the surveyed population, the 11 – 18-year-old Female, 11 – 18-year-old Male, 19 – 64-year-old Female, over-65-year-old Male and over-65-year-old Female groups had mean magnesium intakes below the RNI (Figure 2-13). There was a statistically significant difference between the magnesium intakes of different population groups ($H(9) = 1848.1$, $p < 0.001$). The 19 – 64-year-old Male group had the highest mean intake (301 mg/day), whilst the 1 – 3-year-old Female group had the lowest (140 mg/day) (Figure 2-13). Intakes were lower for Females than Males across all age groups (Figure 2-13).

The 11 – 18-year-old Female group had the largest proportion below the RNI (91.6%), whilst the 1 – 3-year-old Male group had the smallest (1.92%) (Figure 2-13). The percentage of the population with intakes below the RNI was higher for Female than Male groups across all age brackets (Figure 2-13). The 11 – 18-year-old Female group also had the largest proportion below the LRNI (46.3%), whilst both the 1 – 3-year-old Male and 1 – 3-year-old Female groups had no individual below the LRNI (0.0%) (Figure 2-13).

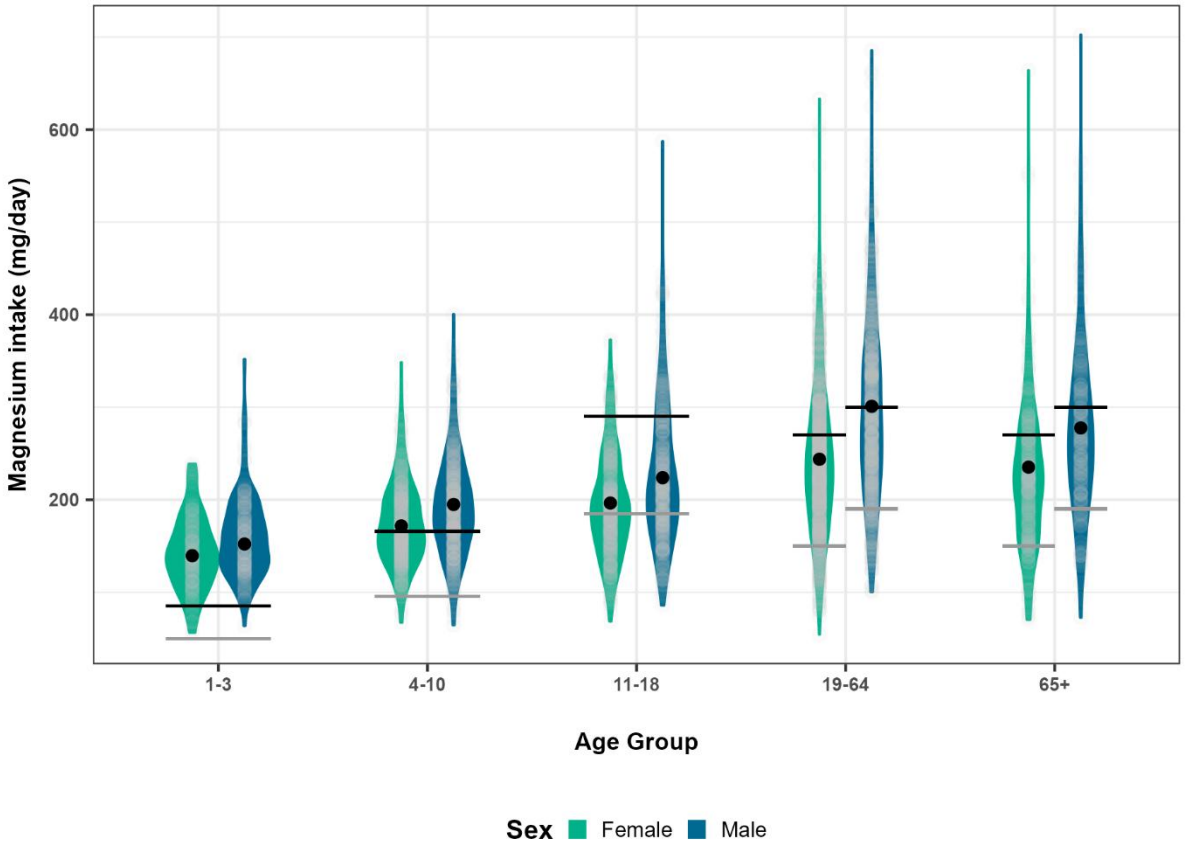


Figure 2-13 Violin plot of the magnesium intakes of individuals in the NDNS dataset Years 9-11 (mg/day). Black point – weighted mean for population group. Black line – RNI for population group. Grey line – LRNI for population group.

2.3.11 Riboflavin (Vitamin B2)

All groups had mean riboflavin intakes above the RNI (Figure 2-14). There was a statistically significant difference between the riboflavin intakes of different population groups ($H(9) = 274.2$, $p < 0.001$). The highest mean intake was in the 19 – 64-year-old Male group (1.72 mg/day), and the lowest was in the 1 – 3-year-old Female group (1.25 mg/day) (Figure 2-14). Intakes were lower in Female compared to Male groups across all age brackets (Figure 2-14).

The 11 – 18-year-old Female group had the largest proportion below the RNI (50.9%) (Figure 2-14), and the 1 – 3-year-old Male group had the smallest proportion below the RNI (2.84%) (Figure 2-14). Across all age brackets, the proportion of the Female group below the RNI was higher than their Male counterparts (Figure 2-14). The 11 – 18-year-old Female group also had the largest proportion below the LRNI. Only the 1 – 3-year-old Male and 1 – 3-year-old Female groups had no individuals below the LRNI (Figure 2-14).

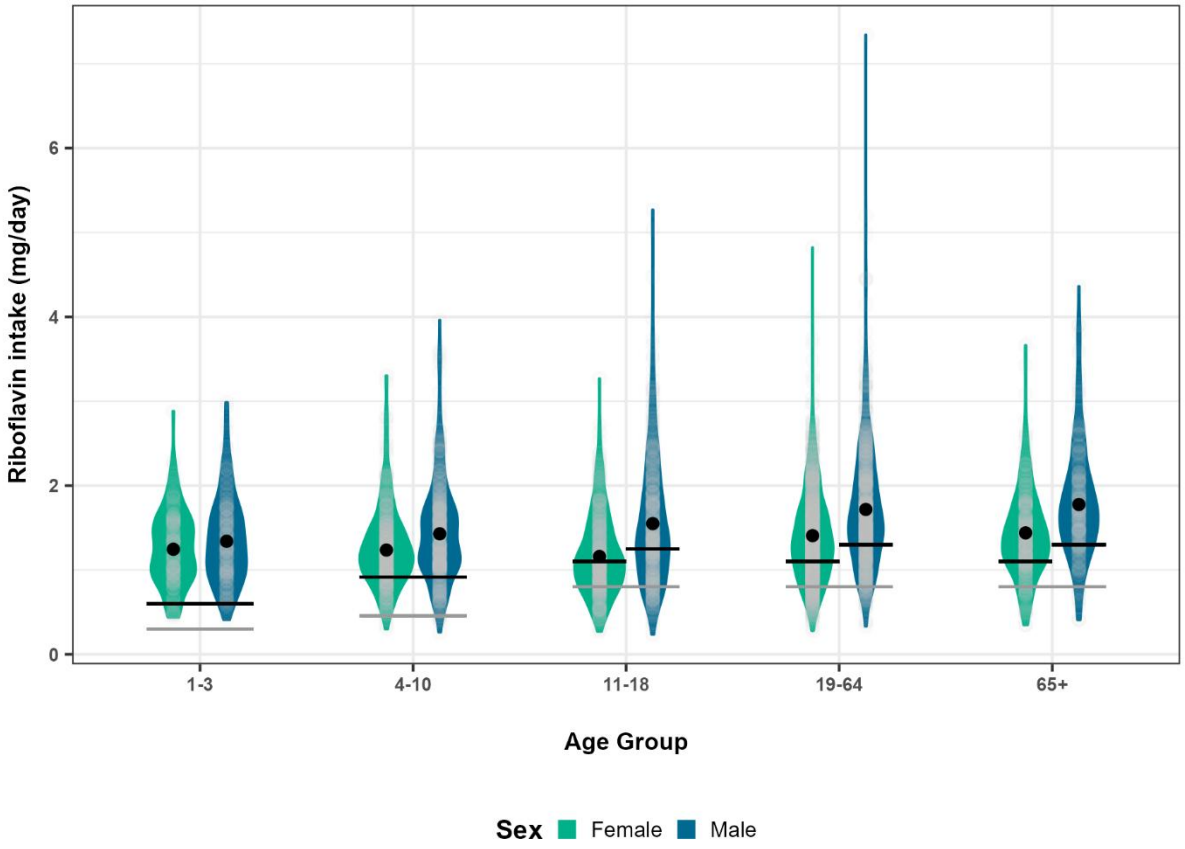


Figure 2-14 Violin plot of the riboflavin intakes of individuals in the NDNS dataset Years 9-11 (mg/day). Black point – weighted mean for population group. Black line – RNI for population group. Grey line – LRNI for population group.

The biomarker for riboflavin is the Erythrocyte Glutathione Reductase Activity Coefficient (EGRAC), for which higher values indicate lower body riboflavin levels. There was a statistically significant difference between the EGRAC values of the different population groups ($H(7) = 106.1$, $p < 0.001$). The 4 – 10-year-old Male, 11 – 18-year-old Male, 11 – 18-year-old Female, 19 – 64-year-old Female and 19 – 64-year-old Male groups all had mean EGRAC levels above the 1.30 threshold, indicating deficiency (Figure 2-15). EGRAC levels were highest in the 11 – 18-year-old Female group (1.46), and lowest in the over-65-year-old Female group (1.26) (Figure 2-15).

All population groups had some individuals deficient in riboflavin, ranging from 31.1% in the over-65-year-old Male group, to 75.1% in 11 – 18-year-old Female group (Figure 2-15). No changes in the levels of deficiency across different age and sex groups were observed (Figure 2-15).

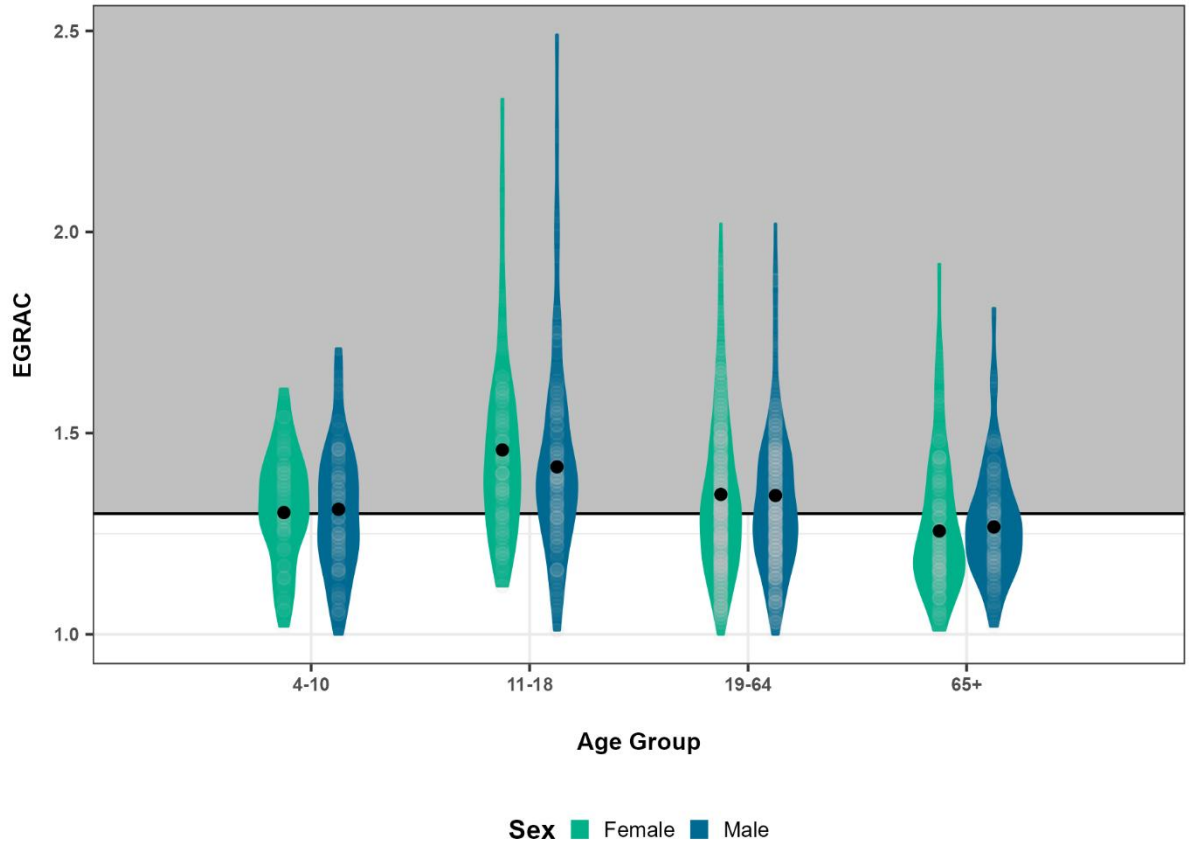


Figure 2-15 Violin plot of the EGRAC values of individuals in the NDNS dataset Years 9-11. Black point – weighted mean for population group. Black line – threshold for deficiency. Grey rectangle – biomarker levels implying deficiency.

2.4 Discussion

Chapter 2 used the NDNS dataset to explore the population level nutritional status of micronutrients found in significant quantities in parsnips. Results showed that all micronutrients assessed had at least some groups with status below recommended thresholds. Every micronutrient had at least one of ten population groups with intakes below the LRNI, and at least eight of ten groups with intakes below the RNI. For micronutrients with biomarker data, at least four of ten population groups included individuals with levels indicating deficiency. These findings suggest that micronutrient status in the UK is generally suboptimal, with broad scope for improvement to benefit public health.

There were, however, differences in the extent of insufficiency across the surveyed micronutrients. For example, niacin intake data showed minimal concern: a maximum of 2% of 11–18-year-old males were below the RNI, 1% of men aged 65+ years were below the LRNI, and mean intakes across all groups were well above the RNI. In contrast, the intake data for folate revealed substantial insufficiency, with up to 74% of the population (11 – 18-year-old Female)

below the RNI, 10% of the population (11 – 18-year-old Female) below the LRNI, and mean intakes close to or below RNI values. Biomarker data also indicated folate deficiency in up to 17% of 11–18-year-old males. Therefore, although there are improvements in micronutrient status that could be made for all nutrients, micronutrients with more severe and widespread insufficiency, such as folate, could be prioritised over those with generally adequate intakes.

It was noted that intake thresholds and biomarker thresholds for the same nutrient did not always present congruent conclusions. These contradictions between conclusions based on the different data types add a layer of complexity to interpretations that subsequently make prioritisation more difficult. For example, the intake data for zinc suggest widespread inadequacy – most groups had a mean intake below the RNI, all groups included individuals with intakes below the LRNI and RNI, including up to 80% of 11 – 18-year-old females with intakes below the RNI. In contrast, biomarker data showed that no population groups had mean biomarker levels below the deficiency threshold, and the only groups with any individuals below the deficiency threshold were 11 – 64-year-old Male (0.26%), 19 – 64-year-old Female (0.83%), over – 65-year-old Male (2.35%) and over – 65-year-old Female (1.03%). Importantly, the groups identified as most deficient by biomarker analysis did not align with those with the poorest intake.

Moreover, biomarker data were only available for a subset of micronutrients present in parsnips (vitamin C, folate, thiamin, zinc, and riboflavin). Several nutrients with severe intake shortfalls—such as potassium and magnesium, for which 96.6% and 91.6% of 11–18-year-old females, respectively, failed to meet the RNI—lacked biomarker data. Without reliable biomarkers, it is uncertain whether low intakes for these nutrients translate into physiological deficiencies, underlining the need for improved biomarker measures.

Despite the complexities introduced by analysing both intakes and biomarkers concurrently, some consistent patterns emerged across the population groups most affected by insufficiency. Adolescents aged 11–18 were most likely to fall below the RNI for nearly all micronutrients assessed, except for copper, where insufficiency increased with age. Females also more often had higher proportions below the RNI than males of the same age, though this trend was sometimes reversed in biomarker data, where males showed higher deficiency rates.

The causes of these sex and age differences were not explored in this chapter. However, it was noted that female groups consistently had lower mean nutrient intakes than the corresponding male groups. Although RNIs for females are often lower, reflecting reduced biological requirements (Department of Health, 1991), these lower thresholds may not fully offset the smaller average nutrient intakes consumed by women. Evidence from the literature suggests that women are more likely than men to eat smaller meals within households and to reduce

food consumption during periods of food insecurity (Pautz and Dempsey, 2020; Public Health England, 2020; Grimaccia and Naccarato, 2022; Shinwell *et al.*, 2022). While portion sizes were not directly assessed in this analysis, reduced intake may help explain the higher prevalence of inadequacy among female groups. Future research should integrate data on overall food intake to distinguish the roles of diet quantity and quality in shaping sex differences in micronutrient status.

It is also important to note that this analysis excluded micronutrient intake from supplements. This decision was deliberate, reflecting the thesis focus on diet-based interventions, therefore prioritising an improved understanding of micronutrient provision from food sources. However, supplementation is relevant: women are more likely than men to use supplements (Conner *et al.*, 2003; Harrison *et al.*, 2004; Dickinson and MacKay, 2014; Smith-Ryan, Cabre and Moore, 2022), which may reduce or even reverse some of the observed micronutrient intake differences. This may also help explain why males were often more deficient in biomarkers despite higher food-based micronutrient intakes. Future studies should compare supplement users and non-users, controlling for factors such as body size, diet quality, and socioeconomic status, to clarify the role of supplementation.

Given these limitations, broad generalisations about the most pressing micronutrient concerns in the UK should be made with caution. Nonetheless, this analysis provides novel insights into a wider range of micronutrients than previous studies, providing a useful starting point for further analyses to be undertaken. Across all measures used in this analysis, folate status appeared especially poor in the UK population, with high proportions of individuals below intake thresholds, mean intakes that fall close to or below these thresholds, and significant proportions of the population with red blood cell folate levels indicating deficiency. Folate is present in parsnips at the second highest concentration of all micronutrients, with literature values suggesting 100 g of parsnip would provide 35% of the RNI for an adult. These findings support the need for interventions to improve folate status in the UK and suggest that parsnips could play a useful role within a broader suite of dietary strategies. Additionally, the importance of targeting interventions towards younger populations is clear for folate, for which 11 – 18-year-olds are by far the worst affected group.

2.5 Conclusions

Overall, this chapter demonstrates that micronutrient insufficiency is common in the UK, with adolescents—especially females aged 11–18 years—emerging as the most affected group. Although all nutrients showed some evidence of inadequacy, folate stood out as of pressing concern, with consistent deficiencies observed across both intake and biomarker data. The

findings highlight the need for targeted, diet-based interventions, and suggest that parsnips, as a natural source of folate and other key micronutrients, could play a useful role in strategies to improve population-level nutritional status.

The conclusions of this chapter informed the direction of the remainder of the thesis. The following chapters narrow in scope to focus on improving folate status specifically, exploring variation in the amount of folate provided by parsnips under a range of pre- and post-harvest conditions, and finally, considering how well existing food systems, particularly school meals, support the folate intakes of young people in the UK. While this thesis focuses on folate as a case study, the approaches developed may also be applied to other micronutrients of public health concern, contributing more broadly to improvements in UK food and nutrition security.

Chapter 3 Varietal Variation in the Folate (Vitamin B9) Content of Parsnip (*Pastinaca sativa* L.)

3.1 Introduction

Parsnip (*Pastinaca sativa* L.) is a monocarpic root vegetable crop, typically cultivated as a biennial in the UK on sandy, well-draining, low-nutrient soils (Greene, 2016). It has been used as both a foodstuff and animal feed in the UK since at least 43 AD (A&G Lamattina & Sons Ptd Ltd, 2017) (Chapter 1 Section 1.8.1). While the root is the main edible part, fresh buds, leaves, and seeds are also occasionally consumed (Jelena *et al.*, 2014; Khadivi, Mirheidari and Moradi, 2023) (Chapter 1 Section 1.8.2).

Parsnips are high in starch and fibre (Stannard, 1982; Bufler and Horneburg, 2013; Khadivi, Mirheidari and Moradi, 2023), and contain a variety of macronutrients and micronutrients, as outlined in Chapter 1 Section 1.8.2. They also contain a range of other bioactive compounds with therapeutic properties, including essential oils (antimicrobial), falcarinols (antimicrobial, anticoagulant, neurologically active), and furanocoumarins (neurologically active, psychiatric, antispasmodic, vasodilatory) (Kenari *et al.*, 2021). Despite this nutritional and pharmacological potential, little information is available on the determinants of macronutrient, micronutrient, and bioactive compound concentrations in parsnips. In particular, it is unclear how much these chemical constituents vary between individuals, across cultivars, or in response to different growing practices.

Among the micronutrients present in parsnip, folate (vitamin B9) is of particular interest for public health in the UK, where, for example, 74.4% of 11 – 18-year-old Females consume less folate than the RNI (Chapter 2). The term folate refers collectively to all natural and synthetic forms of vitamin B9. Folates are essential micronutrients with key roles in DNA synthesis and DNA methylation, as outlined in Chapter 1 Section 1.5.2. Parsnips are known to contain significant quantities of folate, with estimates ranging from 43.2 µg per 100 g (Federal Food Safety and Veterinary Office FSVO, 2021) to 87 µg per 100 g (National Institute for Health and Welfare, 2019; Public Health England, 2021; RIVM, 2021). However, there is no published information on the specific forms of folate—or folate vitamers—present in parsnips. In carrots, 5-methyltetrahydrofolate has been found to be the predominant folate vitamer, with tetrahydrofolate and 5-formyltetrahydrofolate present in smaller quantities (Vahteristo *et al.*, 1997). The composition of folate vitamers is important, as the bioaccessibility of different

vitamers varies (Scott, Rébeillé and Fletcher, 2000). Consequently, the composition of folates in parsnips may influence their efficacy as a dietary source of vitamin B9.

It also remains unclear to what extent the total amount of folate in parsnips varies. Folate levels in food crops can be influenced by multiple factors, including genetic background and agronomic influences. This has been well documented in wheat (Kariluoto, Edelmann and Piironen, 2010; Riaz *et al.*, 2019; Zheng *et al.*, 2022; Tian *et al.*, 2025), beans (Martin *et al.*, 2021), and maize (Islam *et al.*, 2021; Paul *et al.*, 2025). However, the relative importance of these influences remains unresolved, with conflicting findings even within the same species (Zheng *et al.*, 2022). Moreover, most evidence derives from wheat studies, a species distantly related to parsnip, while few investigations have considered any members of the *Apiaceae* family, to which parsnip belongs (Vahteristo *et al.*, 1997). In carrots, variation has been observed in the vitamer composition and total folate content of samples taken at different times of year (Vahteristo *et al.*, 1997). However, the significance of such variation has not yet been explored (Vahteristo *et al.*, 1997).

Addressing this knowledge gap requires a clearer understanding of how genotype and growing environment interact to with respect to folate levels in parsnip. In particular, clarifying the extent to which genotype contributes to folate content would help guide future breeding strategies. If folate levels are strongly genotype-dependent, conventional breeding could represent a viable approach for enhancing the nutritional quality of parsnip.

Extensive breeding programmes for parsnip already exist in the UK, with the primary goal of developing commercial varieties that outperform competitors across a range of grower- and consumer-valued traits (personal communication, Tozer Seeds Ltd). These traits include sensory characteristics such as skin colour, firmness, and susceptibility to discolouration; agronomic traits such as disease resistance and crop uniformity; and other quality attributes such as crown depth and hairiness (personal communication, Tozer Seeds Ltd). Nutritional quality, however, remains a low priority in parsnip breeding programmes. As with other crops, this is largely because nutritional phenotyping, including the quantification of folate content, is expensive and time-consuming, requiring laboratory-based assays (Brubacher, Müller-Mulot and Southgate, 1985; Li *et al.*, 2025), whereas traits like yield or morphological uniformity can be assessed relatively rapidly and at scale. Furthermore, breeders are usually rewarded for traits with clear commercial value—yield, disease resistance, and appearance—rather than for micronutrient density (Mukherjee *et al.*, 2020; Bhardwaj *et al.*, 2024).

Nevertheless, if nutritional traits such as folate concentration can be reliably associated with easily measurable post-harvest characteristics, indirect selection becomes feasible. Attempts to link folate content to phenotypic characteristics have only been conducted in wheat, where

folate content has been correlated with thousand kernel weight (Zheng et al., 2022), grain width (Zheng et al., 2022), heading date (Zheng et al., 2022), and grain colour (Tian *et al.*, 2025). No such analysis has been conducted in parsnip, or indeed in any other vegetable. Establishing correlations between folate content and valued traits such as whiteness, firmness, or disease resistance could therefore provide a valuable opportunity to integrate nutritional quality into parsnip breeding programmes.

3.1.1 Chapter aims and objectives

The hypothesis of Chapter 3 is that there is variation in the folate content of parsnips that can be attributed to genotypic or environmental variables. Given the lack of information on folate content in parsnip and its potential importance for both nutrition and breeding, this chapter aims to characterise folate composition and investigate how it varies across genotypes and environments, as well as to assess whether folate content can be linked to commercially relevant root traits. This was addressed through the following objectives:

1) Determine the identities and quantities of folate vitamers in parsnips.
2) Investigate how the amounts of different folate vitamers vary across different cultivars of parsnip, and different growing conditions.
3) Explore whether correlations exist between yield characteristics or post-harvest phenotypes and folate content in parsnips.

3.2 Materials and Methods

3.2.1 Plant materials

Two locations in Surrey, UK (Site M, coordinates 51.313338, -0.481742 and Site P, coordinates 51.326445, -0.413177), were selected for field experiments. The trial sites were embedded within existing field trial locations used by Tozer Seeds Ltd, with the parsnips situated amongst a range of other crops. Both sites consisted of a free draining sandy loam soil type, but had differences in soil nutrition, trial site features, and agronomic management practices. At Site M, the trial site was in a sheltered position, protected from strong winds and shaded through significant portions of the day. Site P was much more exposed, placed within a larger field setting with little shade or wind protection. In addition, soil characteristics differed between the two sites (Table 3-1), as well as surrounding and previous crop types.

A total of ten parsnip varieties, comprising commercial, pre-commercial, and breeding lines, were planted in April 2024 in plots in a triplicated randomised complete block design. Each plot consisted of four rows of parsnips, planted with a 6.6 cm spacing over 3 m (site M) or 1 m (site

P). Harvesting was carried out in two independent sampling events, with two rows harvested at each event: a “main crop” in November 2024 and a “late crop” in March 2025. Overall, this resulted in four different ‘growing environments’, as referred to in later analysis: M main crop, M late crop, P main crop, and P late crop. Although employees of Tozer Seeds Ltd took primary responsibility for the planting and monitoring of parsnip crops during growth, the assessment, harvest, and preparation of parsnip crops for use in this thesis was a collaborative effort.

Table 3-1 Characteristics of the parsnip trial sites M and P

Trial site	**M**	**P**
Location	51.313338 N, -0.481742 W	51.326445 N, -0.413177 W
Soil type	Sandy loam	Sandy loam
Soil pH	7.2	6.8
Soil mineral levels (mg/L)		
Phosphorus	61.0	114.2
Potassium	170	125
Magnesium	54	66
Boron	0.5	1.1
Calcium	1066.9	1516.0

Soil analysis was conducted in January 2022, prior to commencement of the parsnip trials. Analysis conducted by NRM (Bracknell, UK).

At each harvest, roots were manually lifted, and the total number of roots per plot counted and weighed (Figure 3-1a). From each plot, ten parsnips of intermediate size and commercially acceptable standard were selected (Figure 3-1b). These samples were roughly washed in the field before being trimmed to remove foliage and thoroughly washed to remove any residual soil. Of the ten parsnips collected from each plot, five were randomly allocated to phenotypic trait assessment and five to folate analysis. Roots were bagged, labelled, and stored overnight at 1-4°C pending analysis.

Figure 3-1 Post-harvest parsnips. a) a plot of parsnips immediately after harvest. Image taken on 20/11/2024. b) Ten parsnips of a commercially acceptable standard and intermediate size selected from the main plot. Image taken on 21/11/2024.

3.2.2 Phenotypic trait collection

Phenotypic traits for inclusion in the study were chosen in collaboration with the parsnip breeding team at Tozer Seeds Ltd. All measurements were made on five roots per plot for each growing environment and replicate. Measured values were averaged to provide a single trait value per plot for each growing environment and replicate.

3.2.2.1 Root quality phenotypes

3.2.2.1.1 Shape

The shape of parsnips was assessed by consultation with expert parsnip breeders at Tozer Seeds Ltd immediately after harvest. The shapes of individual parsnips were ranked on a scale based on the distribution of the weight of the parsnip along the root, ranging from 1, long and slender with a pencil-like shape, to 5, top heavy, obovate shape (Figure 3-2).

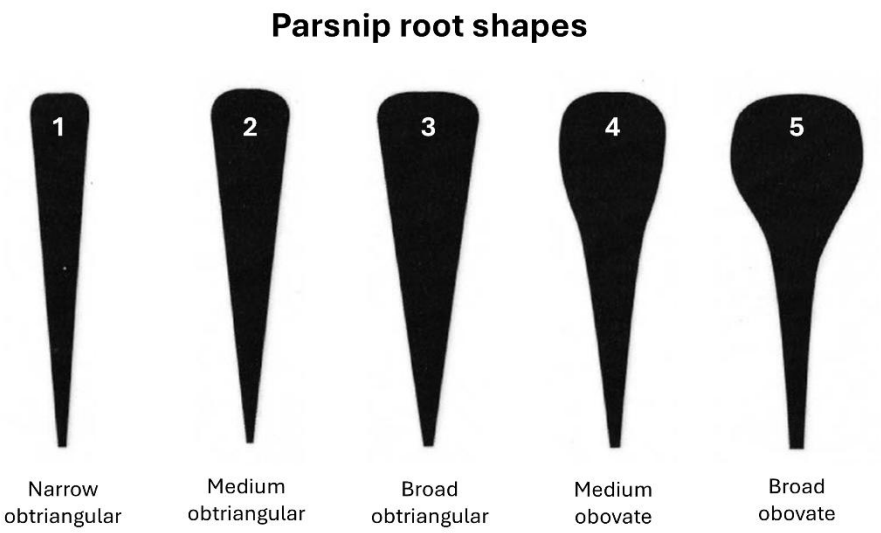


Figure 3-2 Parsnip root shape assessment guide. Adapted from Tozer Seeds Ltd internal assessment material.

3.2.2.1.2 Carrot root fly resistance

The extent of carrot root fly resistance was assessed immediately after harvest by consultation with expert parsnip breeders at Tozer Seeds Ltd. Parsnips were ranked on a scale from 1 to 5, where 1 indicated a root that was completely infested with carrot root fly, and 5 indicated a root with no observable carrot root fly damage. An example of a lesion caused by carrot root fly on a parsnip root ranked as '2' is depicted in Figure 3-3a.

3.2.2.1.3 Canker resistance

The extent of canker resistance was assessed immediately after harvest by consultation with expert parsnip breeders at Tozer Seeds Ltd. Parsnips were ranked on a scale from 1 to 5, where 1 indicated a root that was completely infested with canker, and 5 indicated a root with no observable canker damage. An example of a canker lesion on a parsnip root ranked as '1' is depicted in Figure 3-3b.

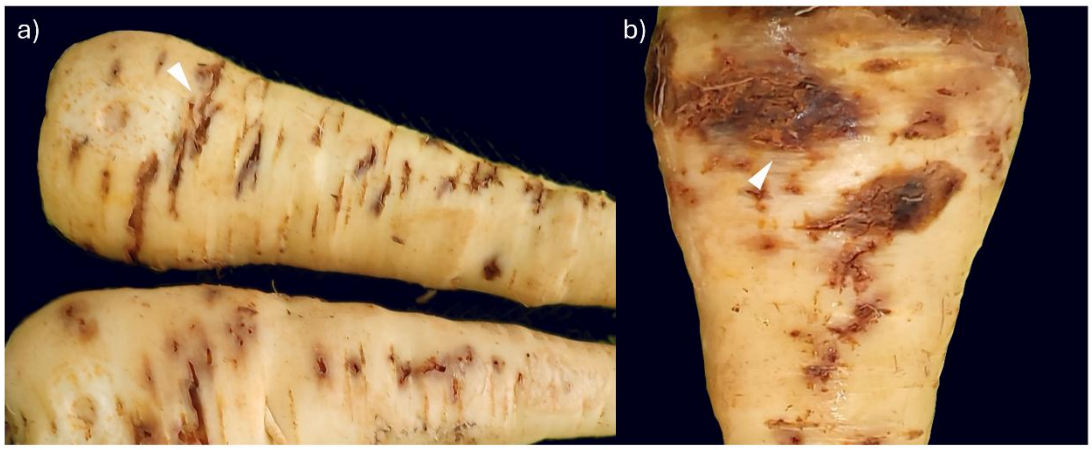


Figure 3-3 Examples of disease lesions on parsnip roots associated with a) carrot root fly and b) canker. White arrows indicate examples of damaged tissue. Images taken on 07/03/2024.

3.2.2.1.4 Firmness

The firmness of parsnip roots was assessed in the laboratory within 24 hours of harvest. At the widest point of each root, two small opposing patches of skin were removed with a peeler. A TAPlus Texture Analyser (Lloyd Instruments Ltd, West Sussex, UK) fitted with an 11 mm cylindrical probe was used to measure the firmness in N of the root at a depth of 8 mm on each peeled location (AMETEK Inc, 2007). These measurements were averaged to give one firmness reading for each individual root.

3.2.2.1.5 Core area

Core area was assessed after all other phenotyping except flesh whiteness and browning, approximately one week post-harvest, as destructive sampling was required. Two transverse cuts were made, each approximately 0.5 cm away from the widest point of each root, producing a 1 cm deep disc of parsnip tissue (Figure 3-4). This tissue was photographed with a marked scale bar using a Nikon D3500 camera (Nikon UK Limited, Surrey, UK). Core and total diameters were measured at approximately the widest and narrowest points in ImageJ (version 1.53k) (Figure 3-4). The mean diameters were used to calculate the percentage core area using the following equation:

$$Percentage\ core\ area = \frac{\pi\left(\frac{d_{core}}{2}\right)^2}{\pi\left(\frac{d_{total}}{2}\right)^2} * 100$$

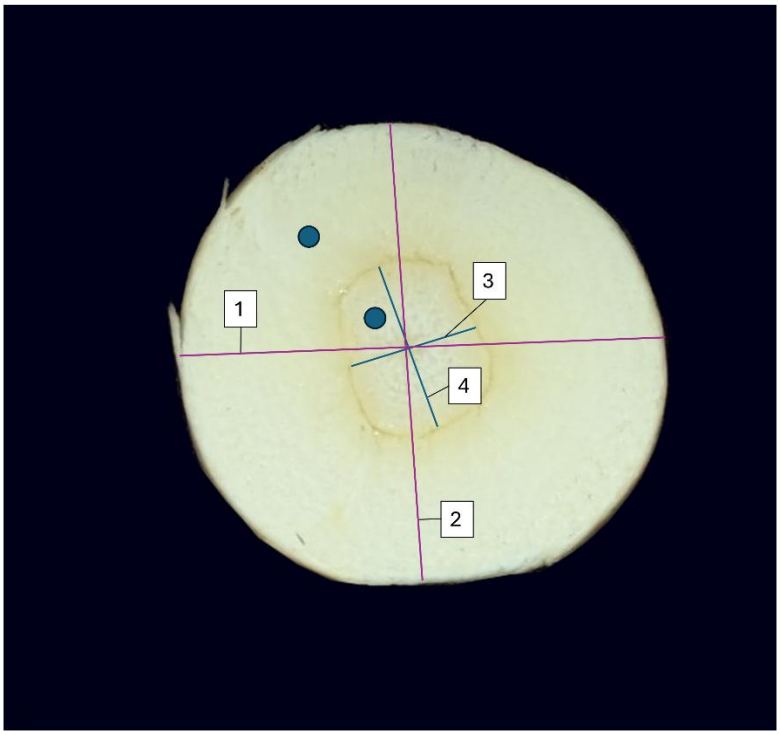


Figure 3-4 A cross section of a parsnip indicating the location of measurements for core area and flesh whiteness assessment. Core area measurements were taken along lines 1 and 2, and 3 and 4, respectively, representing the narrowest and widest points, respectively. Flesh whiteness measurements were taken at the points indicated with blue circles. Image taken on 10/03/2025.

3.2.2.2 Colour phenotypes

3.2.2.2.1 Harvest whiteness

The harvest colour of parsnip roots was assessed in the laboratory within 24 hours of harvest. A Konica Minolta Chroma Meters CR-400 instrument (Konica Minolta, Essex, UK) was used to take two L*a*b* measurements on opposite sides of each parsnip root, near the widest point of the root. The mean L* reading was used as an indicator of harvest whiteness (Hirschler, 2016).

3.2.2.2.2 Stored whiteness

Parsnips were stored in sealed polythene bags at 1-4 °C for one-week. After storage, a Konica Minolta Chroma Meters CR-400 instrument was used to take two L*a*b* measurements on opposite sides of each parsnip root, near the widest point of the root. These measurements

were then averaged, and the L* reading used as an indicator of stored whiteness (Hirschler, 2016).

3.2.2.2.3 Storage discolouration

The discoloration of parsnips roots over storage, ΔE_s, was calculated as the difference between the stored and harvest L*a*b* readings (MacDougall, 2002; Octavia and Choo, 2017):

$$\Delta E_s = \sqrt{(L_s^* - L_h^*)^2 + (a_s^* - a_h^*)^2 + (b_s^* - b_h^*)^2}$$

Where *h* denotes measurements taken at harvest, and *s* indicates measurements taken after storage.

3.2.2.2.4 Flesh whiteness

The flesh whiteness was measured at the same time as core area measurements. L*a*b* measurements were taken at two points on the cross section, once in the core region and once in the surrounding flesh, using a Konica Minolta Chroma Meters CR-400 (Figure 3-4). These measurements were then averaged, and the L* reading used as an indicator of flesh whiteness (Hirschler, 2016).

3.2.2.2.5 Browning

The parsnip discs used for the core area and flesh whiteness measurements were stored in sealed polythene bags at 1-4 °C for a further 24 hours. Subsequently, L*a*b* measurements were taken at two points on the cross section, once in the core region and once in the surrounding flesh, using a Konica Minolta Chroma Meters CR-400 (Figure 3-5). The mean of these measurements was calculated. The degree of browning, ΔE_b, was calculated as the difference between the flesh colour reading and the browned colour reading (MacDougall, 2002; Octavia and Choo, 2017).

$$\Delta E_b = \sqrt{\left(L_b^* - L_f^*\right)^2 + \left(a_b^* - a_f^*\right)^2 + \left(b_b^* - b_f^*\right)^2}$$

Where *b* denotes measurements taken 24 hours after cutting the parsnip discs, and *f* indicates measurements taken immediately after cutting the discs.

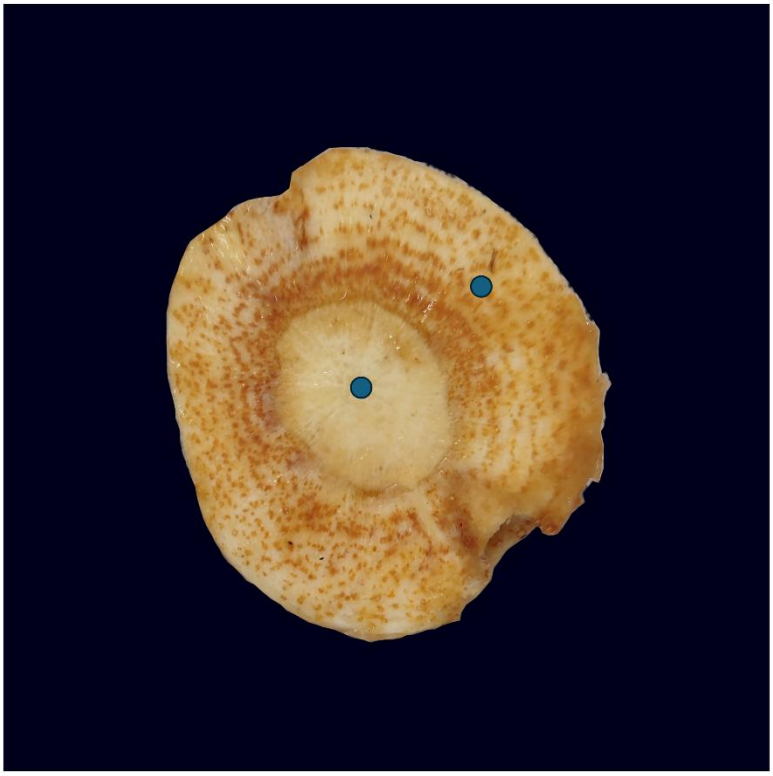


Figure 3-5 A cross section of a parsnip after 24 hours refrigerated storage. Blue circles indicate the location of measurements for browning. Image taken on 05/03/2025.

3.2.3 Folate analysis by high-performance liquid chromatography (HPLC)

3.2.3.1 Sample preparation

The five parsnips selected for folate analysis were trimmed to remove their tops and roughly homogenised using a kitchen blender. The homogenised tissue of all five individuals was then mixed thoroughly, and approximately 50 grams of the mixture was sampled and flash frozen in liquid nitrogen. The exact mass of each sample was recorded. After freezing, the composite sample was lyophilised using a Christ Alpha 1-4 LCSplus Freeze Drier (SciQuip Ltd, Rotherham, UK) for 24 hours or until a pressure increase test showed a less than 5% increase. The final dried mass was recorded. Dried samples were milled to a fine powder using a Ninja NJ1002UKBK Professional Chopper (SharkNinja Europe Ltd, Leeds, UK) and sifted through an 850 µm mesh sieve. Samples were bagged, compressed to remove excess air, and stored in the dark at -80°C until analysis.

3.2.3.2 Chemicals and reagents

A pre-prepared stock solution of folate standards containing known concentrations of 5-methyltetrahydrofolate (5-CH_3-THF), 5-formyltetrahydrofolate (5-CHO-THF), tetrahydrofolate (THF), 10-formylfolic acid (10-CHO-PGA), folic acid (PGA) and 5,10-methenyltetrahydrofolate (5,10-CH+-THF) was obtained from the Department of Agriculture and Forestry at the University of Helsinki. This calibrant mixture was stored in 50 mM sodium borate solution with 0.4% β-mercaptoethanol and 1% ascorbic acid at -80°C until analysis, not exceeding six months of storage.

All chemicals used for analysis were of analytical or HPLC grade, with the exception of activated charcoal (Amazon, London, UK), which was of unspecified purity. Acetic acid (CAS: 64-19-7), acetonitrile (CAS: 75-05-8), ascorbic acid (CAS: 50-81-7), formic acid (CAS: 64-18-6), and potassium phosphate monobasic (CAS: 7778-77-0) were sourced from Sigma Aldrich (Gillingham, UK). β-mercaptoethanol (CAS: 60-24-2), HEPES (CAS: 7365-45-9), hexane (CAS: 110-54-3), methanol (CAS: 67-56-1), potassium phosphate dibasic (CAS: 16788-57-1), sodium acetate (CAS: 127-09-3), sodium ascorbate (CAS: 134-03-2), and sodium chloride (CAS: 7647-14-5) were sourced from Fisher Scientific (Loughborough, UK). The enzymes α-amylase from *Aspergillus oryzae* (EC: 232-588-1, product number: A9857) and protease from *Streptomyces griseus* (EC: 232-909-5, product number: P5147) were sourced from Sigma Aldrich. Rat serum (product number: 10710C) was sourced from Fisher Scientific. All water used in extraction and analysis was of Milli-Q grade.

Enzyme solutions of 20 mg/ml α-amylase in 1% sodium ascorbate and 4 mg/ml protease in 1% sodium ascorbate were prepared in advance of analysis and stored in 10 ml aliquots at -20°C for up to three months. Aliquots were defrosted on the day of use. γ-glutamyl hydrolase (GGH) enzyme solution was prepared from the rat serum by adding 10% w/w activated charcoal to the rat serum and incubating under stirring at 4°C for 1 hour. The solution was centrifuged (4700 rpm, 4643 x g, 4°C) for 30 minutes, the supernatant collected and filtered through a 0.2 µm membrane. The GGH solution was divided into 10 ml or smaller aliquots and stored at -20°C for up to three months. Aliquots were defrosted on the day of analysis.

3.2.4 Folate extraction and purification

A modified version of the tri-enzyme treatment described by Edelmann (2012) was used for extraction of folate from the frozen, freeze-dried parsnip preparation (Figure 3-6). An exact mass of sample between 0.20-0.25 g (accurate to 0.001 g) was suspended in 10 ml HEPES buffer (pH 7) with sodium ascorbate (2% w/v) and β-mercaptoethanol (10 mM). The sample was bubbled with nitrogen gas and then placed in a boiling water bath for 10 minutes. After cooling on ice for

5 minutes, 1 ml of α-amylase solution and 0.5 ml of GGH solution were added to the sample. The mixture was bubbled with nitrogen gas, then incubated in a shaking water bath at 37°C for 3 hours. After incubation, 1 ml of protease solution was added. The mixture was bubbled with nitrogen gas again, then incubated in the shaking water bath at 37°C for a further 1 hour. After the second incubation was completed, the sample was placed in a boiling water bath for 5 minutes to inactivate all enzymes, cooled on ice for 5 minutes, then stored in a -20°C freezer overnight.

Samples were thawed to room temperature the following day. The liquid extract was collected by centrifuging samples (4700 rpm, 4643 x g, 4°C) for 30 minutes, then collecting the supernatant. The pellet was resuspended in 5 ml HEPES buffer (pH 7) with sodium ascorbate (2% w/v) and β-mercaptoethanol (10 mM), centrifuged (4700 rpm, 4643 x g, 4°C) for 30 minutes, and the supernatant collected. The supernatants were combined and made up to exactly 20 ml in volumetric flasks. A minimum of 5 ml of each sample was filtered through a 0.2 µm syringe filter membrane. Exactly 5 ml of filtered solution was then diluted twice in MilliQ water and β-mercaptoethanol added to a concentration of approximately 0.1% v/v.

Purification of the extracts was carried out prior to HPLC analysis by solid-phase extraction (SPE) on strong anion exchange (SAX) cartridges (500 mg, 3 ml, Thermo Scientific™ HyperSep™). A Visiprep SPE Vacuum Manifold (Fisher Scientific, Loughborough, UK) was used for elution under reduced pressure, with a flow rate <1 drop per second. Each cartridge was conditioned with one cartridge volume each of hexane, methanol, and water. The cartridges were then equilibrated with three cartridge volumes of 10 mM phosphate buffer (pH 7) containing 0.2% v/v β-mercaptoethanol. The samples were applied, and the cartridge washed with two cartridge volumes of 10 mM phosphate buffer (pH 7) containing 0.2% v/v β-mercaptoethanol. Retained folate was eluted from the cartridge by the application of 4.5 ml of 100 mM acetate buffer with 10% w/v sodium chloride and 1% w/v ascorbic acid. The eluted sample was collected and made up to 5 ml in a volumetric flask using 100 mM acetate buffer with 10% w/v sodium chloride and 1% w/v ascorbic acid.

A 1 ml aliquot of each sample was transferred to an amber autosampler vial. Nitrogen gas was bubbled through each sample, and samples were stored at -80°C prior to analysis. All analysis was conducted within 2 months of extraction, with samples thawed to 2°C immediately before quantification.

All extractions were carried out in duplicate, with the order of extractions and subsequent folate quantification by HPLC randomised over the analysis period to control for any methodological variation. A third extraction undertaken if the coefficient of variation between the first two extractions exceeded 10%. Blank controls were included in each set of extractions to confirm

that no folate was introduced from the reagents or enzyme solutions. Samples were protected from light wherever possible, and kept out of direct sunlight at all times.

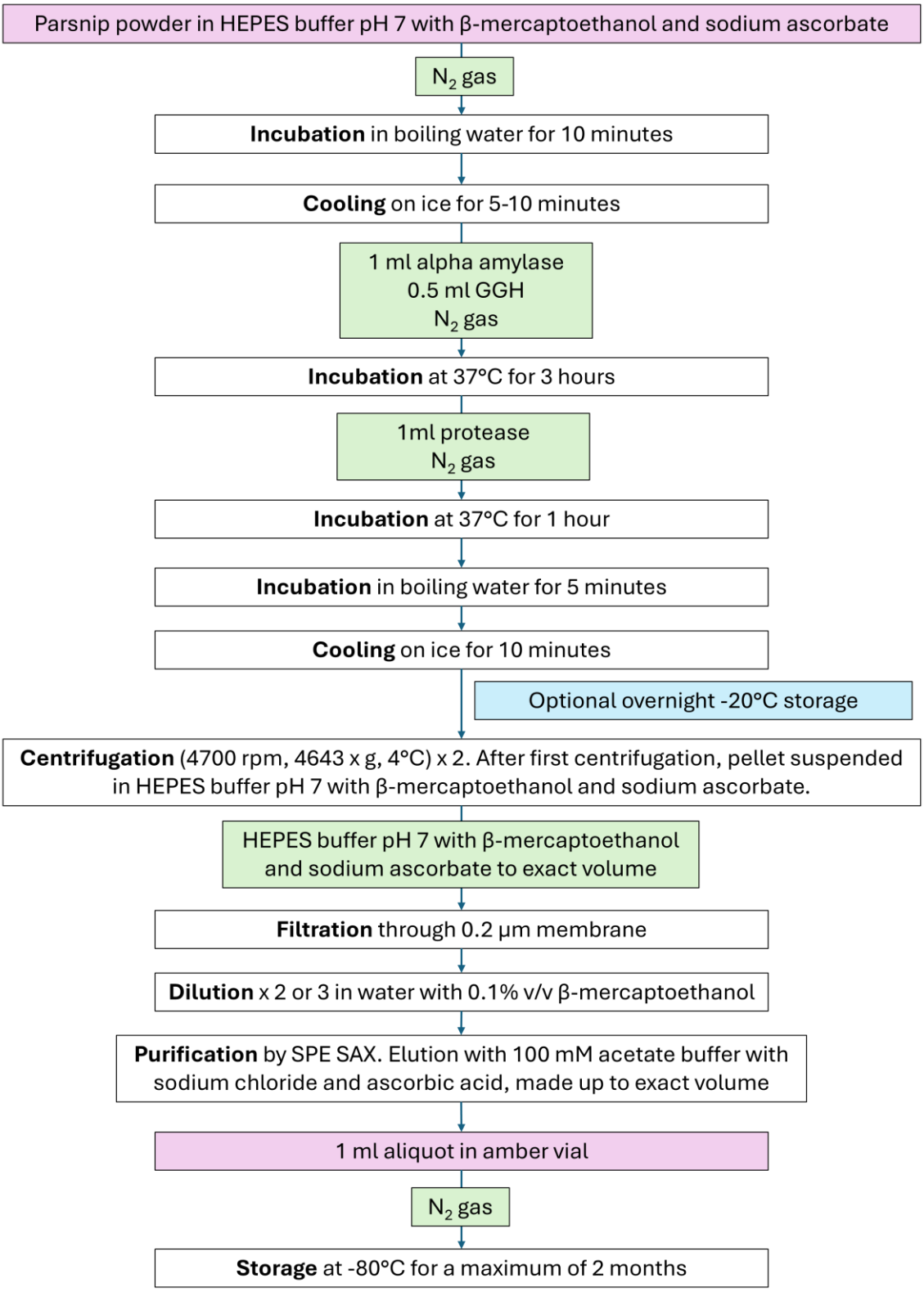


Figure 3-6 Method flow chart for folate extraction from parsnip powder. Purple rectangles – extraction products. Green rectangles – added reagents. Blue rectangles – optional steps. White rectangles – processes.

3.2.5 High-performance liquid chromatography

A reversed-phase high-performance liquid chromatography (HPLC) method was adapted from Edlemann (2012) and used for folate quantification. All analysis was performed using an Agilent 1260 HPLC system (Agilent Technologies LDS UK Limited, Stockport, UK), equipped with a gradient quaternary pump (model G7104C), a thermostatted autosampler (model G7167A), a thermostatted column compartment (model G7155A), a diode array detector (PDA) (model G7115A), and a fluorescence detector (model G7121A). An Acquity HSS T3 column (1.8 µM, 2.1 x 150 mm; Waters, Milford, MA) fitted with an Acquity HSS T3 Vanguard pre-column (1.8 µM, Waters, Milford, MA) was used for compound separation.

A flow rate of 0.2 ml/minute was used for analysis. The temperature of the autosampler and the column compartment were maintained at 4°C and 30°C, respectively. PGA and 10-CHO-PGA detection using the PDA was carried out at 290 nm, 5,10-CH+-THF was detected using the PDA at 360 nm, 5-CH_3-THF and THF were detected by fluorescence detection (excitation 290 nm, emission 360 nm), and 5-CHO-THF was detected by fluorescence detection (excitation 350 nm, emission 450 nm). An injection volume of 20 µL was used for all samples. The mobile phases were 0.7% formic acid in MilliQ water (A) and 0.7% formic acid in acetonitrile (B), and samples were separated using a gradient elution. The proportion mobile phase B was initially held at 5% for 1.5 minutes, then increased linearly to 9.4% from 1.5 minutes to 11.4 minutes. Subsequently, the proportion of mobile phase B was increased slowly from 9.4% to 10.4% from 11.4 minutes to 15 minutes. The concentration of B was increased to 80% from 15 minutes to 15.9 minutes, then maintained at 80% until 17.4 minutes. The proportion of mobile phase B was decreased from 80% back to 5% from 17.4 minutes to 17.7 minutes, then held at 5% for a 1 minute, before being allowed to re-equilibrate to initial conditions for a further 15 minutes. Overall, this resulted in a run time of 35.7 minutes per injection. Each sample was injected twice and quantified separately using the Agilent OpenLab CDS analysis software (version 2.8). Peak areas were averaged across injections to give a final peak area for each extract.

Identification and quantification of folates was based on an external standard method. The stock standard solution was serially diluted and used to create a nine-point calibration curve. Folate vitamers in the sample extracts were identified by matching the peak retention times to the calibration curves, and quantified by comparison of peak areas to the calibration curves. A 5- CH_3-THF standard was run alongside every batch of samples to assess for peak drift and ensure correct peak identification in samples. Additionally, an aliquot of stock standard solution was run through the HPLC after approximately every 20 injections. The coefficient of variation between all repeated stock standard injections was less than 10%.

3.2.6 Statistical analyses

Folate vitamer contents were calculated on a fresh-weight basis (µg/100 g) by adjusting dried-sample concentrations using the percentage dry matter determined before and after lyophilisation. Total folate was expressed as the sum of identified vitamers. Individual vitamer and total folate contents are presented as the mean ± standard deviation.

Data visualisation and statistical analysis were conducted in R (R Core Team, 2024) via RStudio version 2025.05.1+513 (Posit team, 2025). The relative contributions of genotype and growing environment on folate content were analysed using a two-way ANOVA, with genotype and growing environment as fixed effects and the randomised complete block design included as a covariate. A Tukey HSD test was used for post hoc pairwise comparisons between groups, given a statistically significant ANOVA result. Pearson's correlation analysis was used to assess the relationship between folate content, yield characteristics and post-harvest phenotypes. For the correlations between post-harvest phenotypes and folate content, Holm-adjusted p-values were calculated to account for multiple testing. All correlations were considered strong where $R > 0.7$, weak where $R < 0.3$, and moderate when R fell between these thresholds (Hinkle, Wiersma and Jurs, 2003; Akoglu, 2018; Rusakov, 2023)

The following R packages were used for analysis: *dplyr* (version 1.1.4) (Wickham *et al.*, 2023) for data wrangling; *ggplot2* (version 3.5.1) (Wickham, 2016), *multcompView* (version 0.1.10) (Graves, Piepho and Dorai-Raj, 2024) and *patchwork* (version 1.3.0) (Pedersen, 2024) for data visualisation*;* and *rstatix* (version 0.7.2) (Kassambara, 2023b) for statistical testing.

3.3 Results

3.3.1 Folate vitamer composition in parsnips

Six folate vitamers were included in this analysis, but only 5-CH_3-THF and THF were present in detectable quantities in the parsnip samples. The mean amount of 5-CH_3-THF was 61.0 ± 6.61 µg/100 g, ranging from 48.9 µg/100 g to 77.7 µg/100 g. The mean amount of THF was 16.4 ± 2.75 µg/100 g, ranging from 10.0 µg/100 g to 28.8 µg/100 g. Resultingly, the mean total folate content of parsnips was 77.4 ± 7.14 µg/100 g, ranging from 61.0 µg/100 g to 94.3 µg/100 g.

3.3.2 Overall variation in the folate levels in parsnips

Variation in total folate was primarily associated with variety. A two-way ANOVA showed a statistically significant effect of variety on total folate content ($F(9, 76) = 3.707$, $p < 0.001$) (Figure 3-7). Variety 710 had the greatest mean folate content (83.1 ± 6.18 µg/100 g), whilst variety 318

had the lowest (72.0 ± 6.42 µg/100 g) (Figure 3-7). Post hoc testing confirmed statistically significant pairwise differences between varieties 110 and 318 ($p = 0.044$), 318 and Parent 3 ($p = 0.030$), 710 and 712 ($p = 0.010$) and 318 and 710 ($p = 0.009$) (Figure 3-7). No statistically significant effects of environment ($F(2, 76) = 1.139$, $p = 0.325$), or the interaction between environment and variety ($F(27, 76) = 1.478$, $p = 0.095$) on total folate content were observed.

Differences amongst varieties were also evident in 5-CH_3-THF content. A two-way ANOVA revealed a statistically significant effect of variety ($F(9, 76) = 3.669$, $p < 0.001$) (Figure 3-8). Parent 3 had the highest mean 5-CH_3-THF content (66.5 ± 7.34 µg/100 g), whilst variety 712 had the lowest (57.8 ± 6.40 µg/100 g) (Figure 3-8). Post hoc testing revealed statistically significant differences between varieties 318 and 710 ($p = 0.040$), 318 and Parent 3 ($p = 0.020$), 710 and 712 ($p = 0.024$) and 712 and Parent 3 ($p = 0.011$) (Figure 3-8). There was no statistically significant effect of environment ($F(2, 76) = 1.103$, $p = 0.337$), or the interaction between environment and variety ($F(27, 76) = 0.147$, $p = 0.147$) on 5-CH_3-THF content.

By contrast, independent effects of both genotype and environment were observed for THF content. The relationship between variety and THF content was statistically significant ($F(9, 76) = 10.533$, $p < 0.001$), with variety 14 having the highest THF content (19.1 ± 3.63 µg/100 g), and variety 318 the lowest (13.8 ± 2.13 µg/100 g) (Figure 3-9). Multiple pairwise differences were detected by Tukey HSD post hoc testing, indicated by letter differences in Figure 3-9. There was also a statistically significant effect of environment on THF content ($F(2, 76) = 21.763$, $p <0.001$), with parsnips from P late crop having the highest THF content (17.5 ± 3.33 µg/100 g), and parsnips from P main crop the least (14.6 ± 2.43 µg/100 g) (Figure 3-10). Post hoc testing found statistically significant differences between all environments apart from M late crop and P late crop ($p > 0.05$) (Figure 3-10). There was no statistically significant interacting effect of environment and variety on THF content ($F(27, 76) = 1.223$, $p = 0.245$).

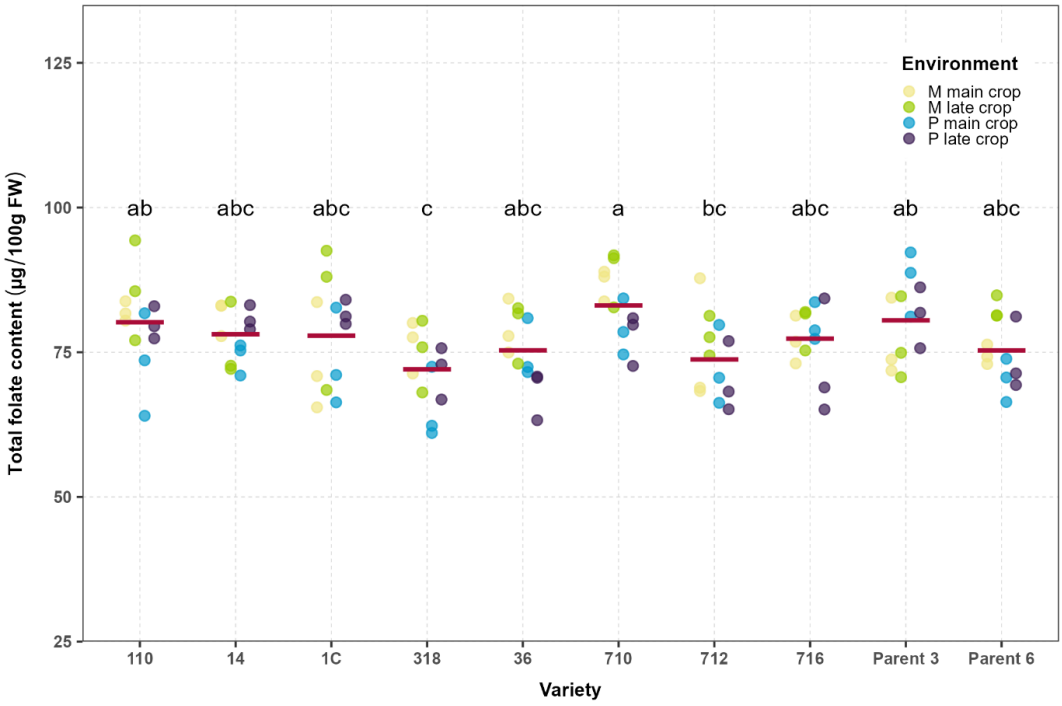


Figure 3-7 . Individual data points are shown by dots, with colours used to denote growing environment. The mean folate content of each variety is indicated by a maroon line. Significant pairwise differences ($p < 0.05$) between varieties are shown using letter notation.

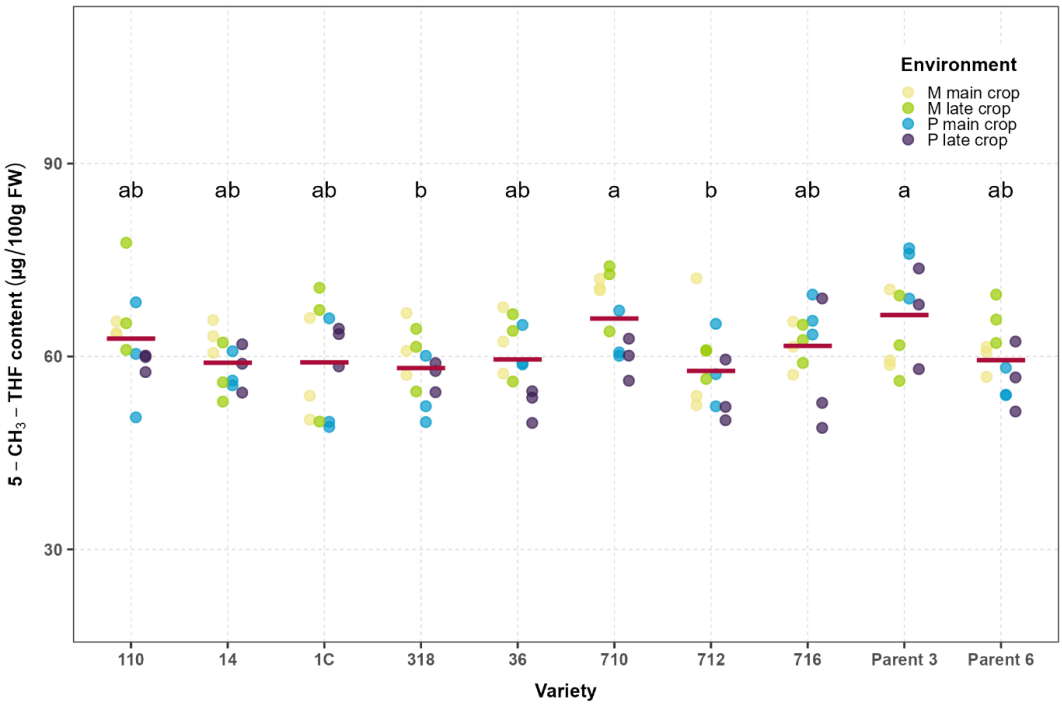


Figure 3-8 Dot-plot of the 5-CH_3-THF content of different parsnip varieties sampled from four growing environments. Individual data points are shown by dots, with colours used to denote growing environment. The mean folate content of each variety is indicated by a maroon line. Significant differences ($p < 0.05$) between varieties are shown using letter notation.

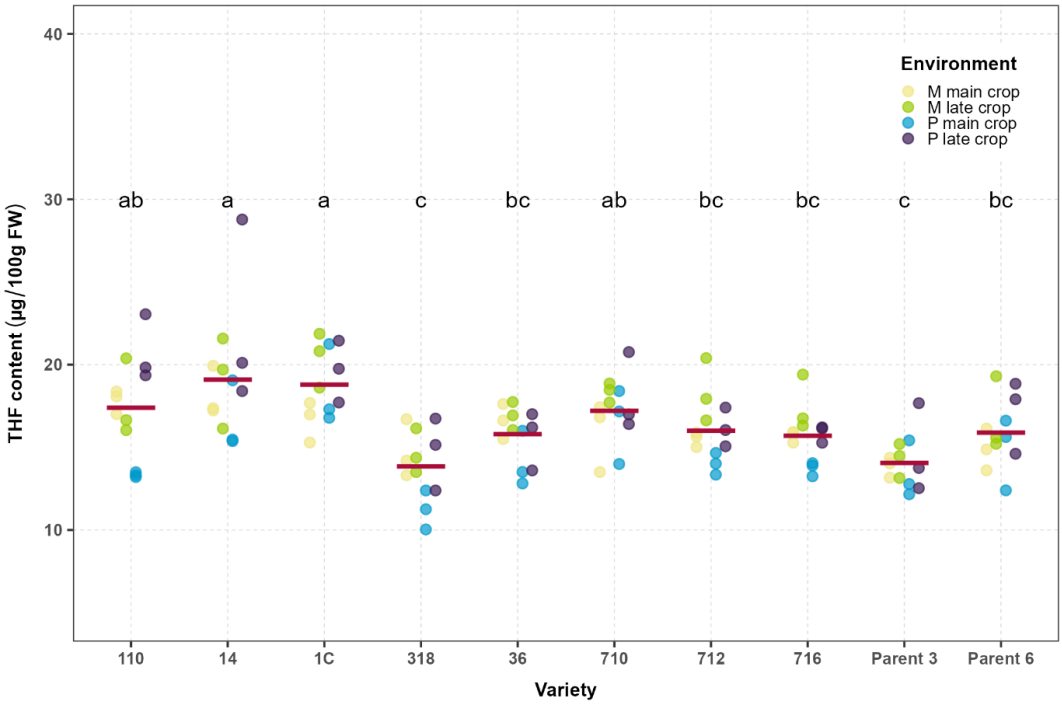


Figure 3-9 Dot plot of the THF content of different varieties of parsnips and different growing environments. Individual data points are shown by dots, with colours used to denote growing environment. The mean folate content of each variety is indicated by a maroon line. Significant differences ($p < 0.05$) between varieties are shown using letter notation.

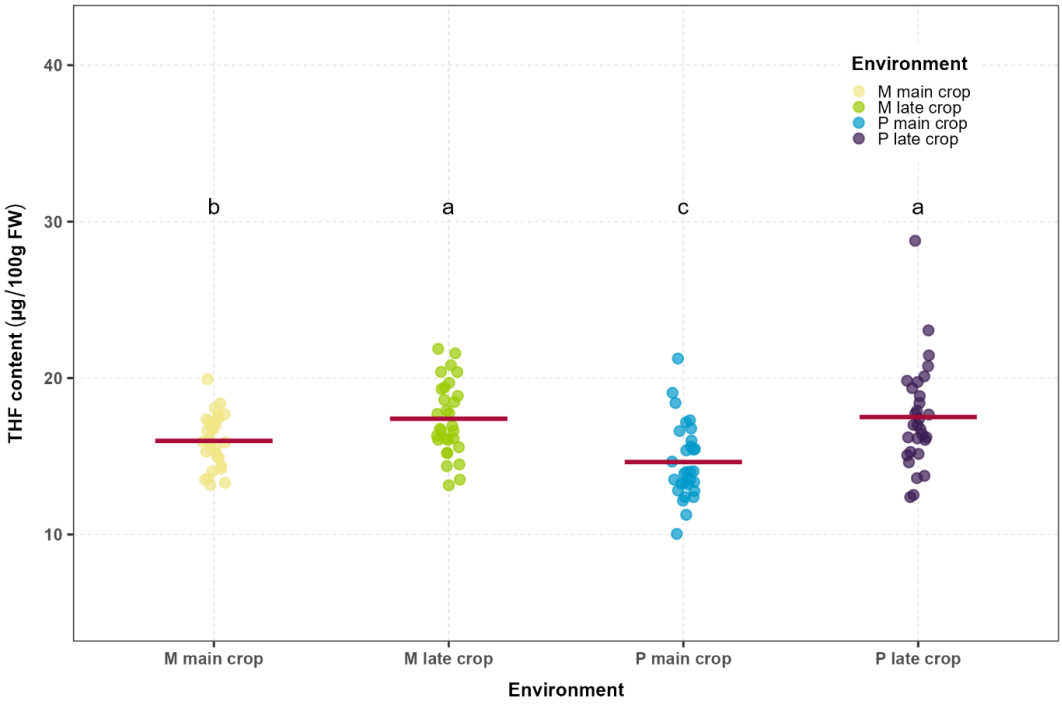


Figure 3-10 Dot plot of the THF content of parsnips from different growing environments. Individual data points are shown by dots. The mean folate content of each growing

environment is indicated by a maroon line. Significant differences ($p < 0.05$) between growing environments are shown using letter notation.

3.3.3 Correlations between folate content and parsnip quality characteristics

3.3.4 Yield

The number of parsnips harvested per plot ranged from 11 to 177, with a mean value of 74.0 ± 38.9 parsnips. The mass of parsnips harvested per plot ranged from 3550 g to 18340 g, with a mean of 9620.0 ± 4500.9 g. Resulting, the average mass per parsnip ranged from 61 to 471 g/parsnip, with a mean of 139.2 ± 44.0 g/parsnip. There was no statistically significant correlation between these yield characteristics and the THF, 5-CH_3-THF,or total folate content of the parsnips (Table 3-2).

Table 3-2 Pearson's correlation of folate contents and yield characteristics

Type	N	Y	Avg
THF	0.07	0.11	-0.02
5-CH_3-THF	0.15	0.22	0.01
Total	0.17	0.25	-0.00

N, Number of parsnips per plot; Y, Mass of parsnips per plot; Avg, Average mass per parsnip

3.3.5 Post-harvest phenotypes

Weak negative correlations were found between browning and both total folate and 5-CH_3-THF content ($R = -0.26$, $p = 0.046$ and $R = -0.27$, $p = 0.041$, respectively) (Table 3-3, Figure 3-11). THF content showed a weak positive correlation with shape ($R = 0.27$, $p = 0.03$), and canker resistance ($R = 0.28$, $p = 0.03$), and weak negative correlations with harvest whiteness ($R = -0.29$, $p = 0.02$) and stored whiteness ($R = -0.36$, $p < 0.001$) (Table 3-3, Figure 3-11).

Table 3-3 Pearson's correlation of folate contents and important post-harvest phenotypes

Type	S	CRF	C	F	CA	HW	SW	SD	FW	B
THF	0.27*	-0.12	0.28*	-0.23	0.02	-0.29*	-0.36***	0.03	-0.12	-0.04
5-CH_3-THF	0.04	0.12	-0.01	0.05	-0.12	0.16	0.13	0.13	0.08	-0.27*
Total	0.14	0.07	0.10	-0.04	-0.10	0.03	-0.02	0.13	0.03	-0.26*

S, Shape; CRF, Carrot root fly resistance; C, Canker resistance; F, Firmness; CA, Core area; HW, Harvest whiteness; SW, Stored whiteness; SD, Storage discolouration; FW, Flesh whiteness; B, Browning. *, ** and *** represent significant difference at the 0.05, 0.01 and 0.001 probability levels, respectively.

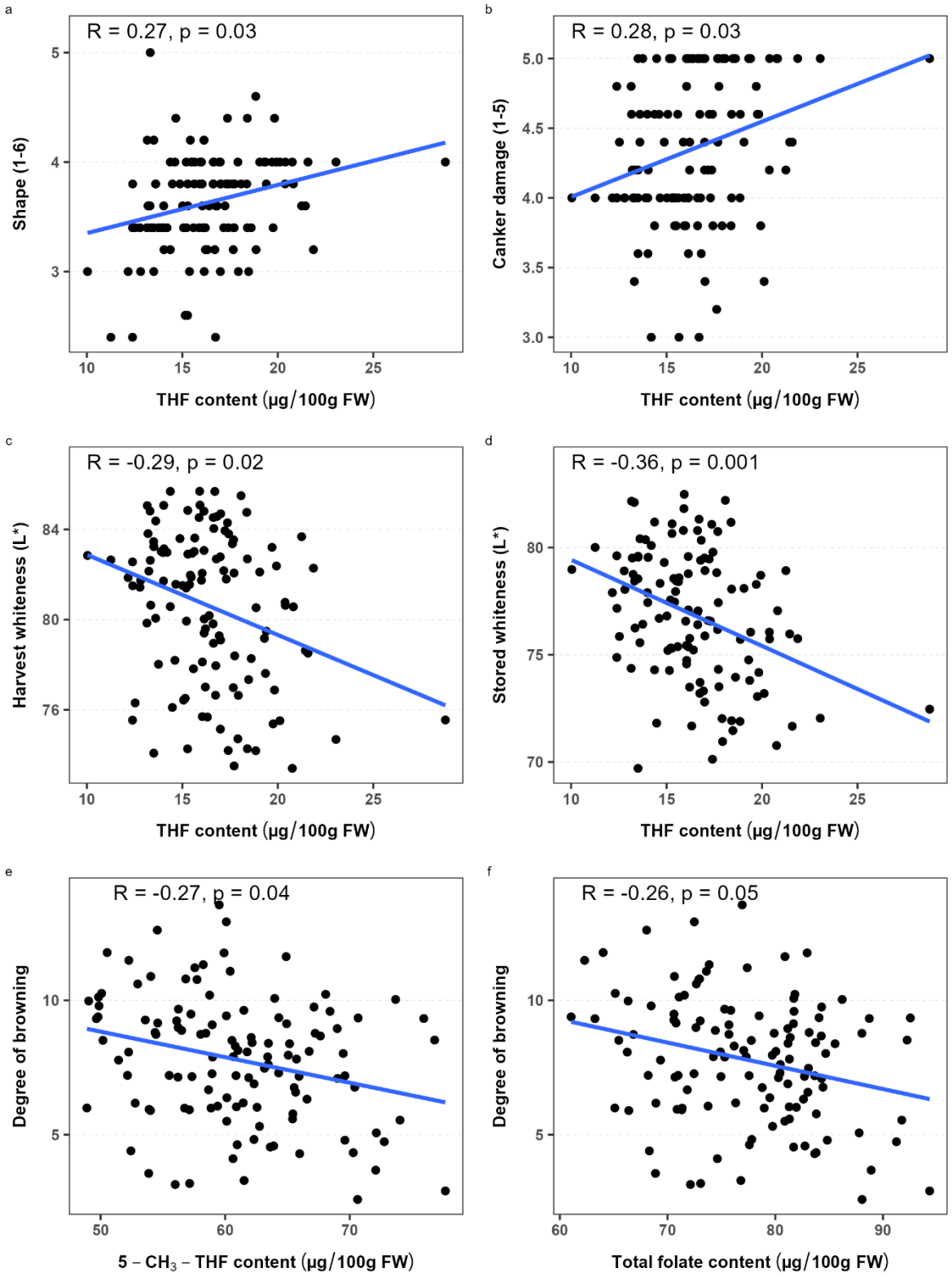


Figure 3-11 Scatter plots of statistically significant Pearson's correlations between post-harvest phenotypes and folate vitamer content. Plots a), b), c) and d) show the relationship between tetrahydrofolate content and shape, canker damage, harvest whiteness and stored whiteness, respectively. Plots e) and f) show the relationship between degree of browning and 5-methyltetrahydrofolate content, and total folate content, respectively. Each black point is an individual datapoint, and the blue line shows the

regression line of y ~ x. Statistical significance was defined as a Holm adjusted p value < 0.05.

3.4 Discussion

3.4.1 The folate content of parsnips

The mean folate content of parsnips in this study was 77.4 ± 7.14 µg/100 g, falling at the upper end of the range reported in national food composition databases (43.2 to 87.0 µg/100 g, Table 3-4). This consistency with established data supports the reliability of the Chapter findings.

Table 3-4 Parsnip folate content listed in national food composition databases

Source	**Reference**	**Parsnip folate content (µg/100 g)**
Slovakian online food composition database	Slovak Food Composition Data Bank, 2008	59
Danish FRIDA database	National Food Institute, 2019	67
Finnish Fineli database	National Institute for Health and Welfare, 2019	87
USDA Food composition database	USDA, 2019	67
French Ciqual Food composition database	Anses, 2020	67
Czech Food composition database	Prague: Institute of Agricultural Economics and Information, 2020	No data
Swiss Food composition database	Federal Food Safety and Veterinary Office FSVO, 2021	43.2
Estonian NutriData Food composition database	National Institute for Health Development, 2021	78
Norwegian Food composition database	Norwegian Food Safety Authority, 2021	78
UK McCance and Widdowson Composition of Foods Integrated Dataset	Public Health England, 2021	87
Dutch NEVO database	RIVM, 2021	87
Swedish Food Agency food database	The Swedish Food Agency, 2021	77.9
Chapter 3	-	77.4 ± 7.14

The predominant folate vitamer was 5-CH_3-THF, which accounted for approximately 78% of the total folate content, while THF contributed around 22%. Both vitamers were therefore important contributors to total folate content, but 5-CH_3-THF was the primary component of the parsnip folate profile. There is no previously published information on the distribution of folate vitamers in parsnips. However, in carrot (*Daucus carota*), a related member of the *Apiaceae* family that also produces an edible taproot, folate also consists predominantly of 5-CH_3-THF (94%) and THF (5.8%), with no other vitamers present in quantifiable amounts (Vahteristo *et al.*, 1997). Therefore, the findings of this study are consistent with expectations from related species.

The distribution of folate vitamers in parsnips is likely to be nutritionally relevant. In general, 5-CH_3-THF is considered one of the most bioavailable and stable naturally occurring form of reduced folate (Indrawati *et al.*, 2004). Furthermore, some studies have indicated that the relative stability of 5-CH_3-THF compared to THF makes it less susceptible to losses during storage, processing, or cooking (Indrawati *et al.*, 2004; Strandler *et al.*, 2015), although this may be dependent on other components of food matrices (Liu *et al.*, 2022). Therefore, the finding that nearly 80% of parsnip folate content is in the form of 5-CH_3-THF suggests that parsnips are a particularly valuable dietary source of nutritionally effective folate.

3.4.2 Factors influencing folate content in parsnips

This analysis found that genotype (variety) was the most influential factor in determining folate content. Differences in folate concentrations were significant between varieties, with total folate ranging from 61.0 to 94.3 µg/100 g. Notably, there was more relative variation in THF content (ranging from 10.0 to 28.8 µg/100 g, a ~97% difference) than in 5-CH_3-THF content (ranging from 48.9 to 77.7 µg/100 g FW, a ~45% difference). This suggests that THF levels may be more responsive to genetic or environmental variation than 5-CH_3-THF levels, although the smaller absolute quantities of THF in relation to overall folate limit its influence on total folate compared to 5-CH_3-THF.

Growing environment (location and harvest timing) influenced THF content, but had no significant effect on the 5-CH_3-THF or total folate content of parsnips. Therefore, while environmental conditions can affect certain aspects of the folate profile, their overall effect on folate content appears relatively modest compared to varietal differences.

To date, studies on the role of genotype (G) and environment (E) in determining folate content have focused on arable crops such as wheat, rye, and beans; no studies have investigated parsnips, *Apiaceae* crops, or root vegetables more generally. In the published literature, there is conflicting evidence on the relative impact of G and E on folate content. Tian et al. (2025) found a statistically significant relationship between G and G x E and the amount of THF, 5-CH_3-THF,

5-CHO-THF, 5, 10-CH^{+}THF and total folate, but only 5-CH_3-THF and 5, 10-CH^{+}THF content had a significant association with E in wheat. Martin et al. (2021) found total folate content to be significantly associated with G but not with E or G x E in common bean, and Shewry et al. (2010) found total folate content to be significantly associated with E but not G in rye. The discrepancies, combined with the distant relation of previously studied crops to parsnips, make it difficult to compare the results of this study to published literature.

However, it has been noted that differences in experimental design may partly explain these inconsistencies: when crops are testing across highly contrasting environments, E is more likely to show significant effects, while inclusion of a large number of diverse genotypes may increase the likelihood of G being found to significantly impact folate content. (Tian *et al.*, 2025). Chapter 3 included 10 different varieties of parsnips, grown in two locations, and harvested over two events. As only approximately 30 varieties of parsnip are currently in commercial production, the different genotypes in this study are assumed to cover a good proportion of the genetic variation present in parsnips, although detailed genotypic investigation would be needed to confirm this. By contrast, parsnips are grown in a variety of soil types, locations, and agronomic contexts across the UK and globally that were not represented in this study. Therefore, it is unlikely that the full potential of the impact of environment on folate content in parsnips has been investigated. Consequently, whilst this study suggests that genotype is the primary determinant of folate content in parsnips, further multi-environment trials are needed to fully quantify the extent to which environmental variation can influence folate content.

3.4.3 Breeding for folate content in parsnips

The post-harvest phenotypes assessed in this study were selected because they are already valued in parsnip breeding programmes. As such, information on how these traits are measured, and why they are desirable to breeders, growers, and consumers, is well established. If folate content had shown strong correlations with any of these traits, the coupling of nutritional and quality traits could have enabled folate to be indirectly selected for without altering the priorities of existing breeding pipelines. Conversely, should folate content be negatively correlated with any valued traits, this would be important information to feed into future breeding efforts that may seek to better align phenotypic and nutritional characteristics.

However, folate content did not correlate with yield characteristics and showed only limited associations with selected post-harvest phenotypes. Total folate and 5-CH_3-THF content were negatively correlated with browning (i.e., higher folate was associated with less browning), while THF content correlated positively with shape (i.e. higher THF content with more obovate shape) and canker resistance, but negatively with harvest whiteness and stored whiteness.

The positive association between THF content and canker resistance is encouraging, as disease resistance is a high-priority breeding target. However, the association of THF with less desirable root shapes and darker colouration runs counter to breeding goals. The practical importance of these associations, however, may be limited, since THF contributes a smaller share of total folate than 5-CH_3-THF. Conversely, the negative correlation between browning and both total folate and 5-CH_3-THF content is noteworthy, both because 5-CH_3-THF is the predominant folate vitamer in parsnips, and because this relationship aligns with existing breeding goals. Historically, browning has been a lower breeding priority than traits such as disease resistance, whiteness, and uniformity, partly because it is more difficult to phenotype consistently, but also because it does not impact yield and therefore the value of the crop to parsnip growers. Further research is needed to establish whether these correlations are robust across environments and to explore the underpinning physiological or genetic mechanisms for these traits. If robust causation could be established, selection for browning as an easily measurable phenotype could be used to indirectly select for higher folate parsnips at the same time as improving consumer acceptability.

This study also lays the groundwork for future works to explore mechanistic links between folate content and wider phenotypes. Different folate vitamers play distinct roles in plant physiology, for example, 5-CH_3-THF feeds into the methionine synthesis pathway (Chapter 1 Section 1.5.2, Figure 1-2), whilst conversion between THF and 10-CHO-THF consumes formate and produces purines (Chapter 1 Section 1.5.2, Figure 1-2). It is possible, therefore, that variation in folate profiles could contribute directly to phenotypic differences such as disease resistance or colour stability (Gorelova *et al.*, 2017). However, much more evidence is needed to evaluate these hypotheses, along with genetic resources to establish stronger links between folate content and phenotypes.

Phenotypic analysis of field-grown parsnip traits in a controlled laboratory context was a novel development in this thesis. Therefore, it is possible that phenotyping methods were not fully optimised for picking up differences in phenotypes that could be associated with folate content. For example, firmness was measured using a 11 mm cylindrical probe, when a smaller probe or different probe shape could have been used. Future optimisation of laboratory phenotyping in parsnips could improve both trait characterisation and the detection of subtle links with folate content. On the other hand, a key aim of this study was to explore traits that were valuable to parsnip breeders, and consequently, measurement protocols were targeted towards detecting differences at a level that was meaningful to the crop physiology and phenotypes. Therefore, it is important that future optimisation should therefore balance experimental precision with practical breeding relevance to main the wider applicability of the work.

The traits that were assessed in this trial were selected for their existing commercial importance, not based on prior evidence of correlation with folate content. Therefore, it could be that the selected traits were not the correct ones to be associated with folate content in the first place. In wheat, the traits of seed coat colour (5-CH_3-THF, 5-CHO-THF, total folate), grain width (THF, 5-CH_3-THF, 5,10-CH^+-THF), grain thickness (5-CH_3-THF, 5,10-CH^+-THF) and thousand kernel weight (THF, 5-CH_3-THF, 5,10-CH^+-THF) have been shown to correlate with folate content (Riaz *et al.*, 2019; Zheng *et al.*, 2022; Tian *et al.*, 2025). There is some overlap with the phenotypes assessed in this analysis, which included colour-based traits (harvest colour, stored colour, flesh colour, storage discolouration, and browning), size and shape phenotypes (average mass per parsnip and shape), and yield characteristics (total mass of parsnips and total count of parsnips). However, it should be noted that parsnips and wheat are distantly related and physiologically distinct crops. Therefore, evidence from wheat may not be applicable to parsnips, and traits that yield significant correlations to folate content in wheat may in fact have no relationship to those phenotypes in parsnips.

3.5 Conclusions and future directions

This study has provided the first detailed characterisation of the folate vitamer profile in parsnips. It confirms that parsnips are a valuable source of dietary folate, dominated by 5-CH_3-THF, the most nutritionally relevant and stable folate vitamer. Folate content varied significantly between varieties but was only modestly influenced by growing environment within the scope of this study. In terms of breeding potential, folate content was not strongly associated with yield or most post-harvest traits, but the observed correlations with browning and canker resistance highlight possible avenues for indirect selection.

In addition to the future steps outlined in the discussion above, it would be useful to perform more extensive genotyping and genetic profiling of parsnips, for which no publicly available genetic resources currently exist. Such work would clarify the causal basis of variety–folate relationships and provide potential screening tools, should links between genetic components and folate content be established.

Genetic insights would also support biofortification strategies, since any effort to increase folate content requires an understanding of the genetic mechanisms underlying the trait. In the wider context of the UK Genetic Technology (Precision Breeding) Act 2023 (UK Government, 2023) and similar international legislation making gene-edited crops more feasible for commercial release, the potential for biofortification of folate content in parsnips with improved genetic resources may even enhance the market value of parsnips as a functional food.

Chapter 4 Variation in the Folate (Vitamin B9) content of Parsnip (*Pastinaca sativa* L.) from Farm to Fork: The impact of storage and cooking on folate content

4.1 Introduction

Parsnip (*Pastinaca sativa* L.), a short-lived monocarpic perennial widely consumed as a root vegetable (Chappell and Dunford, 2021). It is part of the *Apiaceae* family, which contains both other root vegetables such as carrots, as well as a range of other aromatic vegetables such as celeriac, parsley, and cumin (Chapter 1 Section 1.8). Although grown in locations around the world, it is especially popular in the UK, where it has been in production since the 1st century AD (Hendrick, 1919; Laws, 2006; Chappell and Dunford, 2021; AG Pearce Ltd, no date). Its fleshy taproot develops over 16-25 weeks and is valued for it sweet, nutty flavour, high carbohydrate and starch content, and rich profile of vitamins and minerals (Castro, Bergenståhl and Tornberg, 2012; Chappell and Dunford, 2021; Khadivi, Mirheidari and Moradi, 2023, Chapter 1 Section 1.8.2). Amongst these micronutrients, folate, essential for DNA synthesis and cellular function (Chapter 1 Section 1.5.2), is of particular importance in the UK context, due to high levels of deficiency across vulnerable population groups (Chapter 2).

Between harvest and consumption, parsnips may undergo a range of processing steps (Figure 4-1). Many are standard for retail distribution and common across root vegetables, including sorting, grading, trimming, cleaning, polishing, antimicrobial treatment, and refrigerated transport (Gross, Wang and Saltveit, 2016). However, pre-retail storage and domestic cooking methods may vary substantially (Figure 4-1). Such variation in processing conditions can alter both the nutritional profile and sensory characteristics of the parsnips ultimately purchased and consumed.

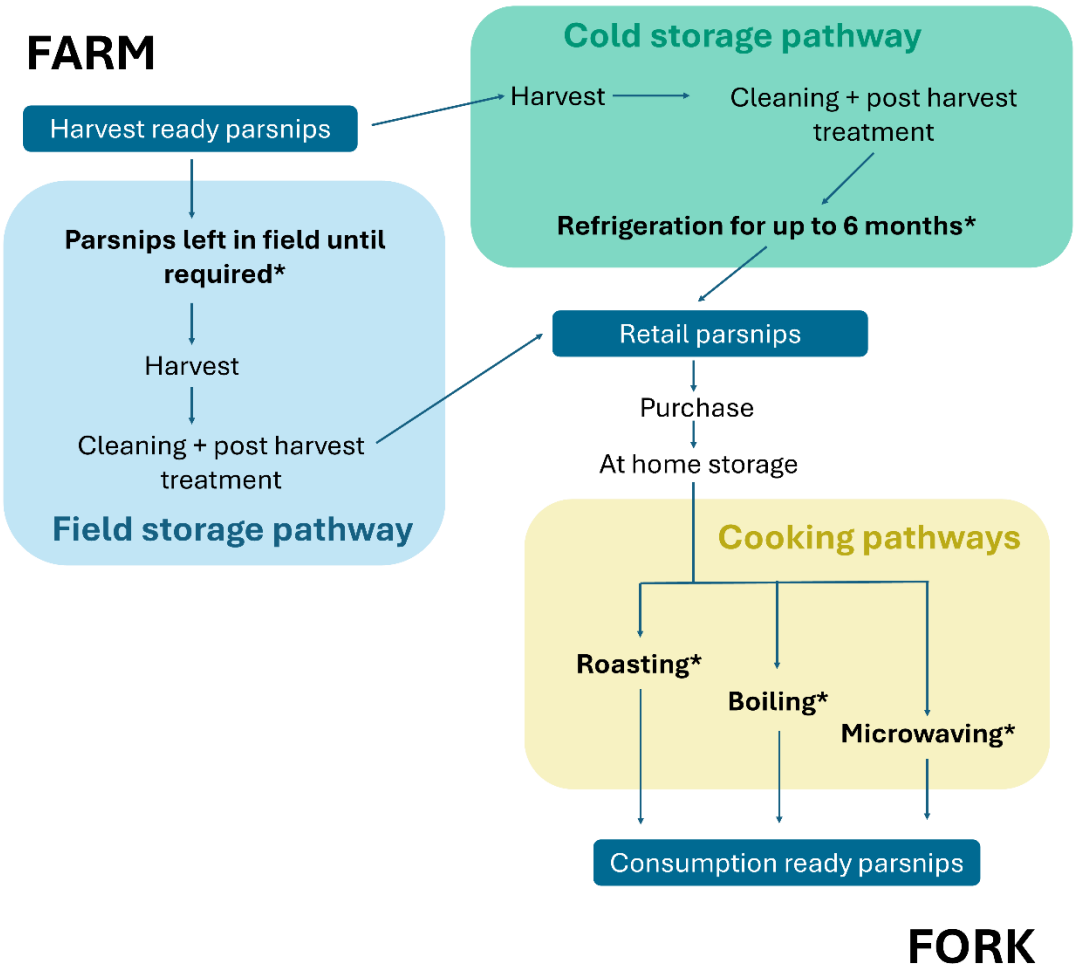


Figure 4-1 Simplified pathway of parsnips processing from farm to fork, highlighting points of variation. Processes investigated in Chapter 4 indicated in bold with an asterisk.

4.1.1 Parsnip storage methods

The capacity of parsnips for long term storage is a key characteristic of the crop that distinguishes them from, for example, carrots, that perish more quickly upon harvest maturity (Ilić *et al.*, 2013, 2016; Ilić and Sunić, 2015). Two main storage approaches are used to preserve parsnips after they reach harvest maturity (CALU, 2007; Ilić and Sunić, 2015). In the UK, it is traditional to leave parsnips unharvested in the field until they are required for sale, harvesting them gradually as needed (CALU, 2007) (Figure 4-1, field storage pathway). This method is thought to enhance flavour, particularly for crops that reach maturity in the autumn, as freezing temperatures trigger the conversion of starches to sugars, making parsnip roots sweeter and more palatable (Boswell, 1923; Rutherford, 1977; Shattuck, Kakuda and Yada, 1989; Bufler and Horneburg, 2013; Shim, Kim and Shin, 2024). However, leaving parsnips in the ground exposes them to pests and diseases, and may result in undesirable overly large, woody roots—especially if sown early in spring (Tozer Seeds Ltd, unpublished, 2022). Together, these factors can result in crop losses of up to 30% (Ilić *et al.*, 2013, 2016).

Alternatively, parsnips may be harvested at maturity and stored under refrigerated conditions until required (Figure 4-1, refrigerated storage pathway). This practice, common in the USA (Tozer Seeds Ltd, personal communication, 2023), allows roots to be stored for up to six months without major quality degradation when well managed (Rydenheim, 2008; Ilić *et al.*, 2013, 2016; Gross, Wang and Saltveit, 2016). However, there are significant costs associated with refrigeration, and prolonged refrigeration may lead to shrivelling and discolouration, rendering roots less acceptable to consumers (Ilić and Sunić, 2015).

4.1.2 Parsnip cooking methods

Although parsnips can be eaten raw (Prakash, 2015; Phipps, 2024), they are generally cooked before consumption (Oddbox, 2022). This distinguishes them from carrots, which are commonly eaten raw, although they may also be cooked. In the UK, roasting is traditional, although they are also commonly boiled for mash or soup (Andersson *et al.*, 2022; Good Food, no date), steamed (Andersson *et al.*, 2022), or even microwaved prior to consumption (Bilenka *et al.*, 2018; Oddbox, 2022; Beck, no date) (Chapter 1 Section 1.8.2). More rarely, parsnip may be pickled (Health, 2022; Hill & Vale, no date), deep fried (Gilson, 2017), stir-fried (Costa, 2020; Davis, no date), or even fermented to make wines (Brown *et al.*, 2010; Wright, 2011; Adamant, 2019).

Cooking may change the structural matrix of parsnip tissues, in ways that vary according to method. For example, steaming reduces cell-cell adhesion and increases cell shrinkage of parsnips compared to boiling, creating a softer texture with enhanced flavour and improved in-mouth sensory qualities (Andersson *et al.*, 2022). This effect has also been observed in carrots, where cooking at 100°C for 20 minutes has been shown to increase cell separation, increase water- and salt-soluble, high-molecular-weight pectic polysaccharides and decrease in the pectic polymers in all cell wall extracts and residue (Ng and Waldron, 1997; *(PDF) Structural Changes in Foods Caused by High-Pressure Processing*, no date). High pressure low temperature processing results in the increased firmness of carrot tissue as starch granule surfaces become more textured increasing adhesion forces and cell walls become more rigid (*(PDF) Structural Changes in Foods Caused by High-Pressure Processing*, no date).

Biochemical changes may also occur with cooking. In a study on potato, carrots, beetroot, black carrot, celery, turnip, and sweet potato, cooking by boiling, steaming, pressure boiling, and pressure steaming was found to significantly alter the dry matter content, total soluble solids, ash content, pH, and titratable acidity of these vegetables (Zor *et al.*, 2022). Additionally, colour parameters of these vegetables were significantly altered by the cooking methods (Zor *et al.*, 2022). Microwaving parsnips for one minute at 650 W prevents tissue darkening post peeling

by deactivating oxidoreductase enzymes, preserving a desirable white colour (Bilenka *et al.*, 2018). Roasting parsnips may result in the production of acrylamide, depending on the amounts of reducing sugars present in the parsnip root (Breitling-Utzmann and Hankele, 2019).

4.1.3 Impact of storage and cooking on parsnip nutritional quality

As outlined above, post-harvest handling steps affect the product acceptability as well as organoleptic and chemical properties of parsnips. Additionally, numerous studies have suggested that post-harvest processes may affect micronutrient, especially vitamin, retention between harvest and consumption across a wide range of crops (Berry Ottaway, 2010; Bouzari, Holstege and Barrett, 2015; Fabbri and Crosby, 2016; Lee *et al.*, 2017; Islam *et al.*, 2021; Huey *et al.*, 2023; Razzak *et al.*, 2023; Mutombo Arcel *et al.*, 2025).However, no studies have been conducted on post-harvest micronutrient retention in parsnips.

4.1.4 The sensitivity of folate to storage and cooking

Folate, introduced in Chapter 1 Section 1.5, is a group of water-soluble vitamers sharing a three-part structure: a pterin ring, a para-aminobenzoic acid moiety, and a variable number of glutamate residues (Rébeillé *et al.*, 2006; Delchier *et al.*, 2016; Saini, Nile and Keum, 2016; Strobbe and Van Der Straeten, 2017) (Figure 1-1). It is an essential micronutrient, with key roles in the synthesis and maintenance of DNA (Chapter 1 Section 1.5.2, Figure 1-2), and is found in large quantities in parsnips (Chapter 1 Section 1.8.2, Chapter 3).

Folates are known to be sensitive to heat, light, and oxidation (Scott, Rébeillé and Fletcher, 2000; Delchier *et al.*, 2016), implying that their bioaccessibility is likely to be impacted by cooking processes (Scott, Rébeillé and Fletcher, 2000; Delchier *et al.*, 2016; Wusigale and Liang, 2020; Bationo, Savadogo and Goubgou, 2022; Siatka *et al.*, 2025). Folates also undergo cycles of synthesis and degradation in plants (Rébeillé *et al.*, 2006; Bekaert *et al.*, 2008), which may influence how well they are preserved during storage (Iniesta *et al.*, 2009; Octavia and Choo, 2017; Pinela *et al.*, 2019; Liang *et al.*, 2020; Islam *et al.*, 2021). However, the potential complexities caused by interactions between folates and other chemicals found in fruits and vegetables such as antioxidants and reducing sugars, has resulted in few studies of folate stability in food matrices (Delchier *et al.*, 2016; Wusigale and Liang, 2020; Siatka *et al.*, 2025).

Despite relatively wide-ranging research on folate in both common (e.g. spinach, broccoli, carrot, strawberry) and rare or regionally consumed crops (e.g. sea buckthorn, drumstick, amaranth) (Siatka *et al.*, 2025), no studies have addressed the effect of cooking or storage on folate content in parsnips. However, studies conducted in carrots, a related member of the

Apiaceae family that is also generally consumed as a root vegetable crop, may provide relevant insights.

In carrots, three studies were identified which explored the impact of cooking on folate content. Carrots vacuum packed in polythene bag and blanched for 10 minutes in 100°C water were found to have higher folate concentrations compared to raw controls (Munyaka *et al.*, 2010). A study by Wang et al. (2011) found mixed effects on the 5-methyltetrahydrofolate (5-CH_3-THF) content of carrots with high pressure processing of vacuum packed samples at 30°C: sample held at 300 MPa for 5 minutes, 450 MPa for 0 minutes, and 450 MPa for 5 minutes all lost folate relative to the reference tissue. All other treatments: 300 MPa for 0 minutes, 600 MPa for 0 minute and 600 MPa for 5 minutes were unchanged relative to the reference (Wang *et al.*, 2011). Juicing of raw carrot yielded juice with 59% of the total folate content of the un-juiced vegetable, with the remaining 41% of folate left in the pulp (Wang, Riedl and Schwartz, 2013). However, none of these methods reflect how carrots or parsnip are typically prepared in the home, and no studies were found that examined the effects of storage on folate in carrots or parsnips.

Despite the lack of information on the effects of cooking and storage on folate content in the scientific literature, there are some available data on cooking in the wider literature: nutrient composition databases typically list separate values for raw and cooked food items. In the UK Composition of Foods Integrated Database (CoFID) (Public Health England, 2021), three parsnip listings are provided: raw, boiled in salted water, and roasted in rapeseed oil (Table 4-1).

Table 4-1 Parsnip listings in the Composition of Foods Integrated Dataset (Public Health England, 2021)

Food Name	Food Code	Amount of folate (µg/100 g)	Method	Amount of water (g/100 g)	Source
Parsnip, raw	13-312	87	Analysis	79.3	Institute of Food Research. *The Nutritional Composition of retail vegetables in the UK*. 1984-1987
Parsnip, boiled in unsalted water	13-631	49	Analysis	80.5	(Roe *et al.*, 2017a)
Parsnip, roasted in rapeseed oil	13-632	96	Calculation	58.6	(Roe *et al.*, 2017a)

The raw value (Food code 13-312) is taken from an Institute of Food Research (now Quadram Institute Bioscience) report conducted between 1984-1987, titled ‘The nutritional composition

of retail vegetable in the UK'. This publication has not been digitised and could not be accessed, so comment cannot be made on sampling design or evaluation methods.

The boiled value (Food code 13-631) was most recently updated in 2017, as part of an analytical review designed primarily to update estimates of fibre content in commonly consumed fruit and vegetables in the UK (Public Health England, 2021). Full details of this review are published at (Public Health England, 2017). Samples for boiled parsnip analysis were collected from across 11 retail locations in Norwich, UK, in November 2015 (Roe *et al.*, 2017b). Samples were washed, trimmed, peeled, cut into slices or chunks, and boiled for 8-12 minutes (Roe *et al.*, 2017b). After cooking, samples were combined into a composite and frozen at -20°C pending analysis (Roe *et al.*, 2017b). Total folate was determined using microbiological assay (MBA) procedures with detection carried out using VitaFast® MBA test kits, although the precise methodological parameters were not specified (Roe *et al.*, 2017a). Quantification was conducted during the period from December 2015 to July 2016 (Roe *et al.*, 2017a). A single value for folate content, 49 µg/100 g, was determined (Roe *et al.*, 2017a).

The folate content of Food code 13-632, "Parsnip, roasted in rapeseed oil", was also updated in 2017 as part of the same analytical review as the boiled parsnips (Public Health England, 2021). The same samples were used for analysis (Roe *et al.*, 2017b). Samples were washed, trimmed, peeled, chopped lengthways into quarters or halves, and coated with 1 tbsp of rapeseed oil before being roasted for 35-55 minutes (Roe *et al.*, 2017b). After cooking, samples were combined into a composite and frozen at -20°C pending analysis (Roe *et al.*, 2017b). Although values for the water and fat content of roasted parsnips are provided in the corresponding analytical report, no values are given for folate content (Roe *et al.*, 2017a), and in the CoFID description for food item 13-632, it is stated that the folate content of roasted parsnips was "calculated from boiled" (Public Health England, 2021). However, no details are given of the calculation used.

The values in CoFID are a useful reference point for expected values for the folate content of raw and cooked parsnips. However, it should be noted that the data were collected at different times, as part of two separate analyses, using a range of experimental methods. Therefore, it is difficult to isolate the effect of cooking on folate content from these reference points, as the parsnips used to generate the 'raw' value are different to those used to generate the 'boiled' and 'roasted' values. This chapter will go beyond the CoFID data by empirically comparing raw and cooked parsnips, including direct measurements of folate content in roasted parsnips.

In addition to affecting the total folate content of parsnips, it is thought that individual folate vitamers may respond differently to processing due to their varying stabilities (Strandler *et al.*, 2015; Saubade, 2016; Liu *et al.*, 2022). In general, formyl- and/or oxidised forms of folate are

more stable than methyl- and/or reduced forms, especially at high temperatures and low pH (Delchier *et al.*, 2016; Saubade, 2016; Siatka *et al.*, 2025). However, inconsistencies across food types suggest that the tissue matrix may influence vitamer response to post-harvest treatments (Siatka *et al.*, 2025). In Chapter 3, the folate vitamer profile of parsnips was established for the first time. Chapter 4 will build on this work by exploring the effects of storage and cooking on the levels of individual folate vitamers in parsnips, and therefore, the overall folate profile.

4.1.5 Chapter aims and objectives

The hypothesis of Chapter 4 is that storage and cooking of parsnips will affect their folate content. The aim of the Chapter is to explore a range of storage and cooking techniques commonly used in the preparation of parsnips and quantify the changes in folate content resulting from these techniques. This aim will be achieved through the following objectives:

1. To quantify the impact of different storage methods on folate content and stability in parsnip roots, including comparing traditional in-field storage with refrigerated storage over time.
2. To assess the effects of common domestic cooking methods on total folate content in parsnips, including boiling, microwaving, and roasting.
3. To identify whether changes in folate content are due to loss or degradation of folate vitamers or due to changes in the parsnip food matrix during storage and cooking.
4. To investigate how different storage and cooking conditions affect the folate vitamer profile of parsnips.

4.2 Materials and methods

4.2.1 Plant materials

4.2.1.1 Storage experiment materials

Parsnip material was sourced from a collaborator at VCS (UK) Ltd (Norfolk, UK). Parsnips were grown by a partner farmer to VCS (UK) Ltd (Norfolk, UK) in a field location in Brandon, East Anglia, UK (GPS: 52.444817, 0.570664). Sown in May 2023, samples were harvested at the beginning of March 2024. All parsnips used were of the cultivar *Javelin* – the most popular variety of parsnip in the UK.

4.2.1.2 Cooking experiment materials

Parsnip material for the cooking experiment was provided by Tozer Seeds Ltd, a partner on this project. These parsnips were cultivated by the trials team at Tozer Seeds Ltd in a field location in Cobham, Surrey, UK (GPS: 51.313963, -0.482111), sown in April 2024 and harvested in March 2025. All parsnips used were of the cultivar *Javelin*.

4.2.2 Experimental design

4.2.2.1 Storage conditions

The storage experiment began in March 2024. Control of the storage conditions and management of parsnips over storage was conducted by VCS (UK) Ltd. Upon harvest, parsnips were industrially cleaned and trimmed to remove foliage. At this stage, approximately 100 cleaned and trimmed parsnips were set aside for baseline analysis. All remaining parsnips were placed in an industrial chiller at 1 ± 0.5°C. Once the remaining parsnips had cooled to 2°C, they were sealed in polythene bags for storage at 1-4°C.

At 2-, 4- and 6-weeks post-harvest, subsamples of ~50 parsnips were removed from cold storage for analysis. On each of these days, an additional 50 parsnips were harvested fresh from the field, cleaned and trimmed as previously described, and set aside for comparative analysis. All samples were then shipped via 24-hour courier to Niab, East Malling, for further preparation by researchers. A schematic of the overall sampling plan is shown in Figure 4-2.

Upon arrival, samples were inspected for damage, defects, or disease, and affected parsnips were discarded. Thirty parsnips were randomly selected per condition and divided into three composite biological replicates of ten parsnips each. Each composite was homogenised to form a mixed tissue sample. Approximately 50 g of homogenate was weighed (exact mass recorded), flash-frozen in liquid nitrogen, transferred to labelled bags, and stored at –80°C in the dark.

Once all samples were collected, they were lyophilised in a single batch using a Christ Alpha 1-4 LCSplus Freeze Drier (SciQuip Ltd, Rotherham, UK), until weight loss ceased. Final dry masses were recorded, and samples were stored at –80°C in the dark until analysis.

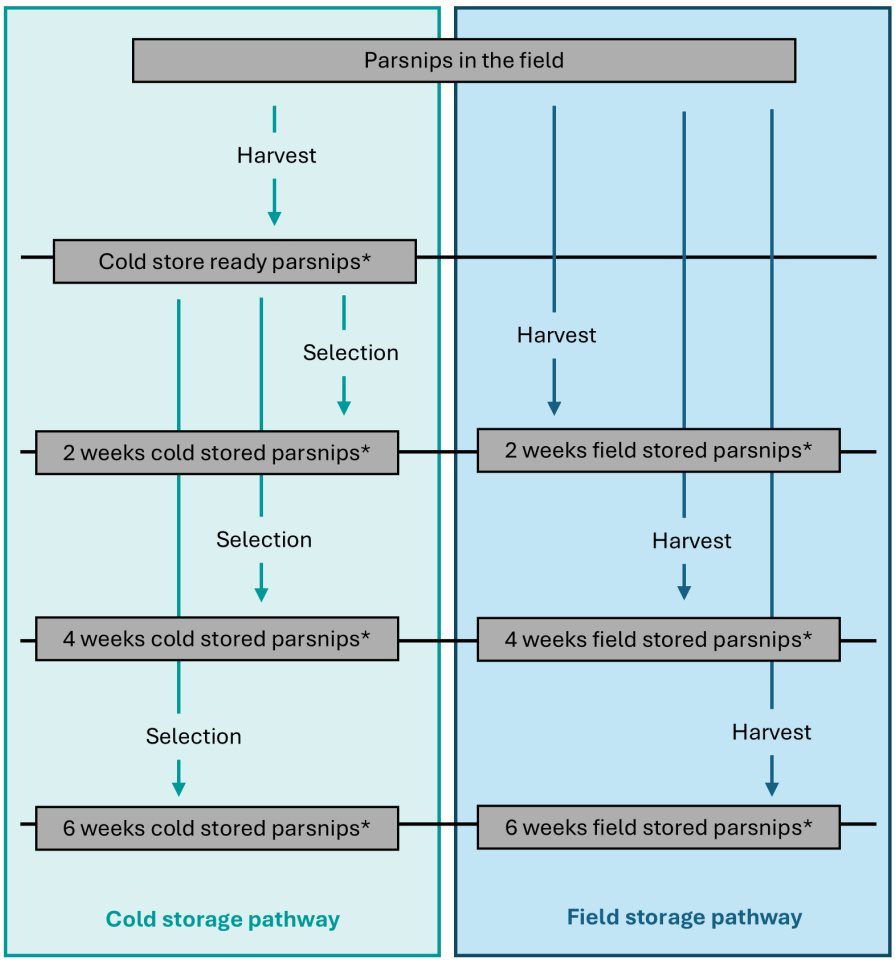


Figure 4-2 Sampling methodology for the storage trial. Asterisks denote points where parsnip samples were taken.

4.2.2.2 Cooking conditions

The cooking experiment was initiated in March 2025. Freshly harvested parsnips were roughly cleaned, trimmed of foliage, and stored in unsealed polythene bags at 1–4°C overnight.

The following day, parsnips were inspected for damage, defects, or signs of disease, and any affected parsnips discarded. The remaining parsnips were randomly allocated into one of five composites, until there were five parsnips per composite group. The individuals in each composite were trimmed (crown and tail removed), then chopped into ~1 cm cubes, mixed, and divided into four ~50 g subsamples (exact mass recorded).

Each subsample was randomly allocated to one of four treatments: raw, microwaved, boiled, or roasted. Raw samples were flash-frozen in liquid nitrogen with no further treatment. Microwaved samples were cooked in a Panasonic NN-CT54JWBPQ microwave oven (Panasonic UK, Bracknell, UK) at 1000 W for 2 minutes, then weighed and flash-frozen. Boiled samples were

cooked in a pan of 500 ml boiling water on a Gionien GCE460TC induction hob (Zhongshan JOYHOT Electrical Technology Co. Ltd, Zhongshan City, China) at a medium heat for 15 minutes, then drained, weighed, and flash frozen. Roasted samples were placed on a baking parchment lined tray in a Russell Hobbs RH72DEO1002SS Fan Oven (Russell Hobbs Limited, Manchester, UK), preheated to 200°C, for 20 minutes, then removed, weighed, and flash frozen.

After flash freezing, samples were transferred to labelled bags, compressed to remove excess air, and stored at –80°C in the dark. All samples were freeze-dried in a single batch as described above, and final dry masses were recorded. Samples were stored in the dark at -80°C until analysis.

4.2.3 Folate analysis by high-performance liquid chromatography (HPLC)

Folate in stored and cooked samples was extracted and quantified using the trienzyme-extraction and HPLC method described in detail in Chapter 3 Section 3.2.3.

4.2.4 Statistical analyses

Across all analyses, the amount of folate is expressed per 100 g dried weight (DW) and per 100 g cooked weight or stored weight (CW or SW). This is because the water content, and therefore mass, of parsnips was expected to differ across the cooking and storage conditions, which may alter the concentration of folates in tissues, regardless of whether the vitamers themselves have been affected by processing. Expressing the folate content per 100 g DW is used to explore whether degradation of vitamers has occurred whilst excluding the effects of water content changes. The folate content per 100 g CW or SW is used to evaluate whether the actual folate content in cooked or stored tissues has changed over the cooking and storage conditions, allowing for changes in water content. The folate content per 100 g CW or SW was calculated by multiplying the folate content per 100 g DW by the percentage dry matter after cooking or storage, calculated from the ratio of the mass of cooked or storage samples before and after lyophilisation.

Each composite was treated as one biological replicate. For the storage trail, 3 composites were analysed per condition per timepoint. For the cooking trial, 5 composites were included per treatment. All data are presented as the mean of the biological replicates ± standard deviation.

Prior to statistical evaluation, all datasets were assessed for conformity to the assumptions of parametric analyses. To evaluate the effects of storage on folate content, a two-way ANOVA was performed, with storage method and timepoint as fixed effects. To assess the effects of cooking on folate content, a one-way ANOVA was used with cooking method as a fixed effect.

Where ANOVA revealed statistically significant effects ($p < 0.05$), Tukey's HSD post hoc tests were used for pairwise comparisons between groups.

For datasets where the assumptions of parametric testing were not met, specifically for individual folate vitamer concentrations after cooking, non-parametric Kruskal-Wallis tests were applied. Where the Kruskal-Wallis test returned a significant result, Dunn's post hoc tests with a Holm-adjusted p value were used for multiple pairwise comparisons between groups.

All data wrangling, data visualisation and statistical analysis were conducted in R (R Core Team, 2024) via RStudio (version 2025.05.1+513) (Posit team, 2025), using the following packages: tidyverse (version 2.0.0) (Wickham *et al.*, 2019), ggplot2 (version 3.5.1) (Wickham, 2016), ggpubr (version 0.6.1) (Kassambara, 2023a), rstatix (version 0.7.2) (Kassambara, 2023b), ggstatsplot (version 0.13.0) (Patil, 2021), and patchwork (version 1.3.0) (Pedersen, 2024).

4.3 Results

4.3.1 Effect of storage on the total folate content and dry matter content of parsnip samples

The total folate content of parsnips over storage is given per 100 g stored weight (SW). There was a statistically significant relationship between timepoint and total folate content ($F(2, 16) = 3.927$, $p = 0.028$). There was no significant interaction between timepoint and storage condition ($F(3, 16) = 0.845$, $p = 0.489$), indicating that the relationship between timepoint and folate content was consistent across both storage conditions. Storage condition alone had no significant effect on total folate content ($F(1, 16) = 2.275$, $p = 0.151$). Post hoc testing revealed a statistically significant difference between the folate content of parsnips after 2 weeks storage (68.6 ± 8.77 µg/100 g SW) and 6 weeks storage (54.4 ± 9.44 µg/100 g FW) ($p = 0.039$).

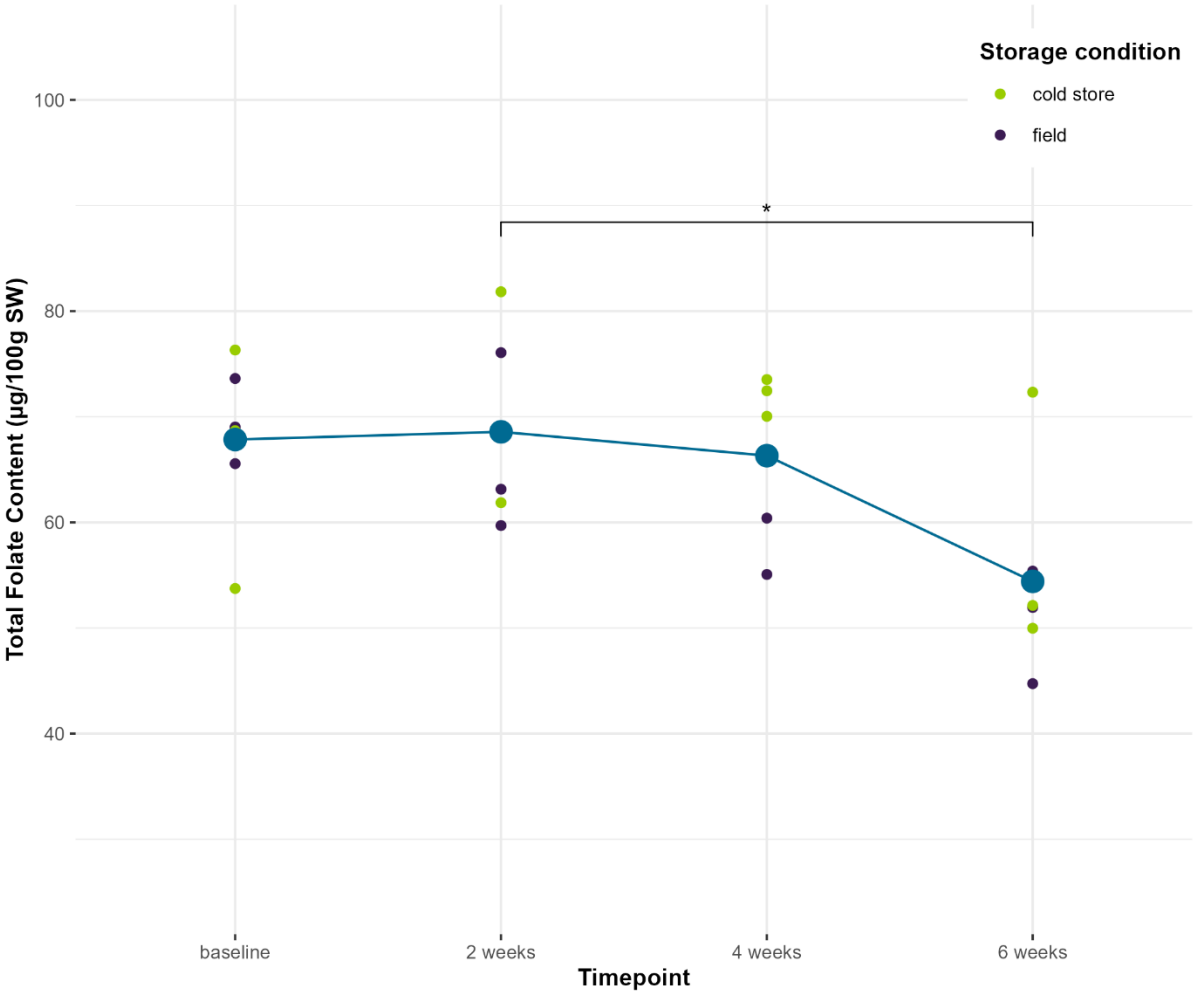


Figure 4-3 Dot-plot of the total folate content in parsnip samples over different storage conditions and durations. Small dots represent individual data points from parsnips stored in the cold store (green dots) and field (purple dots), respectively. Larger blue dots represent the mean folate content across both storage conditions at each timepoint. N = 3 per condition per timepoint. Asterisks between two mean indicates a significant pairwise difference at $p < 0.05$ (Tukey HSD post hoc testing)

Unlike folate per 100 g SW, the folate content per 100 g DW did not significantly vary by timepoint ($F(3, 16) = 2.911$, $p = 0.067$), storage conditions ($F(1, 16) = 1.750$, $p = 0.204$), or the interaction between timepoint and storage conditions ($F(3, 16) = 1.054$, $p = 0.396$). The total folate content remained stable during storage, with a mean value of 373.3 ± 48.4 µg/100 g DW.

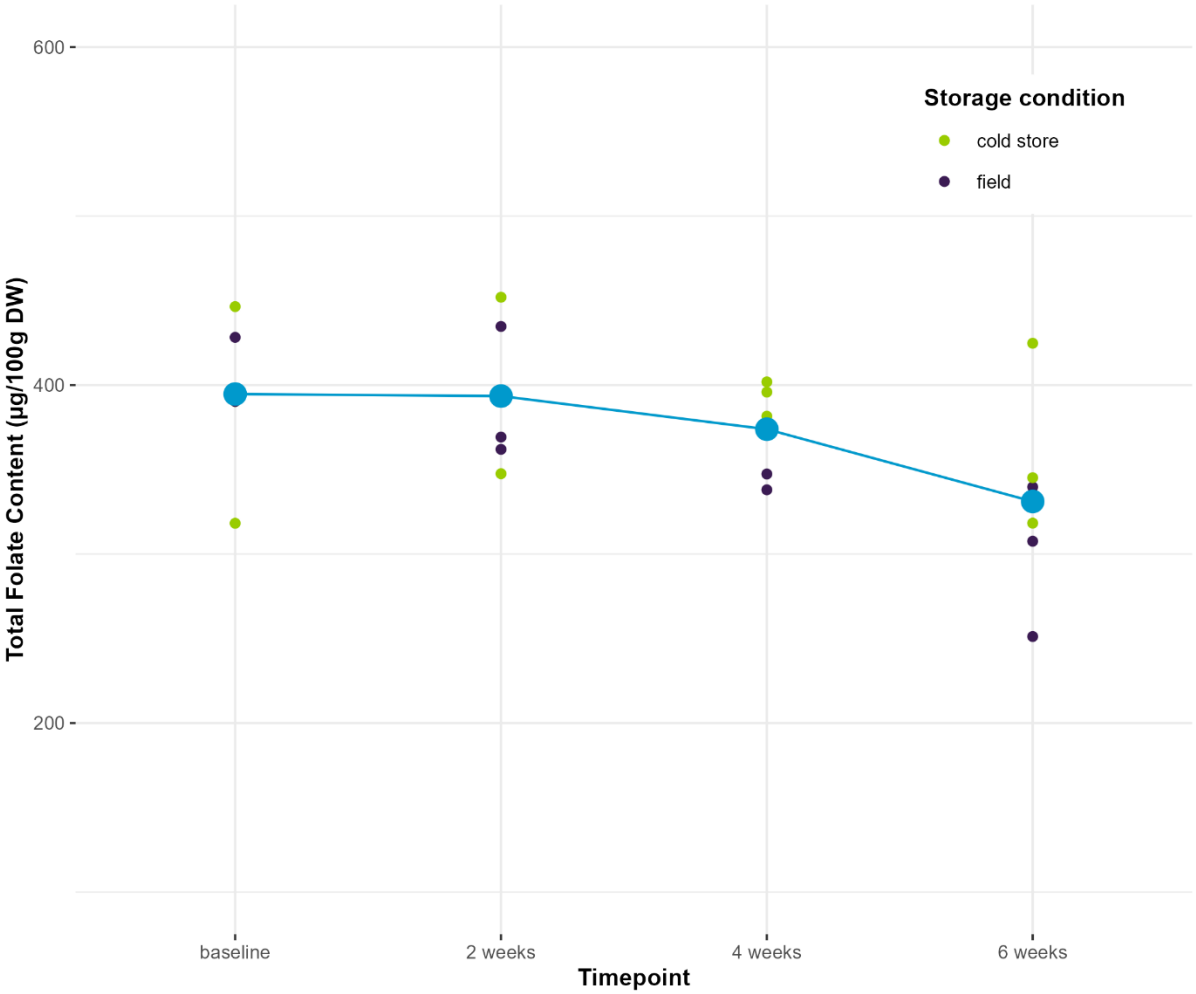


Figure 4-4 Dot-plot of the total folate content in dried parsnip samples over different storage conditions and durations. Small dots represent individual data points from parsnips stored in the cold store (green dots) and field (purple dots), respectively. Larger light blue points indicate the mean each timepoint across both storage conditions. N = 3 per condition per timepoint.

Dry matter percentage significantly changed over time ($F(3, 16) = 5.024$, $p = 0.012$), with different trends observed between cold store and field conditions ($F(3, 16) = 4.632$, $p = 0.016$) (Figure 4-5). However, storage condition alone did not affect dry matter content ($F(1, 16) = 0.839$, $p = 0.373$). Post hoc testing revealed significant differences between the dry matter content of parsnips stored for 2 week (17.8 ± 0.35%) or 6 weeks (15.9 ± 0.86%) in the cold store ($p = 0.021$), and between parsnips kept for 4 weeks or 6 weeks in the cold store (18.3 ± 0.65% and 15.9 ±0.86%, respectively, $p = 0.002$) (Figure 4-5). Dry matter % remained consistent in the field stored samples across all time points (17.1 ± 0.5%) (Figure 4-5).

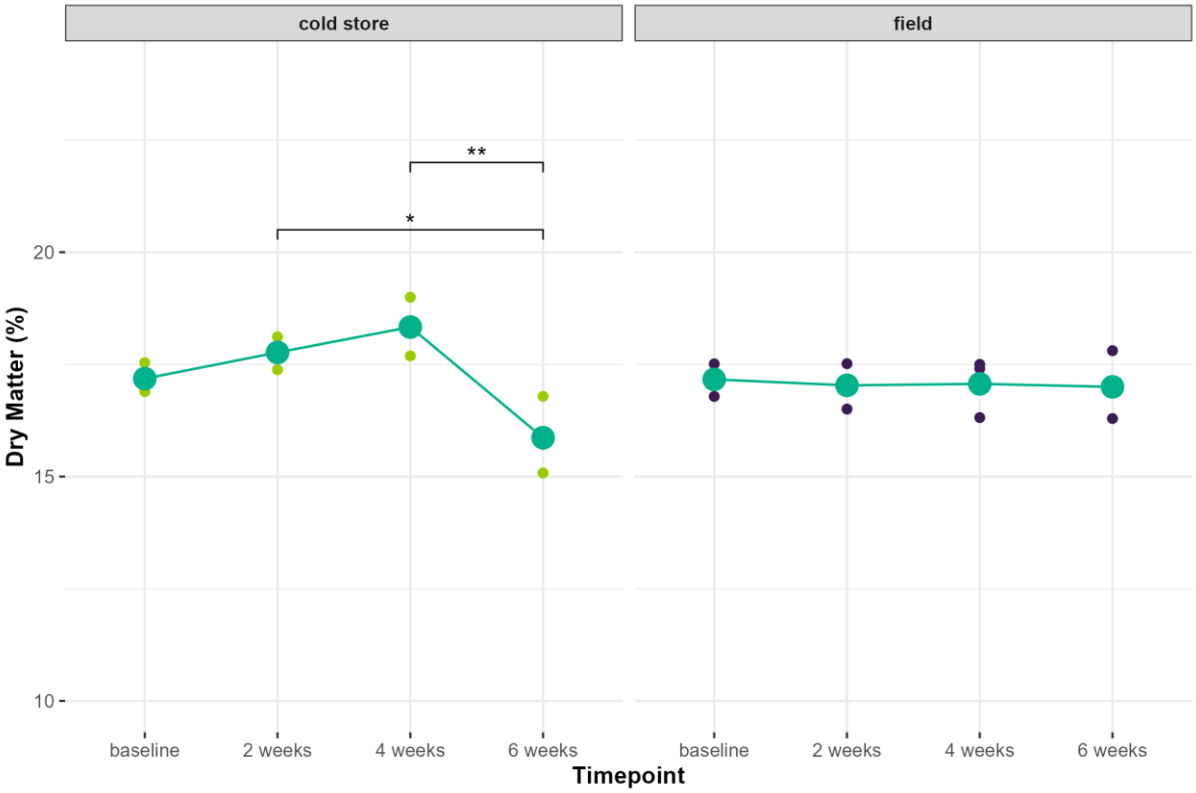


Figure 4-5 Dot-plot of the dry matter percentage of parsnips under different storage methods and durations. Small dots represent individual data points from parsnips stored in the cold store (green dots) and field (purple dots), respectively. Larger dark green points indicate the mean at each timepoint. N = 3 per condition per timepoint. Asterisks between two means indicates a significant pairwise difference (* - $p < 0.05$; ** - $p < 0.01$).

4.3.2 Effect of storage on folate vitamers

Folate content per 100 g DW was also analysed for 5-methyltetrahydrofolate (5-CH_3-THF) and tetrahydrofolate (THF) individually to assess whether storage affected these vitamers differently. No statistically significant effect of timepoint, storage condition, or the interaction effect was found on either 5-CH_3-THF or THF concentrations (Figure 4-6).

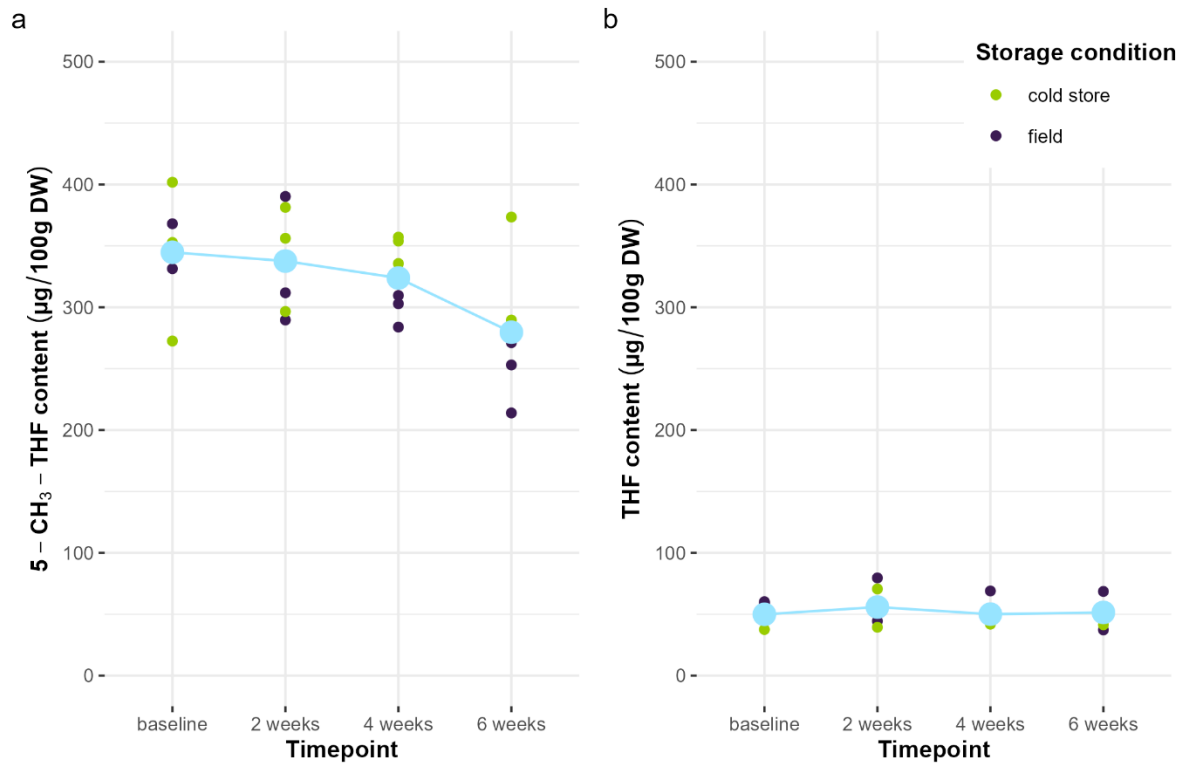


Figure 4-6 Dot-plot of the 5-CH_3-THF and THF content of parsnips over storage. Small dots represent individual data points from parsnips stored in the cold store (green dots) and field (purple dots), respectively. Larger light blue points indicate the mean each timepoint across both storage conditions. N = 3 per condition per timepoint.

4.3.3 Effect of cooking on the total folate content and dry matter content of parsnip samples

The total folate content of parsnips after cooking is given per 100 g cooked weight (CW). There was a statistically significant relationship between cooking method and total folate content ($F(3, 16) = 108.67$, $p < 0.001$). Raw parsnips contained 83.7 ± 5.24 µg/100 g CW, boiled parsnips contained 68.2 ± 4.09 µg/100 g CW, microwaved parsnips contained 164.4 ± 11.8 µg/100 g CW, and roasted parsnips contained 140.0 ± 13.5 µg/100 g CW (Figure 4-7). Post hoc testing revealed statistically significant differences between all cooking methods ($p < 0.05$), apart from between raw and boiled samples ($p = 0.087$) (Figure 4-7).

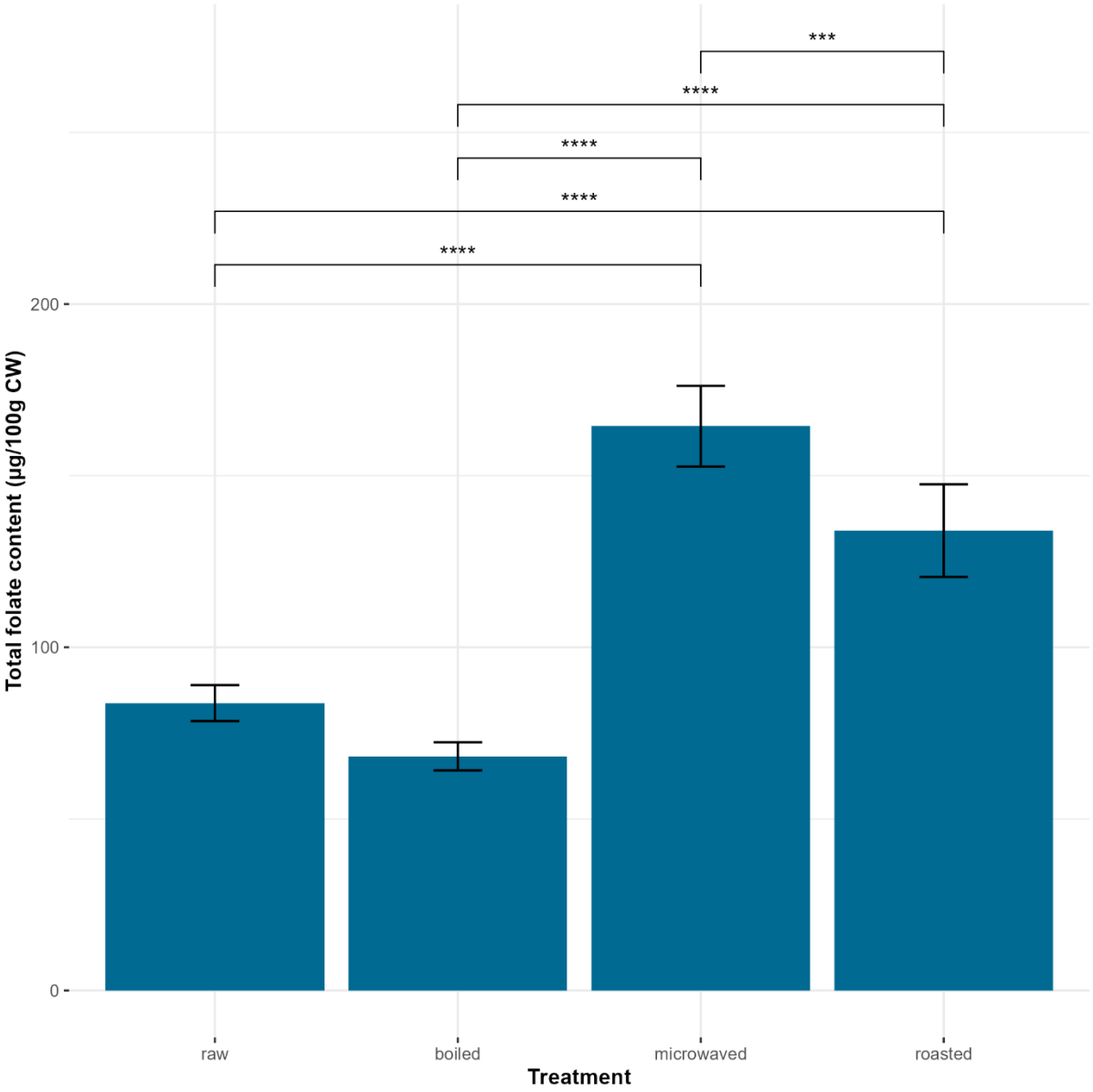


Figure 4-7 Bar-plot of the folate content of cooked parsnip samples per 100 g cooked weight (CW). Bars show means; error bars show standard deviation. N = 5 per treatment. Asterisks denote significant difference (* - $p < 0.05$; ** - $p < 0.01$; *** - $p < 0.001$; **** - $p < 0.0001$).

Statistically significant differences in the folate content per 100 g DW by cooking method were also observed (($F(3, 16) = 9.654$, $p < 0.001$). However, pairwise differences were not consistent with the folate content per 100 g CW (Figure 4-8). Microwaved samples (516.2 ± 28.3 µg/100 g DW) were found to contain greater amounts of folate than to raw (444.6 ± 28.3 µg/100 g DW, $p = 0.004$), boiled (434.5 ± 31.6 µg/100 g DW, $p = 0.001$) and roasted (446.2 ± 27.1 µg/100 g DW, $p = 0.004$) samples; no other significant pairwise differences were observed (Figure 4-8).

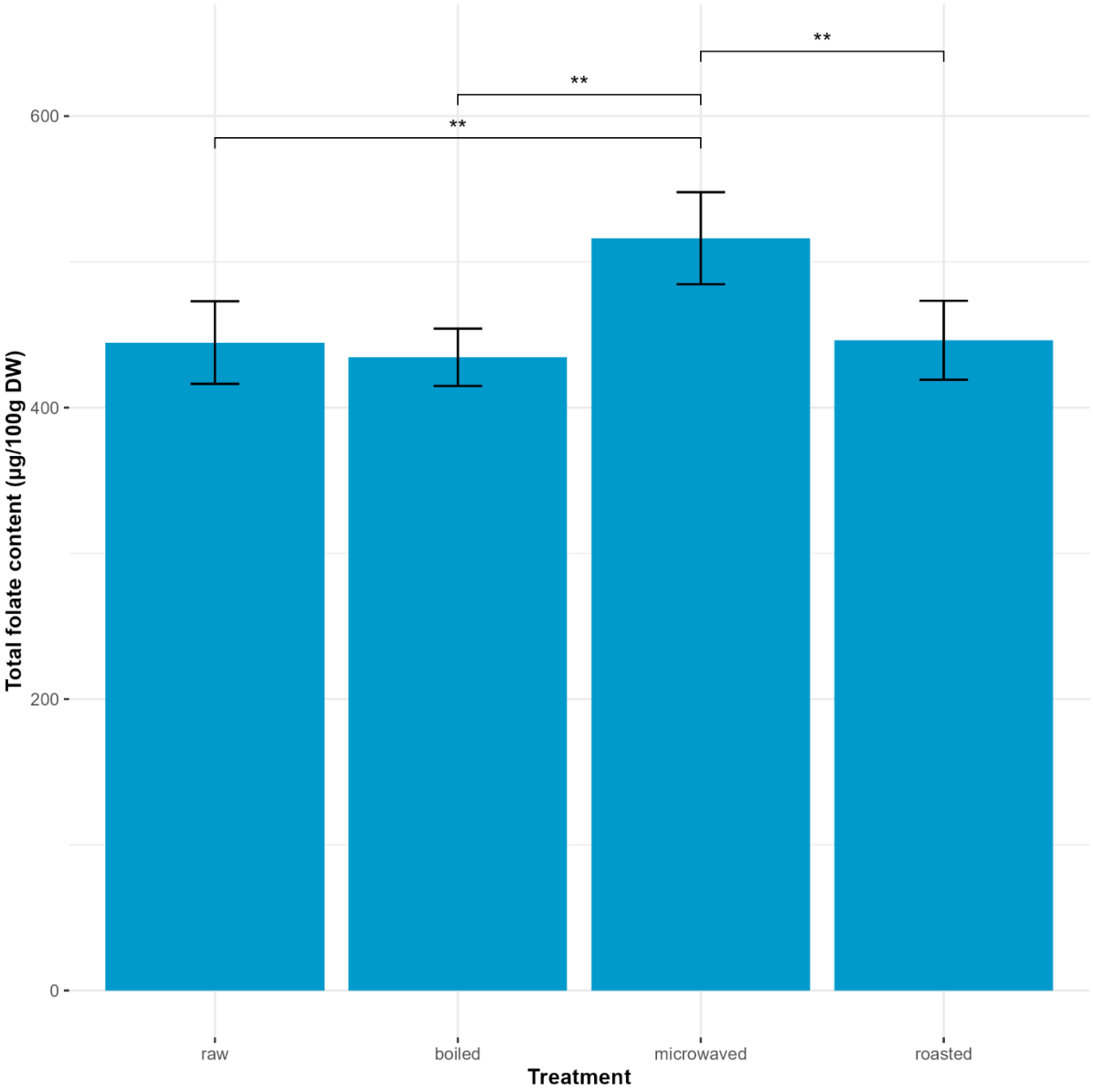


Figure 4-8 Bar-plot of the folate content of cooked parsnip samples per 100 g dry weight (DW). Bars show means; error bars show standard deviation. N = 5 per treatment. Asterisks denote significant difference (* - $p < 0.05$; ** - $p < 0.01$).

Cooking significantly affected the percentage dry matter of parsnip samples ($F(3, 16) = 132.3$, $p < 0.001$) (Figure 4-9). The pairwise comparisons between the dry matter percentage of raw parsnips (18.9 ± 1.0%), boiled parsnips (15.7 ± 1.0%), microwaved parsnips (31.9 ± 2.3%), and roasted parsnips (30.0 ± 1.5%) were all statistically significantly different ($p < 0.05$), apart from the comparison between microwaved and roasted parsnips ($p = 0.249$) (Figure 4-9).

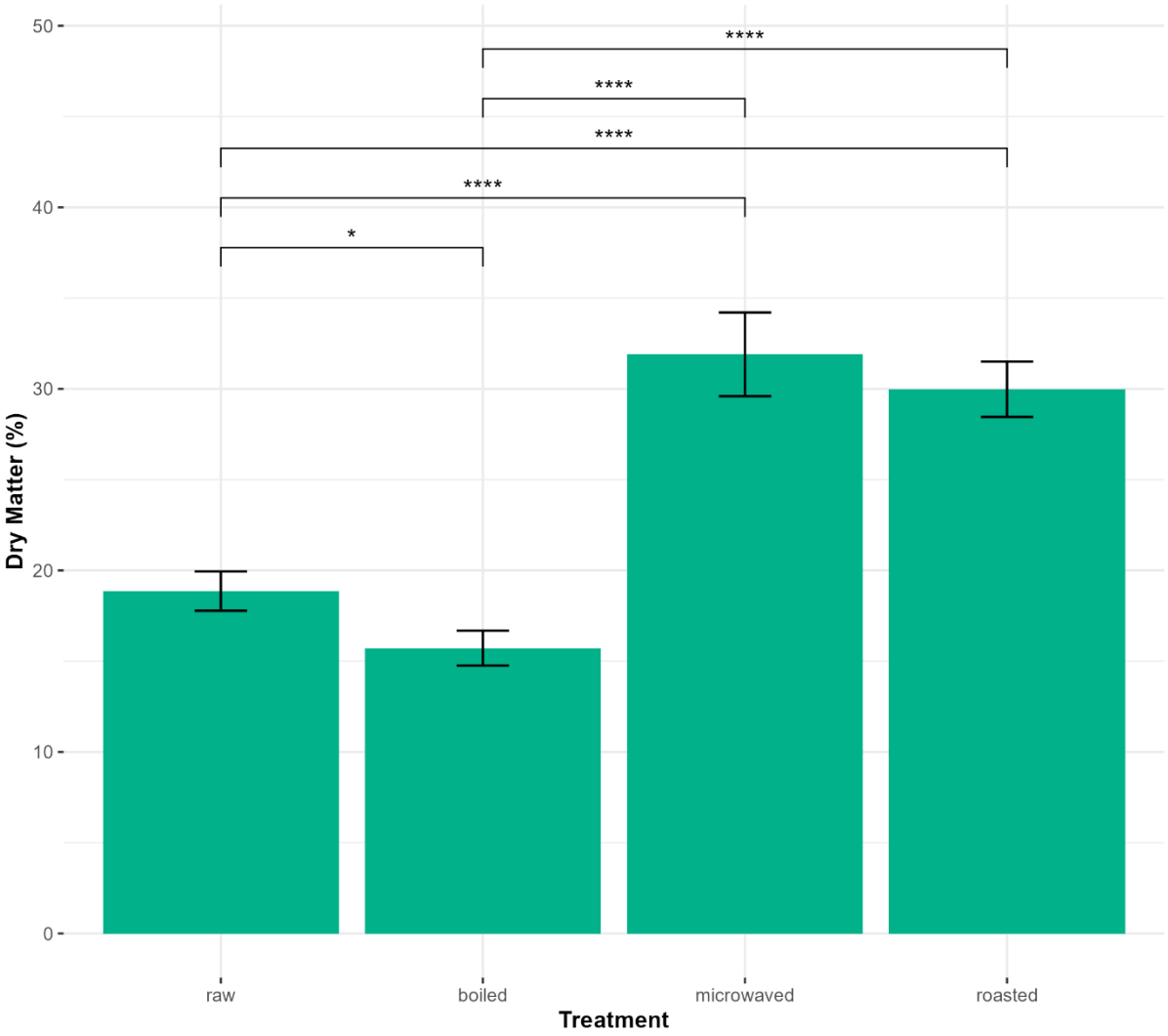


Figure 4-9 Bar-plot of the dry matter percentage of cooked parsnip samples. Bars show means; error bars show standard deviation. N = 5 per treatment. Asterisks denote significant difference (* - $p < 0.05$; ** - $p < 0.01$; *** - $p < 0.001$; **** - $p < 0.0001$).

4.3.4 Effect of cooking on folate vitamers

Kruskal Wallis testing showed that there was a statistically significant effect of cooking on both 5-CH_3-THF content per 100 g DW ($H(3) = 8.67$, $p = 0.014$, $\eta^2 = 0.354$) and THF content per 100 g DW ($H(3) = 17.1$, $p < 0.001$, $\eta^2 = 0.881$) (Figure 4-10). Dunn post hoc tests indicated that microwaved parsnips (399.0 ± 28.9 µg/100 g DW) contained significantly more folate than raw parsnips (346.1 ± 18.1 µg/100 g DW) ($p = 0.045$) (Figure 4-10). For THF, significant differences were observed between raw (98.5 ± 13.3 µg/100 g DW) and roasted (58.3 ± µg/100 g DW) parsnips ($p = 0.028$), and between microwaved (117.2 ± 11.4 µg/100 g DW) and roasted (58.3 ± µg/100 g DW) parsnips ($p < 0.001$) (Figure 4-10).

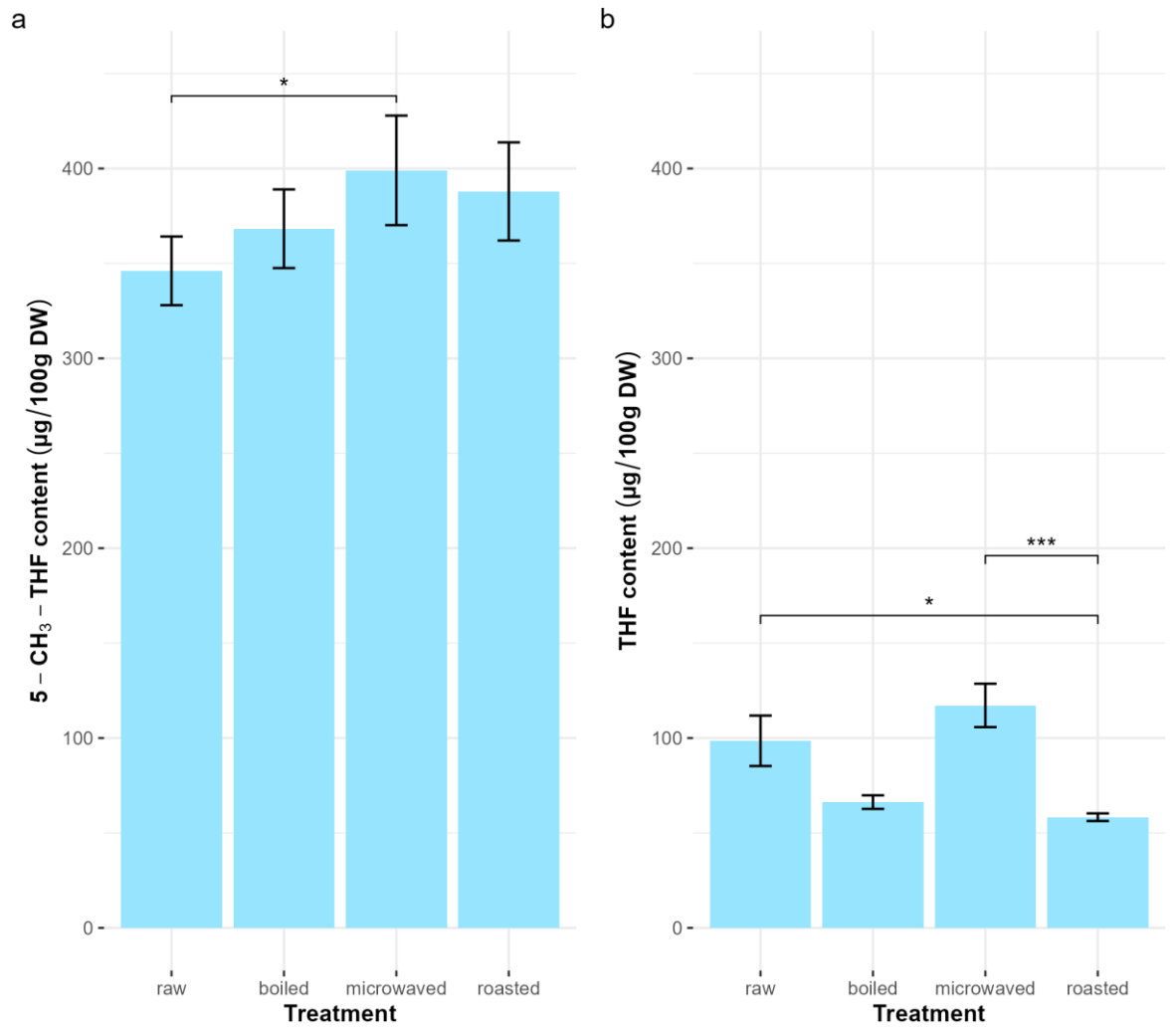


Figure 4-10 Bar-plots of the a) 5-CH_3-THF and b) THF content per 100 g DW of parsnips cooked by different methods. Bars show means; error bars show standard deviation. N = 5 per treatment. a) Asterisks indicate significant difference (* - $p < 0.05$; ** - $p < 0.01$; *** - $p < 0.001$).

4.4 Discussion

4.4.1 Effects of storage on folate content

Across both storage conditions – field and cold store – the folate content per 100 g SW significantly decreased over time. This decline was not linked to the storage method, suggesting that storage duration, rather than the type of storage, is the primary driver of lower folate content in stored parsnips compared with fresh samples. The decline in folate concentration in parsnip samples per 100 g SW was not mirrored in the data from dried parsnip samples, which remained statistically unchanged across timepoints, despite a small decline in absolute values. This indicates that the observed decreases in the folate content of parsnips over storage are likely attributable to shifts in water content rather than changes in the amounts of folates

themselves. Although no research has been conducted in similar crops to parsnip, studies on corn, watercress, sorrel, strawberries, tomatoes and wheat have all found statistically significant declines in folate content over refrigerated storage (Iniesta *et al.*, 2009; Octavia and Choo, 2017; Pinela *et al.*, 2019; Liang *et al.*, 2020; Islam *et al.*, 2021). Therefore, the results of Chapter 4 agree with the consensus from the wider literature.

Notably, after 6 weeks of storage, cold store samples had a significantly smaller dry matter percentage relative to baseline, indicating a gain in water that does not follow the trend of previous timepoints. This result was unexpected, as it has been noted in the literature that parsnips lose water during storage (Shattuck, Kakuda and Yada, 1989; Rydenheim, 2008; Ilić *et al.*, 2013, 2016; Ilić and Sunić, 2015). Although the increase in water content could be a real effect of storage, it may also be the case that an inconsistency in sample generation or preparation resulted in a perceived difference in dry matter content across the 3 biological replicates. For example, technical inconsistencies could have led to the introduction of water into the storage environment after 4 weeks refrigerated storage. Alternatively, there may have been incomplete drying of parsnips samples during lyophilisation. Regardless, the change in parsnip dry matter after 6 weeks in cold storage has a strong influence on the statistical significance of how storage affects their perceived folate content. Consequently, it is important that future works repeat this experiment to establish the validity and repeatability of this observed effect.

When analysed per 100 g DW, neither 5-CH_3-THF nor THF varied significantly across timepoints or storage conditions. This indicates minimal vitamer degradation over a six-week storage period, regardless of storage method. Although not statistically significant, a slight decline in 5-CH_3-THF, the dominant folate vitamer in parsnips, was observed in dried parsnip samples by the end of the study, particularly under field conditions. By contrast, THF levels remained consistent across the entire sampling period. Since pre-retail storage can extend for up to 6 months (Rydenheim, 2008; Ilić *et al.*, 2013, 2016; Gross, Wang and Saltveit, 2016), longer-term studies with larger sample sizes would be useful to determine whether this decline becomes significant over time.

When applying the results of Chapter 4 to the wider context of parsnip storage, this study indicates that that short-term refrigerated storage of parsnips post-purchase does not compromise nutritional quality. However, consumers that may purchase parsnips from retail outlets are unlikely to know how long parsnips have been stored for before purchase, and other properties of parsnips may well degrade over storage (Rutherford, 1977; Ostertag *et al.*, 2002; Rydenheim, 2008; Bufler and Horneburg, 2013; Ilić and Sunić, 2015; Shim, Kim and Shin, 2024) so avoiding prolonged storage at home remains advisable.

4.4.2 Effects of cooking on folate content

The folate content per 100 g CW varied significantly across parsnips cooked by different methods. Microwaving and roasting resulted in cooked parsnips with a higher folate content than raw parsnips, whilst boiling yielded parsnips with a folate content statistically equivalent to raw. When expressed per 100 g DW, only microwaved parsnips had a folate content that was statistically different from other treatment types. The cooking methods also resulted in final parsnip products with significantly different dry matter percentages, reflecting large losses of water from parsnip tissue with microwaving and roasting, and a small gain in water during boiling. Thus, differences in folate appear to result primarily from changes in tissue water balance, with concentration during microwaving and roasting and dilution during boiling.

The apparent increase in total folate content per 100 g DW with microwaving is initially counterintuitive. Folate is a product of active plant metabolism, and cooking induces necrosis in plant tissues by disrupting membranes, denaturing proteins, and inactivating enzymes, leading to a rapid collapse of metabolic activity (Yuan *et al.*, 2009; Fabbri and Crosby, 2016; Distéfano *et al.*, 2017). One possible explanation is that microwaving may liberate folate from cell-bound forms or protein conjugates, effectively increasing the bioaccessibility of folate in plant tissues and therefore the detected folate. However, no experimental studies could be found that investigated this hypothesis. Equally, it should be noted that some experimental protocols use microwaving as part of their folate extraction process (Wang *et al.*, 2011; Wang, Riedl and Schwartz, 2013). Therefore, microwaving may have improved the efficiency of extraction of folate from parsnip tissues, creating an apparent increase in folate content. Future work should investigate this effect in more detail, examining both the mechanisms of microwave-based cooking in parsnips and its impact on folate stability and lability in plant tissues.

Beyond total folate content, cooking also influenced the profile of individual folate vitamers. Concentrations of 5-CH_3-THF per 100 g DW were higher in all cooked samples compared to raw, with a statistically significant increase in microwaved parsnips. THF, by contrast, exhibited a more complicated pattern. Although microwaving increased THF concentration per 100 g DW relative to raw samples, both boiling and roasting caused significant reductions. THF is known to be more unstable than 5-CH_3-THF and is highly sensitive to oxidation and heat-induced decomposition (Wang, Riedl and Schwartz, 2013; Strandler *et al.*, 2015; Siatka *et al.*, 2025). Therefore, the intensity and duration of heating during roasting and boiling may have caused THF in the parsnip tissue to be degraded, whilst 5-CH_3-THF levels were unchanged due to their higher stability. By contrast, the duration of heating was much shorter during microwaving. Therefore, both THF and 5-CH_3-THF may have been stable enough to survive the short interval of

heat treatment. In combination with potential increases in bioaccessibility or extraction efficiency during microwaving, described above, this may explain the differences in 5-CH_3-THF and THF levels per 100 g DW over the tested cooking methods.

Folate is known to be sensitive to degradation through multiple mechanisms and is generally considered to be unstable (Scott, Rébeillé and Fletcher, 2000; Delchier *et al.*, 2016; Wusigale and Liang, 2020; Bationo, Savadogo and Goubgou, 2022; Siatka *et al.*, 2025). However, the effects of cooking on the total folate content of parsnips in this study were relatively minor compared to reports for other crops (Scott, Rébeillé and Fletcher, 2000; Delchier *et al.*, 2016; Czarnowska-Kujawska, Draszanowska and Starowicz, 2022; Siatka *et al.*, 2025). For example, folate losses of ~ 60% have been observed due to boiling of spinach and broccoli (McKillop *et al.*, 2002). Similarly, in leeks, cauliflower, and green beans folate losses of 28%, 10%, and 21%, respectively were attributed to leaching of folate into cooking water and thermal degradation during boiling (Melse-Boonstra *et al.*, 2002). Furthermore, losses of 17%, 52%, and 14% were observed with microwaving, boiling, and roasting in a combi oven of broccoli, whilst losses of 51%, 62%, and 45% occurred in spinach (Czarnowska-Kujawska, Draszanowska and Starowicz, 2022).

In Chapter 4, even boiled parsnip samples, which lost the most folate in this study, retained 97.7% of the total folate found in raw samples and were statistically unchanged from raw samples. It is possible, therefore, that the physical matrix or chemical properties of the parsnip tissue, e.g. cooccurrence of antioxidants in plant tissues, are protective against folate degradation or loss during cooking. This has been found to be the case for other nutrients, explored over a range of crops (Lemmens *et al.*, 2014, 2019; Bationo, Savadogo and Goubgou, 2022; Siatka *et al.*, 2025). For example, the subcellular localisation of β-carotene, the pre-cursor to vitamin A, within chloroplasts in leafy green vegetables like spinach, chard, and mallow is thought to protect β-carotene from degradation during boiling, compared to other vegetables including carrots and zucchini (Lee *et al.*, 2017). However, these effects have not been explored for folate retention in parsnips or other root vegetables. Future studies could explore potential matrix effects in more detail to understand causative factors in the relative stability of folate in parsnips, both individually and by comparison with other, more sensitive, food crops. In addition, the wider chemical context of parsnips could be explored to identify molecules that may be interacting with folate to prevent degradation or loss.

One of the closet points of reference for the current study is the published CoFID values for raw and cooked parsnips. The CoFID values for the folate content of raw parsnips per 100 g is within one standard deviation of the value found in this study. Therefore, the folate content of raw parsnips in this study agrees with official CoFID data. Additionally, similar trends to those

described in CoFID were observed when comparing the folate content of raw parsnips to boiled and roasted: boiled parsnips had less folate than raw per 100 g CW, whilst roasted parsnips had more. However, the folate content of both boiled parsnips and roasted parsnips was found to be greater in this study than the CoFID values, with mean values of 68.2 ± 4.09 µg/100 g CW and 140.0 ± 13.5 µg/100 g CW, compared to CoFID values of 49 µg/100 g and 96 µg/100 g, respectively.

It could be the case that the different folate quantification methods used in CoFID compared to this study are responsible for the observed differences – this study used HPLC for folate quantification, whilst CoFID employed microbiological assays and computational estimates. However, studies in other crops have shown that folate quantification by HPLC generally results in lower overall estimates of folate content compared to the microbiological assay (Vahteristo *et al.*, 1997; Koontz *et al.*, 2005; Strandler and Jastrebova, 2011; Czarnowska-Kujawska, Gujska and Michalak, 2017; Ringling and Rychlik, 2017). Therefore, methodological differences do not help explain the lower folate content recorded in CoFID compared to the results of Chapter 4.

It should also be noted that CoFID does not use paired raw and cooked data – different parsnips were used to derive the raw and boiled parsnip folate values, whilst the roasted value was based on calculation from the boiled value. Therefore, it could be that the parsnips used to experimentally determine the folate content of boiled parsnips for CoFID, and therefore to calculate roasted parsnip folate content, had an initial folate content that was lower than the raw value to start with. Therefore, comparing the raw and boiled values in CoFID could results in an overestimation of the effect of boiling on folate loss. By contrast, this study determined the folate content of parsnips directly before and after boiling, thereby controlling for differences in the initial folate content of parsnips and directly investigating the effect of cooking on folate content. Consequently, the results of this chapter add value to the existing knowledge base by directly comparing raw and cooked samples, expanding the range of cooking methods tested, and providing updated, empirically derived folate values for cooked parsnips.

Based on the results of this Chapter, consumers could be advised to avoid boiling parsnips, particularly when the water the parsnips are boiled in is not consumed as part of the final dish, to avoid folate losses. Microwaving of parsnips as a cooking method should be promoted, particularly as a fast, cheap and easy way to prepare parsnips. However, the change in weight of a portion of parsnips when cooked is substantial, with 1.4 times more parsnip needed to produce 100 g of microwaved parsnip compared to boiled parsnip. Where satiety is a primary goal, boiling may be a more appropriate form of cooking as it preserves food mass. Despite minor folate losses, boiled parsnips still qualify as a rich source of folate (>60 µg/100 g FW) (DHSC, 2025).

All of the cooking methods that were investigated yielded parsnip products that were rich in folate (DHSC, 2025). Therefore, increased consumption of parsnips could be suggested by dieticians and healthcare professionals to boost dietary folate intake, as part of a varied and balanced diet. Notably, consuming 125 g, or a single small parsnip, of microwaved parsnip daily would fulfil the average RNI for an adult in the UK (Figure 4-11). For infants under one year of age, only 31 grams of microwaved parsnip is needed to meet daily requirements (Figure 4-11). However, meeting the RNI for pregnant women through parsnip consumption alone would be difficult, even with enhanced folate levels from microwaving.

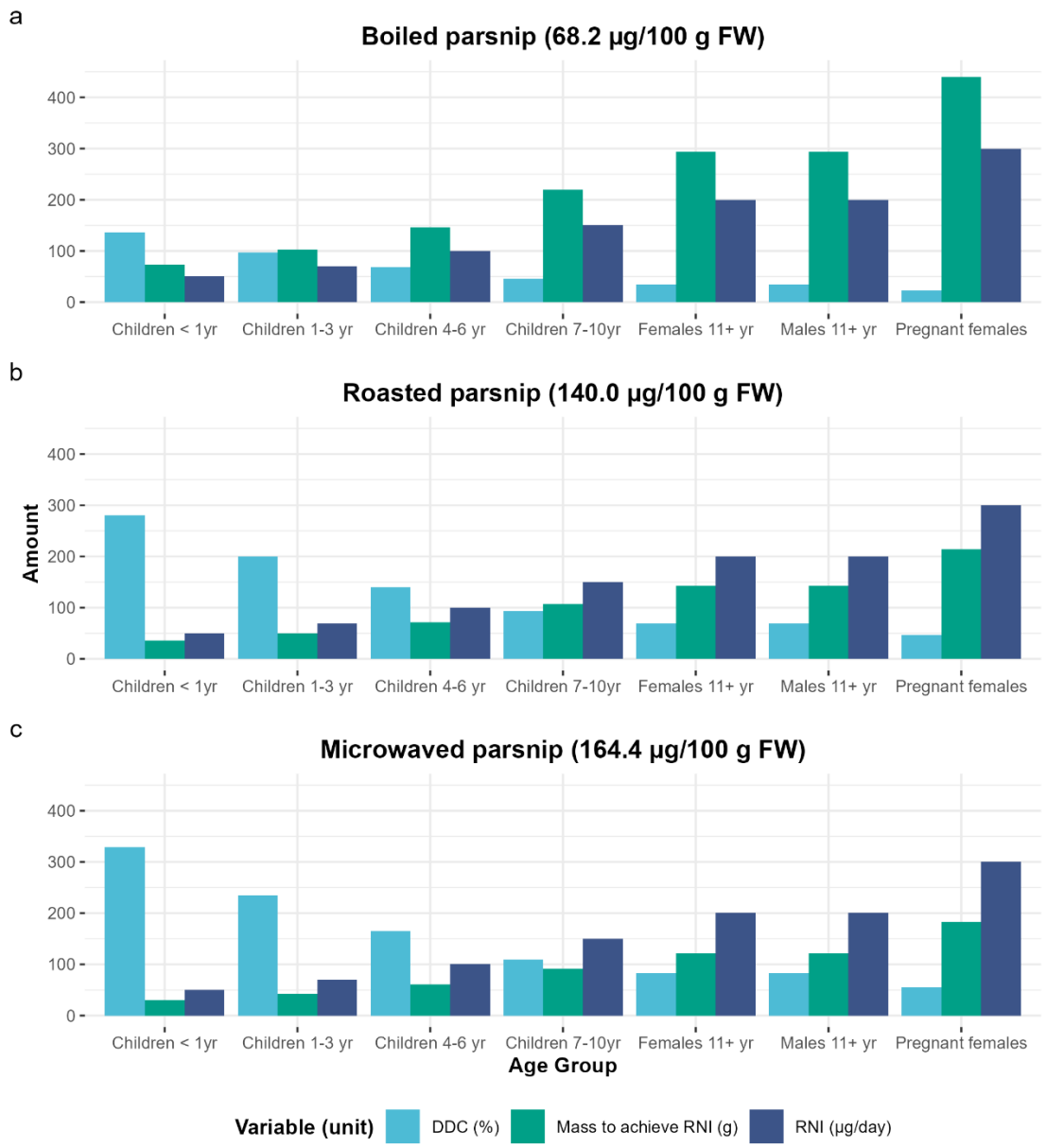


Figure 4-11 Bar chart showing the folate RNI, Daily Demand Coverage (DDC) of 100 g of boiled, roasted, or microwaved parsnips and amount of parsnip needed to be consumed to satisfy the RNI for different demographic groups RNI data source: (Public Health England, 2016). DDC metric adapted from (Ložnjak Švarc and Jakobsen, 2023)

4.4.3 Future directions

The findings of this chapter highlight how cooking modifies both the total quantity and vitamer profile of folate in parsnips, which may have implications for nutritional efficacy. However, questions regarding how digestion affects folate bioaccessibility in parsnips remain. For example, the enhanced folate content in microwaved samples may render them more susceptible to degradation under acidic digestive conditions, potentially offsetting observed benefits (Liu *et al.*, 2022). Future studies should incorporate digestion models, such as in vitro gut cell lines, to explore the bioaccessibility of folate in parsnips after storage and cooking.

This study focused on a subset of storage and cooking conditions relevant to the UK food system, but other practices, like frozen storage, blanching, steaming, and pressure cooking, may also affect folate stability. In particular, pre-prepared frozen parsnips are increasingly common in UK retailers, and offer year-round convenience. These parsnips are often blanched, sometimes fried, and otherwise treated before freezing, and are designed to be cooked directly from frozen by the consumer. It would be interesting to explore folate retention over long term frozen storage, as well as the combined effects of cooking and storage used for such pre-prepared items on folate content.

Finally, future works could develop a more detailed understanding of folate sensitivity to storage and cooking by exploring the effects observed in this study in greater resolution and scope. It was noted earlier in Chapter 4 that parsnips may be stored for up to 6 months in refrigerated conditions, which is far beyond the time period investigated in this study. Future works could be conducted over a longer period to determine whether there is greater folate loss with more extensive storage durations, as well as the dynamics of folate loss from tissue, should loss occur. For cooking, refining parameters within methods—such as temperature and duration—could provide insights into folate loss dynamics, helping to optimise cooking conditions for folate retention while preserving palatability.

4.5 Conclusions

This study demonstrates that folate content in parsnips is moderately sensitive to cooking and storage, but that much of the variation observed in stored and cooked parsnips was due to changes in dry matter, i.e. water content, rather than folate degradation. Microwaving emerged as the optimal method for folate retention and concentration, both in total content and bioactive vitamer levels, while boiling posed the greatest risk for folate loss. Storage had minimal effect on folate stability, indicating that parsnips can be stored short-term without significant nutritional losses. These findings offer evidence-based recommendations for food

preparation and storage practices to maximise the nutritional value of parsnips, with broader implications for root vegetable handling and folate nutrition.

Chapter 5 Investigating the provision of folate in school meals in Southampton and exploring the potential for improvements

5.1 Introduction

Folate (vitamin B9) is an essential micronutrient required for DNA synthesis, gene expression, cell division, and the formation and development of red blood cells (Lynn B. Bailey *et al.*, 2015; Bo *et al.*, 2022; Bjørke-Monsen and Ueland, 2023; Fallah *et al.*, 2025). Humans cannot synthesise folate *de novo*, and it must therefore be obtained through dietary sources (Bekaert *et al.*, 2008; Delchier *et al.*, 2016; Siatka *et al.*, 2025). Rich food sources of folate include liver, spinach, broccoli, strawberries, parsnips, and beetroots (Public Health England, 2021). For a more detailed overview of folate, see Chapter 1 Section 1.5.

In the UK, government-defined thresholds specify the recommended folate intake for different population groups (Table 5-1). The reference nutrient intake (RNI) is set at a level sufficient for 97.5% of individuals, while the lower reference nutrient intake (LRNI) represents the minimum required by approximately 2.5% of people with the lowest needs (Department of Health, 1991). These thresholds were originally established in 1991 and reviewed in 2017, with no revisions deemed necessary (Department of Health, 1991; Scientific Advisory Committee on Nutrition, 2017).

Table 5-1 Reference nutrient intake and lower reference nutrient intake values for folate

	1 – 3 years old	**4 –6 years old**	**7 – 10 years old**	**11 – 18 years old**	**>18 years old**	**Pregnant females**
RNI (µg/day)	70	100	150	200	200	300 (+ 400 FA supplement)
LRNI (µg/day)	35	50	75	100	100	200 (+ 400 FA supplement)

Data sources: (Department of Health, 1991; Public Health England, 2016; Gunter, 2020). RNI – reference nutrient intake. LRNI – lower reference nutrient intake. FA – Folic acid

As illustrated in Chapter 2, folate intakes in the UK are substantially below recommended levels. Up to 74% of the population were found to fall short of the RNI, with approximately 10% consuming less than the LRNI, aligning with government data and related studies (Gunter, 2020; Jones *et al.*, 2023). Adolescents (11–18-year-olds) had especially low folate intakes, with the

highest proportion of individuals falling below both thresholds (Chapter 2). Whilst the reasons for this marked inadequacy are not fully understood, one suggested factor is greater autonomy over food choices, combined with limited dietary management skills and a lower sense of personal health responsibility (Croll, Neumark-Sztainer and Story, 2001; Lupu *et al.*, 2025). At the same time, adolescence is a period of increased folate demand due to rapid growth, body mass increases, and metabolic changes associated with puberty (Croll, Neumark-Sztainer and Story, 2001; Lynn B Bailey *et al.*, 2015, 2015; Bailey *et al.*, 2017; Jones *et al.*, 2023). The combination of higher requirements and lower intake is concerning, particularly given the long-term health implications of poor adolescent nutrition (Croll, Neumark-Sztainer and Story, 2001; Kim and Lim, 2019; Sinai *et al.*, 2021).

One strategy to improve folate intake is through public health campaigns promoting dietary change and encouraging greater consumption of folate-rich foods (Chapter 1 Section 1.7.4) (Lehner, Mont and Heiskanen, 2016; Flynn *et al.*, 2025). However, as adolescents gain independence over their diets they become harder to reach through such interventions (Croll, Neumark-Sztainer and Story, 2001; Stevenson *et al.*, 2007; Nepper and Chai, 2016; Neufeld *et al.*, 2022). In contrast, dietary habits formed in early childhood are more malleable, and may persist into adolescence and adulthood (Mikkilä *et al.*, 2007; Craigie *et al.*, 2011; Simmonds *et al.*, 2016; Kim and Lim, 2019; McIntyre *et al.*, 2022). Therefore, supporting adequate folate nutrition in younger children, who are more accessible to interventions, may improve both immediate intake and long-term dietary quality.

In the UK, widespread school meal programmes offer a practical means for improving the nutrition of children (Crawley, 2005; Micha *et al.*, 2018). As of 2005, 45% of children in the UK accessed school meals (Crawley, 2005). Whilst there have been no more recent assessments of overall school meal uptake, data from 2025 indicate that 25.7% of children in England are eligible for free school meals, with this set to expand to all children of parents on Universal Credit by September 2026 (Department for Education, 2025c, 2025a). Additionally, all children in Reception, Year 1, and Year 2 are entitled to free school meals irrespective of household income (Education and Skills Funding Agency and Department for Education, 2025). These programmes therefore provide valuable opportunities to improve the nutritional status of children and young people in England and the UK (Micha *et al.*, 2018; Rose *et al.*, 2019).

Across the UK, the School Food Standards are a set of regulations “designed to help children develop healthy eating habits, and ensure that they have the energy and nutrition they need to get the most from their whole school day” (Department for Education, 2025b). First introduced in 1940, the School Food Standards have since undergone multiple revisions, including a complete repeal in 1980 and subsequent independent reintroduction across England, Wales,

Scotland and Northern Ireland. The pace and scope of implementation have varied across the four nations, reflecting differences in political priorities and public health approaches (Adamson *et al.*, 2013; Woodside *et al.*, 2021; McIntyre *et al.*, 2022). The current English standards emphasise a positive eating environment, sustainability, and food-based guidance on portion sizes and frequency of food groups (Department for Education, 2025b). They also offer advice for increasing intake of key micronutrients like iron, zinc, and calcium through the diet (Department for Education, 2025b). However, they stop short of specifying measurable targets and omit several essential micronutrients from guidance, including folate.

This omission is particularly notable when contrasted with Wales and Scotland, where school food standards set explicit minimum levels for iron, zinc, calcium, vitamin A, vitamin C, and folate (Welsh Government, 2014; Scottish Government, 2021). The contrast reveals a policy divergence within the UK: while some nations adopt nutrient-based safeguards, England relies solely on food-based guidelines, leaving the adequacy of folate provision unmonitored.

Attempts to evaluate the nutritional impact of school food provision in the UK have been limited and inconsistent (McIntyre *et al.*, 2022), hampered by weak compliance monitoring and a lack of robust data (Spence *et al.*, 2013, 2014; McIntyre *et al.*, 2022). Importantly, no research has compared nutrient- versus food-based standards across the UK nations, and no study has directly assessed the micronutrient composition of school meals. As a result, there are no available data on the folate content of school meal programmes, and it remains unclear whether school meals provide adequate folate for children and adolescents in England and the UK.

This chapter seeks to address this evidence gap by evaluating the contribution of school meals to folate requirements among primary school-aged children in Southampton, UK. Through detailed recipe-level analysis of school menus and a focused investigation of parsnip as a folate-rich ingredient, the study identifies both strengths and limitations of current provision. By doing so, it not only assesses present adequacy but also highlights opportunities for reform, positioning school meals as a potential lever to improve folate nutrition in childhood and beyond.

5.1.1 Chapter aims

The hypothesis of Chapter 5 is that the folate content of school meals varies between the menu items available, and this in turn impacts the amount of folate provided over the school day and week. This chapter aims to assess the folate content of school meals and determine how well they meet the nutritional needs of primary school-aged children in Southampton, Hampshire, UK. Specifically, the objectives are to:

1. Quantify the folate content of school meals in Southampton and compare provision against UK reference nutrient intake (RNI) and lower reference nutrient intake (LRNI) thresholds.
2. Evaluate the impact of children's dietary choices within the framework of school meal menus on overall folate provision.
3. Identify opportunities for improvement by examining how adjustments to menu composition could enhance folate intake in school settings.
4. Investigate the potential of parsnip as a folate-rich ingredient, by reformulating an example school meal (Bangers and Mash).

5.2 Materials and methods

5.2.1 Data sources and wrangling

5.2.1.1 School meal menus and recipe data

School meal menus are often published on school meal provider websites. However, to meet the aims of this chapter, more detailed information on ingredients and recipes was required - data not typically available online. A major school meal provider (SMP) in Southampton, UK, were therefore contacted with a project outline and invited to contribute by providing access to their recipes and menus. Following an initial consultation to define the roles and expectations of both parties, the SMP agreed to provide full access to their recipe management and procurement software. In return, research findings would be shared.

The collaboration began in July 2023, when the SMP provided access to their Summer 2023 three-week rotating menu. Corresponding recipes were retrieved from the recipe management and procurement software by matching recipe names to menu items, with year identifiers used to ensure the most up-to-date versions were included. The menus were transcribed into Microsoft Excel, with the week and date of service for each item recorded (Table 5-2).

Table 5-2 Three-week rotating menu of school meals provided by the SMP in Summer 2023

	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**
Week 1					
Main 1	Pork sausages	Roast pepper and chicken wrap	Vegan sausage roll	Roast beef	Fish fingers
Main 2	Vegetarian Bolognese	Pizza	Tomato pasta	Quorn nuggets	Omelette muffin
Main 3	Jacket potato with either cheese, tuna, or baked beans	Jacket potato with either cheese, tuna, or baked beans	Jacket potato with either cheese, tuna, or baked beans	Jacket potato with either cheese, tuna, or baked beans	Jacket potato with either cheese, tuna, or baked beans
Carb side 1	Mashed potato	Mini potato bites	Potato crispers	Roast potatoes	Chips
Carb side 2	Pasta	-	-	-	-
Veg side 1	Seasonal vegetables	Seasonal vegetables	Seasonal vegetables	Seasonal vegetables	Seasonal vegetables
Veg side 2	Seasonal salad	Seasonal salad	Seasonal salad	Seasonal salad	Seasonal salad
Dessert 1	Ice cream	Fruit wedges with mini flapjack	Iced apricot loaf	Melting moment cookie	Fruit brownie
Dessert 2	Seasonal fruit and yoghurt	Seasonal fruit and yoghurt	Seasonal fruit and yoghurt	Seasonal fruit and yoghurt	Seasonal fruit and yoghurt
Week 2					
Main 1	Turkey meatball pasta	Chicken curry	Mac cheese	Roast chicken and stuffing	Battered fish
Main 2	Quorn burger	Pizza	Nacho bean bites	Vegetarian sausage turnover	Tomato pasta
Main 3	Jacket potato with either cheese, tuna, or baked beans	Jacket potato with either cheese, tuna, or baked beans	Jacket potato with either cheese, tuna, or baked beans	Jacket potato with either cheese, tuna, or baked beans	Jacket potato with either cheese, tuna, or baked beans

Carb side 1	Mashed potato	Mini potato bites	Potato crispers	Roast potatoes	Chips
Carb side 2	-	Rice	-	-	-
Veg side 1	Seasonal vegetables	Seasonal vegetables	Seasonal vegetables	Seasonal vegetables	Seasonal vegetables
Veg side 2	Seasonal salad	Seasonal salad	Seasonal salad	Seasonal salad	Seasonal salad
Dessert 1	Ice cream	Chocolate oat slice	Banana muffin	Shortbread	Pineapple cake
Dessert 2	Seasonal fruit and yoghurt	Seasonal fruit and yoghurt	Seasonal fruit and yoghurt	Seasonal fruit and yoghurt	Seasonal fruit and yoghurt
Week 3					
Main 1	Chicken nuggets	Beef chilli potato wedges	Vegetable curry	Roast pork	Salmon fishcake
Main 2	Chickpea and vegetable burger	Pizza	Vegetarian sausage	Sweet potato parcel	Rainbow pizza
Main 3	Jacket potato with either cheese, tuna, or baked beans	Jacket potato with either cheese, tuna, or baked beans	Jacket potato with either cheese, tuna, or baked beans	Jacket potato with either cheese, tuna, or baked beans	Jacket potato with either cheese, tuna, or baked beans
Carb side 1	Potato crispers	Mini potato bites	Mashed potato	Roast potatoes	Chips
Carb side 2	-	-	Rice	-	-
Veg side 1	Seasonal vegetables	Seasonal vegetables	Seasonal vegetables	Seasonal vegetables	Seasonal vegetables
Veg side 2	Seasonal salad	Seasonal salad	Seasonal salad	Seasonal salad	Seasonal salad
Dessert 1	Honey cookie	Fruit wedges with mini shortbread	Orange drizzle cake	Fruit sundae	Iced cookie
Dessert 2	Seasonal fruit and yoghurt	Seasonal fruit and yoghurt	Seasonal fruit and yoghurt	Seasonal fruit and yoghurt	Seasonal fruit and yoghurt

Menu adapted from the SMP Summer 2023 menu. Abbreviations: Main – main course; Carb side – carbohydrate side option; Veg side – vegetable side option; Dessert – dessert course. Text coloured in red indicates items no longer supported by the wholesaler for the SMP, for which no recipes could be sourced.

Two menu items, ‘turkey meatball pasta’ and ‘nacho bean bites’, were no longer available through the SMP’s wholesaler, and their recipes could not be retrieved within the analysis timeframe. These items were therefore excluded from analysis. The remaining menu items were categorised into four groups based on the original menu: “main”, “carbohydrate side (carb side)”, “vegetable side (veg side)”, and “dessert” (Table 5-2). This classification allowed systematic evaluation of different combinations of menu components over the school day.

Recipes were downloaded in PDF format from the recipe management and procurement software. Relevant data were extracted, including ingredient quantities, number of servings, expected portion weight in grams, and any preparation instructions. Ingredient quantities were standardised to single-portion values and entered into an Excel spreadsheet.

For pre-processed or composite ingredients, sub-recipes were retrieved from the recipe management and procurement software and substituted into each recipe. Portion weights were tracked throughout to ensure consistency in ingredient matching. Ingredients were then matched to the daily menus, linking each menu item with its ingredients. The final dataset was exported as a .csv file for analysis in RStudio (version 2025.05.1+513) (Posit team, 2025).

5.2.1.2 Food composition data

Nutrient data were sourced from the publicly available Composition of Foods Integrated Dataset (CoFID) (Public Health England, 2021). The data sheet relevant to vitamin contents of food was extracted from the multi-sheet Excel file and converted to a .csv file for analysis in RStudio.

Each ingredient from the school meal dataset was manually matched to a corresponding CoFID item by name. If a recipe listed an ingredient in its raw form but it would be consumed cooked, the cooked version was selected from CoFID where available. Where cooking was known to significantly alter the weight of an ingredient, a conversion factor was applied to the quantity of the ingredient in the final dataset (Appendix B). For example, a recipe requiring 45 g of raw fusilli pasta was matched to 100 g of “Pasta, white, twists, fusilli, dried, boiled in unsalted water” (CoFID code 11-720). In some cases, unit conversions were also required to match recipe items to listings in the CoFID dataset. For example, ice cream is typically measured and sold in ml, whilst CoFID reports nutritional content per 100 g. Therefore, the density of ice cream was used to convert ml to grams for analysis, using an online conversion tool (Appendix B). Finally, where oil was used in preparation methods (e.g., roasting), and not expected to be entirely retained in the final product, oil quantities were adjusted or excluded. For example, roast potatoes listed as ‘potatoes, old, roasted in rapeseed oil’ in CoFID already include oil content; thus, oil was not counted separately for this item. For a full list of conversions made, see Appendix B.

To protect the SMP's proprietary recipe information, ingredients were aggregated into food groups before analysis. These were adapted from the Eatwell Guide (Office for Health Improvement and Disparities, 2024) but tailored to ingredient-level categorisation. Seven food groups were defined: "fruit and vegetables (fruit and veg)", "herbs and spices", "potatoes, bread, rice, pasta, and other starchy carbohydrates (carbohydrate sources)", "beans, pulses, fish, eggs, meat, and other proteins (protein sources)", "dairy and alternatives (dairy)", "oils, spreads, and sugar", or "other". After cleaning and checking for inconsistencies, this dataset was merged with the menu data to produce vitamin composition by recipe. The dataset was then filtered to retain only folate values and imported into RStudio for further wrangling and analysis.

5.2.1.3 UK Dietary Recommendations

Folate RNI and LRNI data were obtained from Public Health England (2016) and the Department of Health (1991), respectively. To derive benchmarks for primary school-aged children, an average RNI and LRNI were calculated across ages 4–11 years. The resulting thresholds were 137.5 µg/day for the RNI and 68.8 µg/day for the LRNI.

5.2.2 Data analysis

The folate content of each menu item was calculated as the sum of the folate provided by each food group, expressed per portion:

$$F_{item} = \sum\left(\left(\frac{c_i}{100}\right) \cdot \ q_i\right)$$

Where i is the ingredient in the menu item; c_i is the folate concentration of the ingredient (µg/100 g) and q_i is the mass of the ingredient (g per portion).

A combination of one main, one carb side, one veg side, and one dessert is collectively referred to as a 'dinner'. The folate content of each possible dinner was calculated by summing the folate content of its components:

$$F_{dinner} = \sum F_{item}, m \quad for\ m \in \{main, carb\ side, veg\ side, dessert\}$$

Only menu items that were available on the same day were combined into a dinner, except in the optimisation analysis, where combinations across any day were permitted. Consultation with the SMP identified the following further constraints on allowable dinner combinations:

1. If a jacket potato is chosen as a main, no carbohydrate side option is selected.
2. If "curry" is chosen as a main, "rice" must be the carbohydrate side, and vice versa.
3. If "pasta" is chosen as the main, no carbohydrate side option is selected.

4. If no carbohydrate side is chosen, the main must include either “potato” or “pasta”.

For each day, the mean folate content was calculated across all allowable dinner combinations, along with minimum and maximum values. Results are reported as mean ± standard deviation. Additionally, the proportion of dinners that fell below the LRNI and RNI thresholds was recorded.

To evaluate weekly provision, the three-week menu was split into weekly intervals. The total folate content of every combination of dinners over a week was calculated and divided by five to yield a “daily folate equivalent” (µg/day) for each weekly dinner pattern:

$$DFE_{week} = \left(\frac{1}{5}\right) \cdot \sum_{d \in \{Mon,Tue,Wed,Thu,Fri\}} F_{dinner}$$

Two dietary patterns were defined for this analysis, ‘vegetarian’, where no menu items chosen across the sampling period contained meat, and ‘meat eater’, where at least one meat-containing item was selected. All dinner combinations across a week were classified into one of these patterns. A two-way ANOVA, with dietary pattern and week as fixed effects, was used to compare the daily folate equivalents. Where significant relationships were identified ($p < 0.05$), Tukey’s HSD post hoc tests were used for pairwise comparisons between groups.

All data wrangling, data visualisation and statistical analysis were conducted in R (R Core Team, 2024) via RStudio (version 2025.05.1+513) (Posit team, 2025), using the following packages: tidyverse (version 2.0.0) (Wickham *et al.*, 2019), ggplot2 (version 3.5.1) (Wickham, 2016), rstatix (version 0.7.2) (Kassambara, 2023b), ggstatsplot (version 0.13.0) (Patil, 2021), cowplot (version 1.1.3) (Wilke, 2024) and patchwork (version 1.3.0) (Pedersen, 2024).

5.2.3 Case study: Bangers and Mash

Bangers and Mash, a colloquial name for a meal consisting of sausage, mashed potato, and vegetables, is included in the SMP’s Summer 2023 menu (Table 5-2, Monday week 1). However, the quantities of ingredients used to produce this dinner remain the proprietary information of the SMP. Therefore, a new recipe was generated using School Food Standards portion guidance (Department for Education, 2025b) and open-access recipes (Table 5-3).

Table 5-3 Example recipe for one portion of Bangers and Mash

Ingredient	CoFID Food Code	Quantity (g)
Pork sausages	19-654	84 (1 unit)
Broccoli	13-583	60
Boiled potato	13-605	120
Margarine	12-500	1.5

To contextualise nutritional analysis within the wider food system, retail prices of ingredients were obtained from Sainsbury's (Table 5-4). While retail prices differ from wholesale prices used by school providers, they provide a benchmark for assessing the cost implications of substituting potatoes with parsnips. The prices per kg were used to calculate an overall price per portion for each recipe formulation.

Table 5-4 Prices of ingredients used to make Bangers and Mash

Ingredient	Sainsbury's product	Price per kg
Pork Sausages	Sainsbury's Butcher's choice British Pork Sausage x 8 454 g	£3.94
Broccoli	Sainsbury's Broccoli Loose	£2.30
Potato	Sainsbury's White Potatoes 2 kg	£0.68
Margarine	Clover Spread Alternative to Butter 1 kg	£4.30
Parsnip	Sainsbury's Parsnips Loose	£1.48

All prices sourced from Sainsburys.co.uk, correct as of 23rd August 2025

Traditionally, Bangers and Mash does not contain parsnip. However, boiled potatoes used in mash can be partly or fully replaced with parsnips on a 1:1 weight basis, with only minor preparation adjustments. Substitution at 50% or 100% parsnip by weight was therefore investigated to evaluate the impact on folate content. The possibility of using microwaved parsnip to make the mash was also explored. To account for mass loss during microwaving, as shown in Chapter 4, the mass of parsnip in the recipe was multiplied by a factor of 1.4.

The folate content values for parsnip used in this case study are shown in Table 5-5. In CoFID, the folate content of boiled parsnip (Food code 13-631) is listed at 49 µg/100 g (Public Health England, 2021). However, Chapter 4 found no difference in the folate content per 100 g of boiled parsnips compared to raw. Therefore, the CoFID listing was compared directly to the mean (77.4 µg/100 g), maximum (83.1 µg/100 g, variety 710), and minimum (72.0 µg/100 g, variety 318) folate content of varieties from the variety trial in Chapter 3. Additionally, Chapter 4 showed that microwaving increased folate concentration in parsnips 1.98-fold. Using the average folate

content from Chapter 3, microwaved parsnip was estimated to contain approximately 152.0 µg folate/100 g cooked weight.

Table 5-5 Measures of parsnip folate content used in reformulated Bangers and Mash

Recipe name	Mash formulation	Parsnip folate content (µg/100 g)	Source of parsnip folate content value
Original	100% potato mash	-	-
50% parsnip mash - CoFID	50% potato and 50% parsnip mash	49.0	(Public Health England, 2021)
100% parsnip mash – CoFID	100% parsnip mash	49.0	(Public Health England, 2021)
100% parsnip mash – Avg Ch3	100% parsnip mash	77.4	Chapter 3
100% parsnip mash – Max Ch3	100% parsnip mash	83.1	Chapter 3
100% parsnip mash – Min Ch3	100% parsnip mash	72.0	Chapter 3
100% parsnip mash – Microwaved Avg Ch3	100% parsnip mash from microwaved parsnip	152.0	Chapter 3 and Chapter 4

5.3 Results

5.3.1 Menu items

Over the 3-week sampling period, there were 52 menu items on offer: 28 mains, 7 carb sides, 2 veg sides, and 15 desserts (Figure 5-1). Folate content varied widely both within and across categories. Among mains, folate content ranged from 2.0 µg/portion (Roast pork) to 92.9 µg/portion (Vegetarian Bolognese) (Figure 5-1). For veg sides, the two options of seasonal salad and seasonal vegetables contained 10.5 and 31.2 µg folate/portion, respectively (Figure 5-1). The folate content of carbohydrate sides ranged from 5 µg/portion (Pasta) to 27.0 µg/portion (Chips), whilst the folate content of desserts ranged from 2.0 µg/portion (Ice cream) to 35.0 µg/portion (Iced apricot loaf) (Figure 5-1).

There was no clear trend in which food groups were key contributors to folate content across all menu items (Figure 5-1). Amongst mains, protein sources contributed over 50% of the total folate in 14 of the 28 main options, including Vegetarian Bolognese and Jacket Potato with Baked Beans—two of the three highest folate mains (Figure 5-1). For Quorn burger, the second-highest folate main, 63% of folate came from the ‘other’ food group (Figure 5-1). Veg sides consisted entirely of the ‘fruit and veg’ food group, whilst carbohydrate sides were derived exclusively from ‘carbohydrate sources’ (Figure 5-1). In the dessert category, iced apricot loaf,

ranked highest in folate, derived 89% of its folate from the 'other' food group (Figure 5-1). Protein sources made notable contributions to folate in the banana muffin, orange drizzle cake, and fruit brownie, all of which ranked in the top 6 desserts for folate content (Figure 5-1). Fruit and veg contributed to the folate content of all of the desserts in the top 7 of 15 desserts for folate content (Figure 5-1).

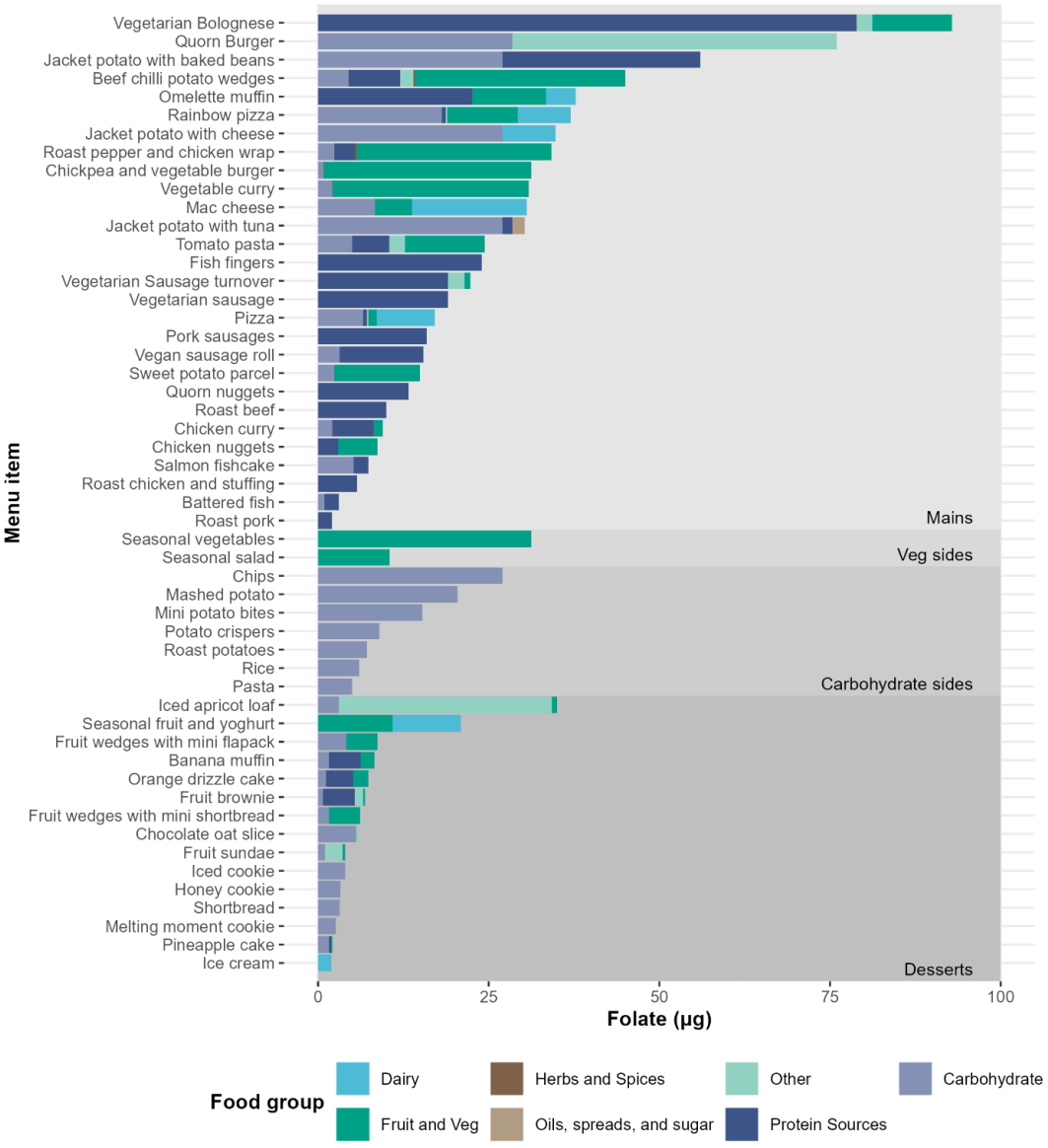


Figure 5-1 Stacked bar chart showing the contributions of ingredients by food group to the total folate content of menu items.

5.3.2 Menu item combinations across a day

There were 286 possible dinners across the 3-week period (Figure 5-2). On most days, 20 different dinners were possible (Figure 5-2). More choice was observed on Monday – 1, which had 28 possible dinners (Figure 5-2). By contrast, Monday – 2, Wednesday – 1, Wednesday – 2, and Thursday – 2, had 16 possible dinners, and Thursday – 1 had 10 possible dinners (Figure 5-2). The mean folate provided on a day ranged from 62.4 ± 21.8 µg/dinner (Thursday – 3) to 88.0

± 36.8 µg/dinner (Monday – 1) (Figure 5-2). Five of the 286 possible dinners provided an amount of folate that exceeded the RNI, 122 dinners provided less folate than the LRNI, and 159 dinners provided an amount of folate that was between these two thresholds (Figure 5-2).

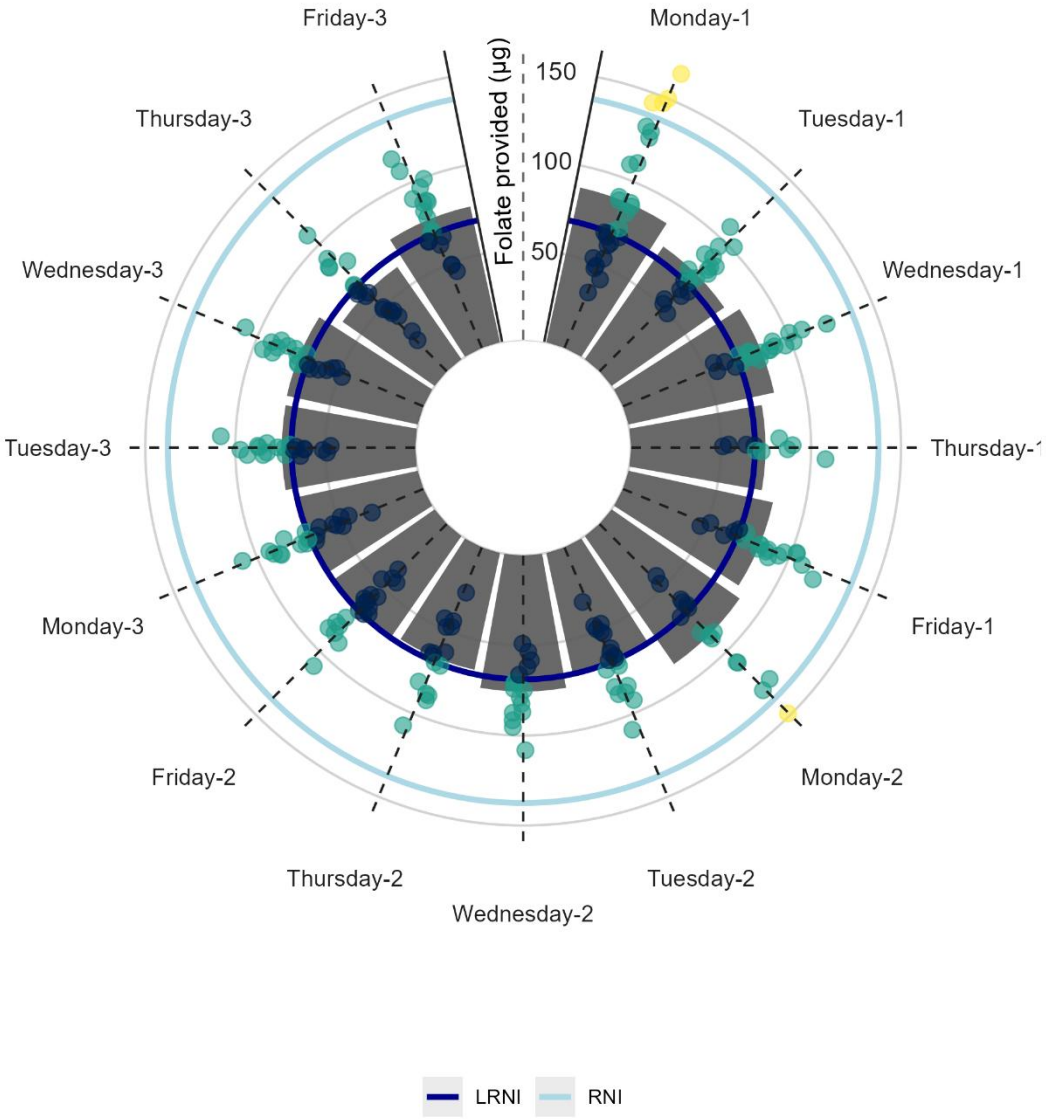


Figure 5-2 Radar plot showing the total folate provided by school dinners on each day over a three-week sampling period. Dark blue line – Lower reference nutrient intake (LRNI) of a 4–11-year-old child. Light blue line – Reference nutrient intake (RNI) of a 4–11-year-old child. Grey bars show the mean folate provided on a given day. Each point represents the total folate provided by a particular combination of a main, veg side, carbohydrate side, and dessert, a dinner. Points are colour coded; yellow points – total folate exceeds RNI threshold; green points – total folate is between LRNI and RNI thresholds; navy blue points – total folate is less than LRNI threshold.

All of the top five folate content dinners provided more folate than the RNI, and in each case the main alone provided enough folate to surpass the LRNI (Figure 5-3). All top five dinners were vegetarian (Figure 5-3). By contrast, four of the five bottom folate content dinners were meat-based, with the two lowest being roast dinners (Figure 5-3). Four of the top five folate content options had mashed potatoes as the carbohydrate side, four of five options had seasonal vegetables as the veg side, and four of five options had seasonal fruit and yoghurt as the dessert option (Figure 5-3). All the bottom five folate content combinations had seasonal salad as their veg side, but the carbohydrate option and dessert option were more varied in the bottom five compared to the top five folate content dinners (Figure 5-3).

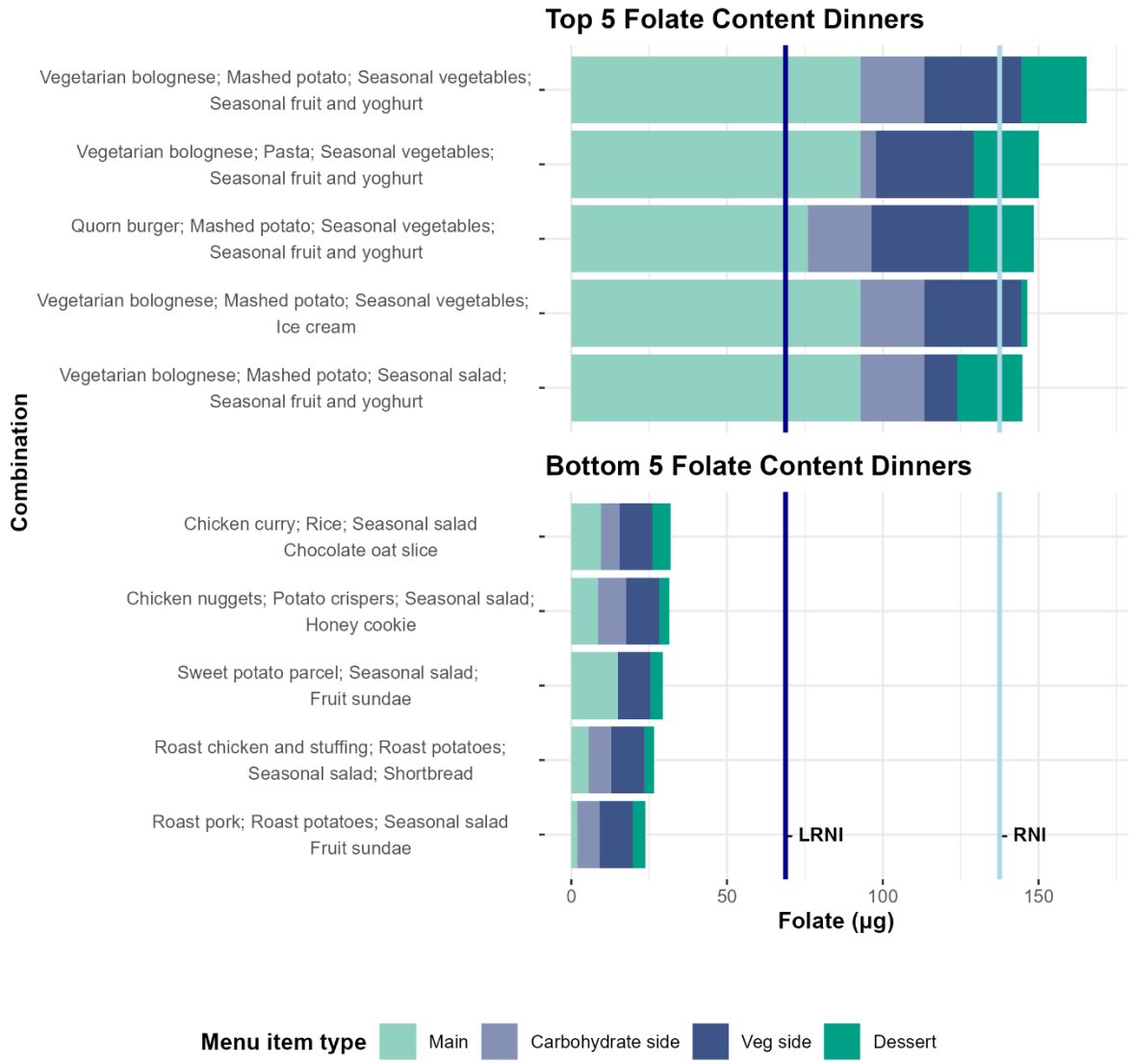


Figure 5-3 Stacked bar chart showing the contributions of the main, veg side, carbohydrate side, and dessert to total folate content of the top and bottom five dinners for folate provision across the sampling period. Dark blue line – Lower reference nutrient intake (LRNI) of a 4–11-year-old child. Light blue line – Reference nutrient intake (RNI) of a 4–11-year-old child.

5.3.3 Optimised menu item combinations

When restrictions on day-specific availability were removed, the maximum folate per dinner rose to 186.1 µg/dinner, achieved by combining Vegetarian Bolognese, Chips, Seasonal vegetables and Iced apricot loaf. The lowest-folate combination under this scenario was Roast pork with Pasta, Seasonal salad, and Ice cream, providing 15.5 µg/dinner.

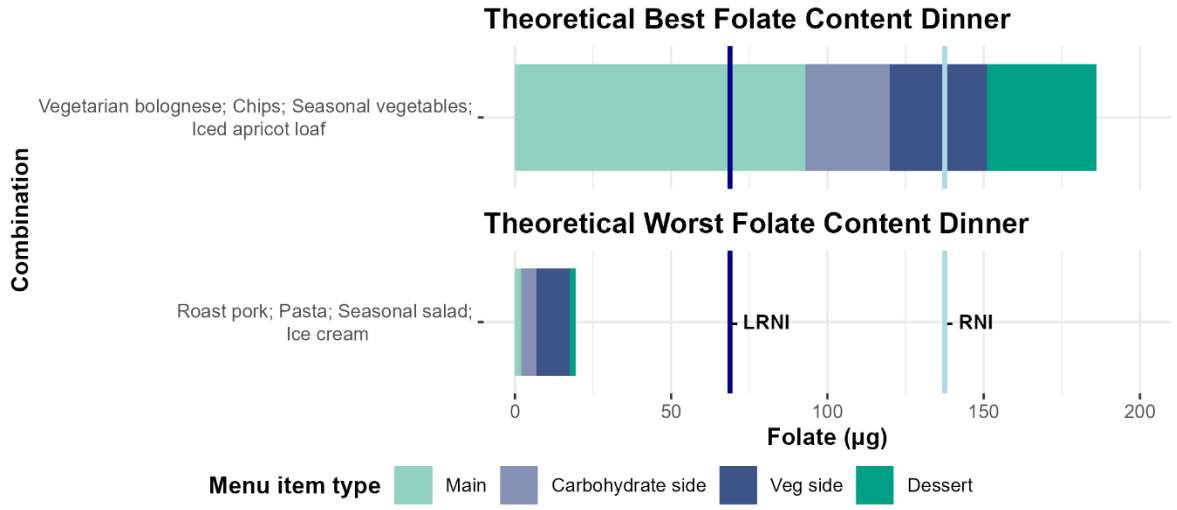


Figure 5-4 Stacked bar chart of the dinners that would provide the most and least folate if there were no constraints on which days different menu items were available. Dark blue line – Lower reference nutrient intake (LRNI) of a 4–11-year-old child. Light blue line – Reference nutrient intake (RNI) of a 4–11-year-old child.

5.3.4 Dinner combinations across a week sampling period

The number of possible weekly dinner combinations was very large: 2.24 million in week 1, 1.64 million in week 2, and 3.20 million in week 3 (Figure 5-5). Mean daily folate equivalents were 80.8 ± 9.9 µg/day in week 1, 72.9 ± 9.4 µg folate/day in week 2, and 71.4 ± 8.10 µg folate/day in week 3 (Figure 5-5). The maximum daily folate equivalent was 124.4 µg/day, 116.2 µg/day and 109.8 µg/day for weeks 1, 2, and 3, respectively. The minimum daily folate equivalents were 47.5 µg/day, 37.4 µg/day, and 39.0 µg/day, for weeks 1, 2, and 3, respectively (Figure 5-5). No weekly combinations of dinners resulted in a daily folate equivalent exceeding the RNI (Figure 5-5). In week 1, 89.2% of combinations exceeded the LRNI, in week 2, 65.2% of combinations exceeded the LRNI, in week 3, 61.8% of combinations had a daily folate equivalent that exceeded the LRNI (Figure 5-5).

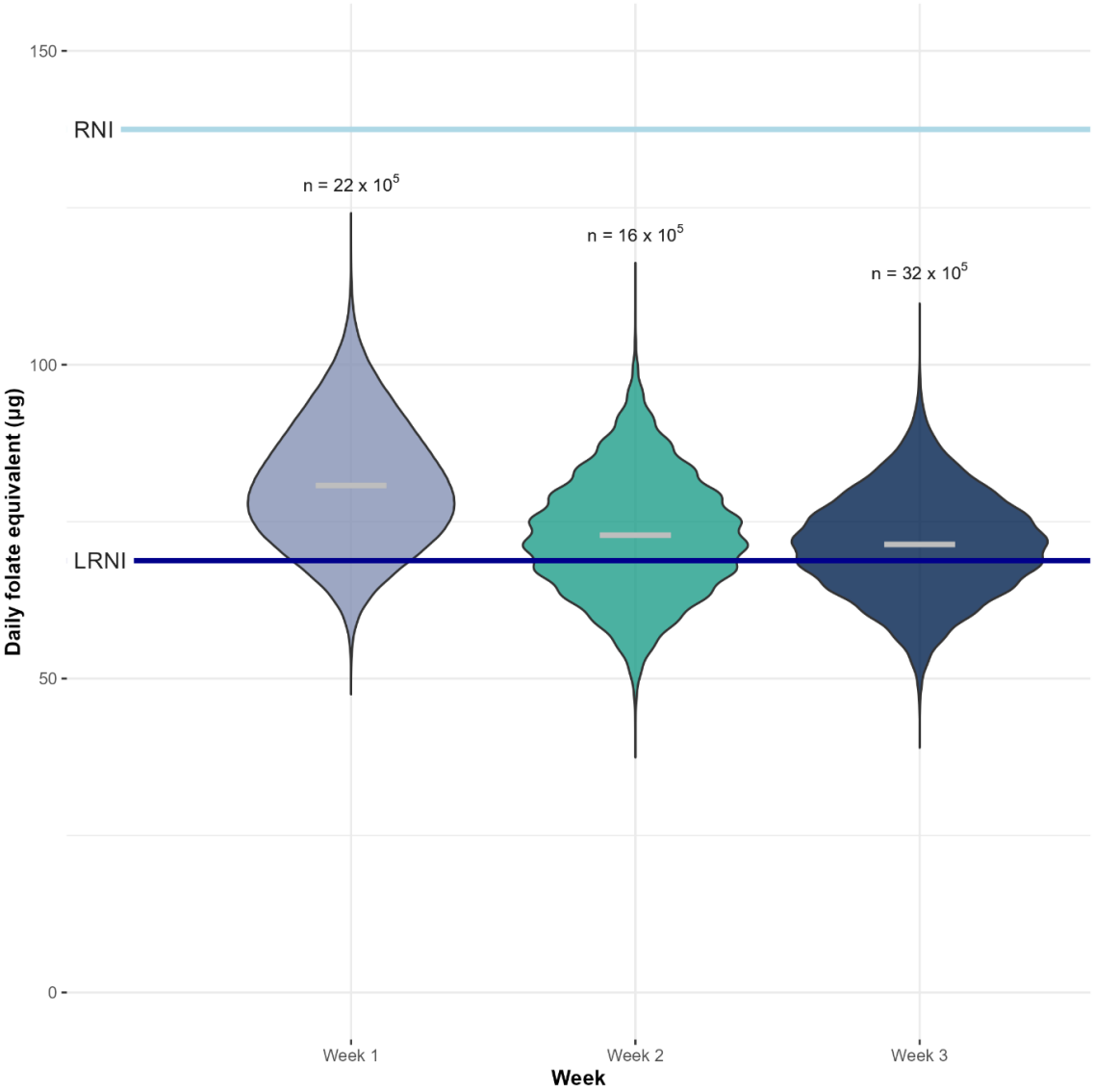


Figure 5-5 Violin plot of the daily folate equivalents provided by combinations of dinners across each sampling week. Dark blue line – Lower reference nutrient intake (LRNI) of a 4–11-year-old child. Light blue line – Reference nutrient intake (RNI) of a 4–11-year-old child.

5.3.5 Impact of dietary pattern across each week in the sampling period

Across all three weeks, vegetarian school dinner combinations provided higher mean daily folate equivalents than meat-containing combinations (Figure 5-6). In week 1, the mean daily folate equivalent was 83.0 ± 10.0 µg/day for vegetarian options compared with 79.5 ± 10.0 µg/day for meat-containing options (Figure 5-6). In week 2, the values were 75.4 ± 9.2 µg/day and 70.5 ± 9.2 µg/day, respectively, while in week 3 they were 73.5 ± 7.9 µg/day and 69.9 ± 7.9 µg/day, respectively (Figure 5-6).

The proportion of combinations exceeding the LRNI also differed between dietary patterns (Figure 5-6). In week 1, 92.6% of vegetarian combinations exceeded the LRNI compared with

87.2% of meat-containing combinations (Figure 5-6). In week 2, 75.6% of vegetarian combinations exceeded the LRNI compared with 55.7% of meat-containing combinations, while in week 3 the proportions were 71.8% and 54.9%, respectively (Figure 5-6).

Statistical analysis confirmed significant main effects of both week ($F(2, 7{,}078{,}394) = 837{,}995.4$, $p < 0.0001$) and dietary pattern ($F(1, 7{,}078{,}394) = 331{,}920.2$, $p < 0.0001$) on daily folate equivalents. A significant interaction between week and dietary pattern was also observed ($F(2, 7{,}078{,}394) = 3{,}485.1$, $p < 0.0001$). Post hoc Tukey HSD testing indicated statistically significant differences between all pairwise comparisons of week and dietary pattern ($p < 0.0001$).

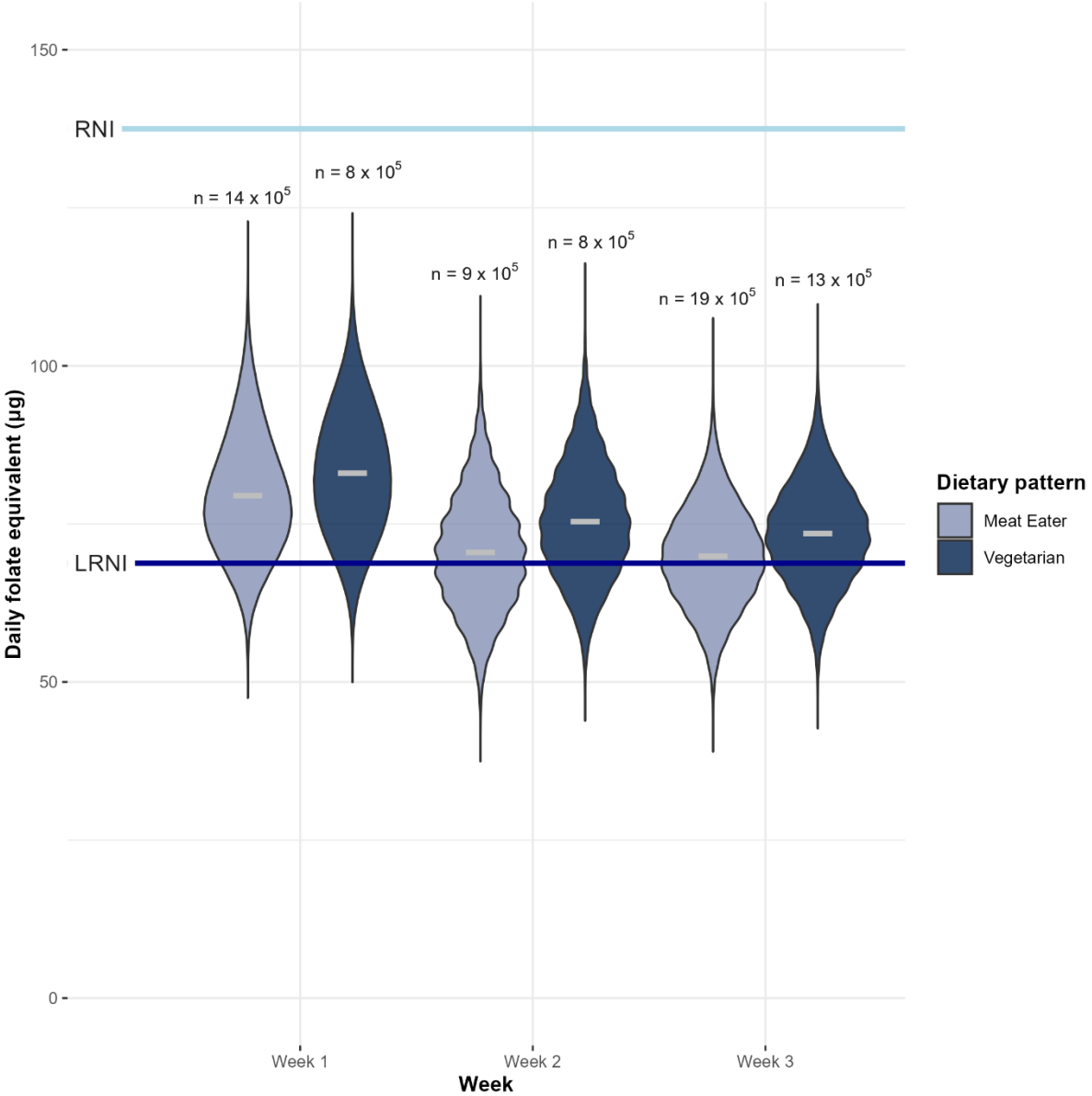


Figure 5-6 Paired violin plot of the daily folate equivalent provided by combinations of school dinners suitable for vegetarian compared to meat eater dietary patterns. Dark blue line – Lower reference nutrient intake (LRNI) of a 4–11-year-old child. Light blue line – Reference nutrient intake (RNI) of a 4–11-year-old child.

5.3.6 Case study: Bangers and Mash

All ingredients in Bangers and Mash contributed to overall folate provision, apart from the 'Baking fat or margarine' (Figure 5-7).

Using the folate content of boiled parsnips listed in CoFID (Public Health England, 2021), substituting the potato mash with 50% or 100% parsnip would increase the folate provided above the LRNI (68.5 µg/day), to 76.6 µg/portion and 95.2 µg/portion, respectively, with a cost increase of 8.9% and 16.1%, respectively (Figure 5-7). This equates to a portion providing 42% of the RNI, 56% of the RNI (50% Parsnip Mash), or 69% of the RNI (100% Parsnip Mash) (Figure 5-7).

Using mean parsnip folate values from Chapter 3, 100% parsnip mash increased the amount of folate provided to 129.2 µg/portion, or 94% of the RNI (Figure 5-7). Substituting potato with the highest and lowest folate containing varieties from Chapter 3 to make the parsnip mash would increase the folate provided to 136.1 µg/portion, 99% of the RNI, or decrease the folate provided to 122.8 µg/portion, 89.3% of the RNI, respectively (Figure 5-7).

Using microwaved parsnip to make the mash would increase the amount of folate provided in the adjusted Bangers and Mash to 218.8 µg/portion, equivalent to 159% of the RNI threshold (Figure 5-7). However, the greater quantity of parsnip needed to produce the mash from microwaved parsnip increased the cost of the dinner by £0.16 (29%) compared to the original recipe (Figure 5-7).

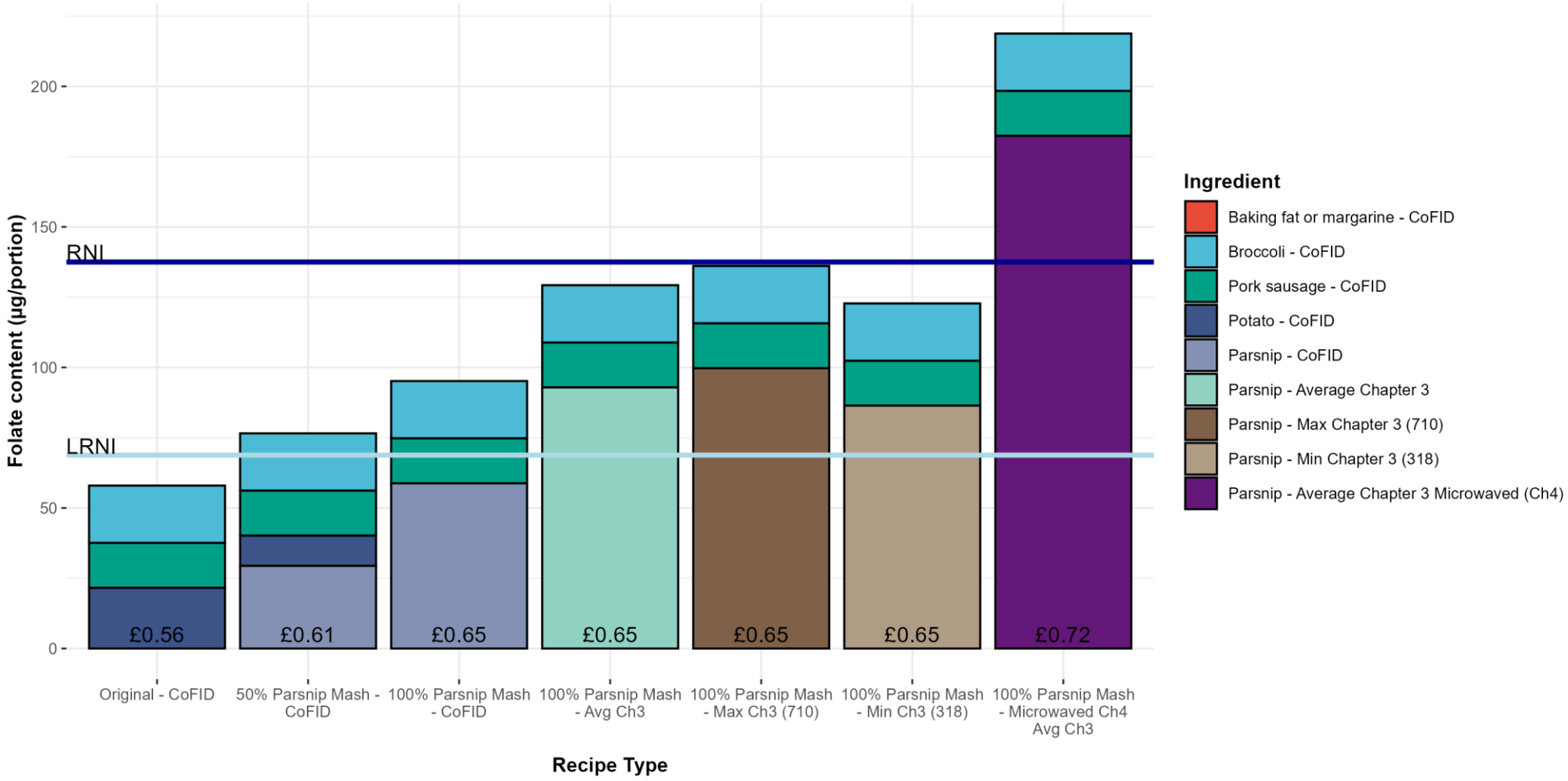


Figure 5-7 Bar plot integrating the results across chapters into the effect on the folate content of a portion of 'Bangers and Mash'

5.4 Discussion

5.4.1 Folate provided by menu items

The amount of folate provided by menu items varied considerably both within and between the main, carb side, veg side, and dessert categories. Items with notably high folate levels within each category included vegetarian Bolognese (main), Quorn burger (main), chips (carbohydrate side), seasonal vegetables (veg side) and iced apricot loaf (dessert). In contrast, roast pork (main), battered fish (main), pasta (carbohydrate side), seasonal salad (veg side) and ice cream (dessert) were poor sources of folate. Folate provision was not, however, associated with the quantity of any particular food group in a recipe. Food composition databases show that good sources of folate span multiple food groups, including organ meat/offal (protein sources), spinach or strawberries (fruit and veg), and parsnips (carbohydrate sources) (Public Health England, 2021). Therefore, a 'balanced' menu that avoids overemphasising any one food group can still provide adequate folate to support primary-school aged children. Instead, the targeted inclusion of folate rich foods from various food groups may be a more effective strategy for improving the folate content of individual menu items. This principle is exemplified in the Bangers and Mash case study, where replacing potato with parsnip significantly increased the folate content of the meal without major changes to the overall recipe.

Interestingly, items that were high in folate were not always those considered to be traditionally 'healthiest'. For example, chips were the best folate source amongst carbohydrate sides, and iced apricot loaf, a bread-based dessert, had the most folate in the dessert category. Both are relatively calorie dense and may contain added salt (chips), oil (chips), and sugar (iced apricot loaf). These findings highlight the need for a broad, systematic understanding of healthy food, which includes macronutrients and micronutrients as direct contributors to healthy metabolism, but also considerations of how appealing foods are to young people, and wider factors such as affordability and environmental sustainability (Hammond and Dubé, 2012; Willett *et al.*, 2019; Fanzo *et al.*, 2021; Flynn *et al.*, 2025). Otherwise, strategies that attempt to improve one standard of health, for example, decreasing quantities of salt, fat, and sugar in foods, may inadvertently compromise other nutrition objectives, for example, of providing sufficient folate and other micronutrients. The analysis in this chapter has attempted to embed understanding of the folate content of foods within existing frameworks of school food provision, therefore including considerations of some of the wider factors outlined above. However, in future it would be useful to go further, investigating a wider range of nutrients and other factors that are also important to a systematic understanding of healthy school food provision.

This analysis also raises questions about whether the English school food standards, which provide guidance on food group quantities but not nutrient provision, adequately support school meal providers in delivering folate-rich meals. It has been highlighted in this chapter that folate is not strongly associated with any food group, and instead, folate rich foods are distributed across a range of different food groups. Therefore, it could be suggested that school food standards should provide guidance as to which foods are rich in folate, similar to their advice for zinc, iron, and calcium (Department for Education, 2025b). This may help school meal providers to identify ways to improve folate provision in school meals, although it should be noted that this would not itself establish any benchmarks or enforce any minimum requirements for folate provision.

5.4.2 Folate provision compared to physiological requirements

Individual menu items are not eaten in isolation. Instead, it is expected that a child will consume a main, carb side, veg side, and dessert in a school day, collectively referred to here as a "dinner". Most dinners in this analysis provided an amount of folate that fell between the RNI and LRNI thresholds for primary school-aged children. Five dinners exceeded the daily RNI, particularly those featuring vegetarian Bolognese or Quorn burgers. However, 42% of dinners fell short of the LRNI threshold. Additionally, the optimisation analysis showed that the most folate-rich combination of menu items was not actually offered, suggesting potential to improve folate provision by reconfiguring existing menus. The Bangers and Mash case study provides a practical illustration of how reformulating an existing recipe with alternative ingredients can raise folate content above the LRNI, and in some cases close to or even above the RNI.

When assessed over a week, no combination of dinners had a daily folate equivalent that exceeded the RNI, and up to 38.2% of combinations provided less than the LRNI. This reflects a buffering effect – dinners high in folate offset those low in folate over the week, bringing the daily folate equivalent for the week closer to the mean.

The school food standards provide guidance as to the frequency of provision of different foods and food groups over a weekly interval (Department for Education, 2025b). Therefore, the 'daily folate equivalent' metric measured over a week may be more relevant for planning of school meals. Furthermore, comparable nutritional guidance in Welsh school meal standards states that the average folate in a school meal measured **over a week** should exceed a given threshold of 40 µg (Welsh Government, 2014), rather than exceeding a daily threshold. Additionally, the Caroline Walker Trust review that underpinned reinstatement of the school food standards in the 2000s also proposed a weekly interval for folate measurement, although their threshold was set higher, at 60 µg (Crawley, 2005). Physiologically, it has also been suggested that stores of

folate in the human body can last 2-3 months, further indicating that between-day fluctuations in folate provision may be less important for folate status than longer term folate provision (Lynn B Bailey *et al.*, 2015).

However, the Scottish school food standards require folate provision to exceed 30 µg every day (Scottish Government, 2021), aligning with the RNI and LRNI, which are intended as daily targets. Therefore, it could also be argued that by averaging the folate requirement over a week there is an increased potential for dinners that provide very little or no folate to be continued to be served in school menus. For children with existing folate deficiencies, affecting one in 6 adolescents and one in 20 children in the UK (Chapter 2), this may present a particular issue. In a situation where existing folate provision is poor, therefore, it may be advisable to establish daily folate targets to improve folate status, particularly among at-risk groups.

Across all assessment approaches, the appropriate threshold for folate provision in school meals remains under debate. Both the Welsh and Scottish standards aim to provide 30% of the RNI of folate as part of their school meal service (Welsh Government, 2014; Scottish Government, 2021), based on the guidance that food in schools should provide 30% of the energy requirements of primary school-aged children, with nutrient provision scaled proportionately (Welsh Government, 2014; Scottish Government, 2021). However, it has been suggested that this scaling may not be appropriate to school dinners, as children may supplement their energy intake with snacks and other foods throughout the school day, but some nutrients are disproportionately consumed at mealtimes (Crawley, 2005). Therefore, it has been argued that the threshold for nutrients provided in school dinners or lunches should be exceed 30% (Crawley, 2005). Furthermore, in low-income communities children may rely more heavily on school meals for their energy and nutrition. During discussions with the SMP, it was noted that children at some schools they service may get their only meal of the day from their school meal. Although not always the case, it is often those in low-income households and communities that are most at risk of food and nutrition insecurity, with correspondingly lower folate intakes (Roberts *et al.*, 2018; Jones *et al.*, 2023; The Food Foundation, 2023; Carrillo-Alvarez *et al.*, 2025). Therefore, setting a threshold that is higher than 30% of the RNI may be helpful to improve folate intakes for young people, particularly in at-risk communities.

This analysis explored two thresholds directly, the RNI and the LRNI. The LRNI, at half the RNI, exceeds the 30% benchmark used in Welsh and Scottish guidelines. Measured across a day, approximately half of meals surpassed the LRNI, and averaged across each week, at least 61.8% of combinations provided at least the LRNI in daily folate equivalents. This suggests that if English school meals were benchmarked at 30% of the RNI, most – but not all – meals would meet this target. It should be emphasised, however, that this is not a standard set for English

school meals, and there is no legislative expectation or requirement to meet this threshold. In future research, it would be useful to evaluate the 30% of RNI threshold directly, both in terms of the current folate provision of school meals in England, and to explore the suitability of this threshold for supporting and improving folate intakes in primary school-aged children. Future research could also investigate whether achieving the LRNI daily or weekly is feasible and beneficial, particularly for those most at risk of folate deficiency.

5.4.3 The impact of choice on folate provision

This analysis assumed all dinners were equally likely to be chosen. In reality, personal preferences, dietary patterns, which other options are available, and a range of other factors may influence children's choices, and therefore, their folate intake (Lehner, Mont and Heiskanen, 2016; Garnett *et al.*, 2020; Guys and St Thomas' Charity, 2020; McIntyre *et al.*, 2022; Flynn *et al.*, 2025). This was evident in the section of analysis that compared vegetarian versus meat eater dietary patterns across the three weeks, consistently finding that vegetarian offerings provided more folate than those containing meat. Therefore, a child that was a vegetarian may be more likely meet their folate needs through school dinners than one that chose the meat options.

Why the vegetarian options outperformed the meat-based dinners is not certain from this analysis. One possible reason could be that the vegetarian items contained more ingredients that are known to be high in folate, such as lentils, and soy protein. By contrast, whilst some organ meats like liver and kidney are high in folate, they are not popular with children and are therefore not included in the menu. Instead, meat-based dinners contain muscle meats, which are much lower in folate than organ meats.

Choice also affected folate provision beyond dietary pattern. For example, the two vegetable sides—seasonal vegetables and seasonal salad—had very different folate contents; seasonal vegetables provided more than twice the folate of seasonal salad. As these options are available every day, one or the other is present in all combinations across a day and week. Therefore, choosing seasonal salad on a day, or across the week, results in much lower folate provision overall than choosing the seasonal vegetable option.

Understanding which choices have a big impact on folate provision by school meals is important for targeting interventions or improvements. For example, the findings of this analysis indicate that there may be more opportunity to improve folate provided in meat-containing menu items compared to vegetarian ones. Additionally, adjusting the ingredients of the seasonal salad menu item may represent a more effective target for improving folate provision

than for an item that is only available one day a week, or is already much higher in folate content.

This analysis has identified key decision points where children's choices influence folate intake. However, more work is needed to quantify this impact. Future research could gather data on the popularity of menu items, either qualitatively by consultation with the SMP, or quantitatively through sales data from the SMP, and use this to create a weighted index of folate provision by different dinners and menu items. This could be incorporated into future analyses to enhance the accuracy of collate assessments and better reflect the folate that children are actually consuming.

5.4.4 Bangers and Mash as a case study

Bangers and Mash was used as a case study in this analysis for several reasons. During initial discussions with the SMP, it was noted as one of the most popular dinners supplied, particularly in disadvantaged communities where schools often request it more frequently to ensure students eat at least one hot meal in their day. For this study, it was also useful because parsnip could be easily substituted into the mashed potatoes, a simple substitution compared to other dinner options that might require extensive changes to incorporate parsnips. This unique combination of characteristics made Bangers and Mash ideal for exploring the effects of recipe reformulation on folate content.

Incorporating parsnip into Bangers and Mash improved the amount of folate provided, especially when parsnips were assumed to contain the average amount of folate established in Chapter 3. Using the highest- and lowest-folate varieties from Chapter 3 changed folate provision slightly, though the effect was modest compared to the initial substitution of potato with parsnip. This suggests that regardless of variety, integrating parsnip into leverage points such as school meals could improve folate provision. Whilst cooking method did affect folate levels—with microwaving producing meals that exceeded the RNI for a school-aged child—this was associated with higher costs due to the greater raw input required.

Overall, the Bangers and Mash case study exemplifies how targeted, practical adjustments to familiar meals can improve folate intake in primary school children. It reinforces the broader findings of this chapter by demonstrating that relatively small changes in recipe formulation can have disproportionate effects on micronutrient provision, with implications for both nutrition and food system planning.

However, the extent to which high-folate ingredients such as parsnips can be incorporated through recipe reformulation is variable. In the case of Bangers and Mash, substitution is

straightforward, as parsnip can replace potato on a 1:1 basis within the mash. Discussions with the SMP also highlighted other meals where similarly simple substitutions may be feasible. For instance, Thursdays, identified in this analysis as having relatively low folate provision, are designated 'roast days', during which children receive a traditional roast dinner comprising meat (or vegetarian alternative), roast potatoes, and vegetables or salad. Although parsnips are not currently included, they could be incorporated by replacing a portion of the roast potatoes, mirroring the approach used in the Bangers and Mash case study. In contrast, some dishes, such as the sweet potato parcel which featured among the lowest-folate meals, may be less amenable to folate-focused reformulation. In such cases, optimisation may instead target other micronutrients, for example, improving Vitamin A provision through sweet potato. Moving forward, the potential for recipe reformulation should be explored collaboratively with school food caterers to identify opportunities to enhance folate and other micronutrient provision, while acknowledging dishes where reformulation is more constrained. This approach would enable the school menu as a whole to be strategically aligned with improving micronutrient intake, particularly for nutrients with persistently low consumption, such as folate.

5.5 Conclusions and future directions

This analysis offers new insights into folate provision through school meals in Southampton, UK. A novel aspect of this work was the detailed breakdown of menu items into their ingredients and matching these to CoFID entries, an approach not seen in other research where recipes for menu items have not been available. Furthermore, few analyses have focussed specifically on folate, with most centred on macronutrients or food group provision through school meals. By embedding this nutrient-specific analysis within existing school food frameworks, the study expands the scope of school meal research and introduces a methodological template that could be applied to other nutrients.

With the methodology now established, expanding the study to include other seasonal menus and school meal providers both in Hampshire and across the UK would be valuable. It would be interesting too to establish whether the contrasting types of School Food Standards across the UK have impacted the nutrients provided in school meals, particularly for folate, which has different guidance across the four nations of the UK.

Future work could build on this collaborative foundation with the SMP to explore a range of further research topics. Additional data from the SMP, such as pricing, environmental impacts, waste and/or purchasing data, could further progress a food systems approach to understanding school meals, with valuable research outputs beneficial to the SMP as well. Working together in the future could provide a more holistic understanding of nutrition,

sustainability, and health in the context of school meals that needed to inform developments in school meal policy across the UK in future.

Overall, this analysis highlights both the challenges and the opportunities of improving folate provision through school meals in England. While overall provision across menus often fell short of recommended thresholds, the analysis shows that modest but deliberate adjustments—whether through menu planning, daily food choices, or recipe reformulation—can substantially increase folate intake. The Bangers and Mash case study provides a concrete example of how small, feasible modifications to widely accepted meals can enhance nutritional quality, supporting the chapter's broader aim of identifying practical strategies to improve folate provision for primary school children in Southampton and, by extension, the wider UK school food system.

Chapter 6 General Discussion

The underlying aim of this thesis was to explore the potential for diet-based interventions to improve food and micronutrient security in the UK, using parsnip (*Pastinaca sativa* L.) as a case study. Parsnip was selected on the recommendation of Tozer Seeds Ltd., who co-funded and were partners on this thesis, and because parsnip is domestically produced, traditionally consumed, affordable, and understudied. As such, parsnip presents concurrent opportunities for increasing food security through its improved utilization and wider uptake. To enable detailed exploration, the provision of folate, a micronutrient identified as of key public health concern in the UK (Chapter 2), was used as a focal case study for broader improvements in food and nutrition security. The capacity of parsnips, and the wider food system, to deliver folate was explored in detail.

A range of methods were used to address these questions. In silico, national level datasets were wrangled into formats suitable for exploration and visualisation in RStudio, with insights being drawn from statistical evaluation and inspection of visualised data. Additionally, a nutritional dataset was generated for a case study of school meal provision in Southampton, UK, and used to model folate intake sufficiency. In the laboratory, folate was extracted from parsnips by a multi-step tri-enzyme extraction process, followed by HPLC quantification of extracted folate and back calculation using dry matter percentages to equate folate content to the original samples. This quantification method is performed by only a handful of laboratories worldwide, and the development of this technique at the University of Southampton, by collaboration with the Kariluoto research group at the University of Helsinki, was a key accomplishment of this work.

In Chapter 2, micronutrient status in the UK was explored both using intake data and biomarker status for a range of micronutrients that are present in parsnips. This novel two-pronged approach identified deficits in a range of micronutrients. Additionally, inconsistencies between conclusions drawn from different data types were highlighted. Overall, folate was identified as a key micronutrient of concern to public health in the UK, with widespread deficiencies across many population groups that were especially pronounced in adolescents. Based on this finding, this thesis focused on the folate content of parsnips, and subsequently school meals, as potential options for improving folate status in the UK.

In Chapter 3, significant variation was identified in the folate content of parsnip cultivars, with variety shown to be an important determinant. Growing environment, within the scope of this study, had no measurable effect. Analysis of individual folate vitamers identified 5-

methyltetrahydrofolate (5-CH_3-THF) and tetrahydrofolate (THF) to be the predominant folate vitamers in parsnips. Although folate content was not strongly associated with most observable phenotypes, several weak correlations were detected. For example, total folate and 5-CH_3-THF showed negative correlations with browning, while THF was positively associated with root shape and canker resistance but negatively correlated with harvest and stored whiteness. These findings suggest that while phenotypic traits are unlikely to be reliable direct predictors of folate content, certain quality traits may offer some potential for indirect selection in breeding programmes.

In Chapter 4, it was observed that the folate contained in parsnips was robust to storage over 4 weeks, in both field storage and refrigerated storage conditions. The folate in parsnips was also maintained over cooking by microwaving, roasting, and boiling. Investigating individual folate vitamers provided additional insights that 5-CH_3-THF and THF may have different sensitivities to cooking, with THF content in particular decreasing during roasting. However, changes in water content of the tissue during cooking impacted the concentration of folate the most, resulting in higher concentrations of folate in microwaved and roasted parsnip in comparison to raw or boiled parsnips. These findings highlight both the relative resilience of parsnip folate and the importance of preparation method in determining its nutritional value.

In Chapter 5, it was demonstrated that the folate provision in school meals varied substantially across menu items, dinner, and weekly combinations in the Summer 2023 menu from the School Meal Provider (SMP). Most dinners, measured individually or averaged over a week, provided more folate than the LRNI threshold but did not exceed the RNI for a school aged child. Differences were also found between the folate provided by meals that did or did not contain meat. Optimisation analyses showed that relatively small adjustments, such as reformulating a popular meal like Bangers and Mash to include parsnip, could substantially increase folate provision for a modest additional cost. These findings illustrate how institutional food provision represents a practical leverage point for diet-based interventions.

6.1 Addressing folate deficiency in the UK population with school meal provision

The analysis presented in Chapter 2 highlighted the extent of folate insufficiency across the UK population, confirming that folate is a micronutrient of significant public health concern. Biomarker data showed that the majority of women of reproductive age fall below thresholds associated with increased risk of neural tube defects, while intakes in other demographic groups were also often inadequate. These findings are in line with expectation from the published literature (Gunter, 2020; Jones *et al.*, 2023), and illustrate that folate deficiency is not

restricted to specific subgroups but represents a broad nutritional challenge affecting the wider UK population. In turn, these results indicate that the current strategy of reliance on individual decision-making and voluntary supplementation is not sufficient to ensure adequate folate status for all.

Institutional meal provision, in this case school meals, represents a potential structural intervention where choices are partially determined for the consumer, and consumers can therefore be directed towards higher folate food options. Chapter 5 revealed substantial variation in the folate content of current school meals in Southampton, with some dishes contributing meaningfully to daily requirements and others providing very little, highlighting opportunities for improvements in folate provision as well as identifying dinners that are already good sources of folate. Importantly, the optimisation analysis showed that relatively modest adjustments to menu planning, such as pairing higher-folate items more consistently, could significantly improve folate provision without major cost increases or changes to food sourcing. Since no published analyses currently exist on folate content in school meals in England or the wider UK, this analysis constitutes a novel contribution of the thesis.

However, Chapter 5 also illustrates some of the broader challenges associated with food-based interventions for improving folate intakes. For example, the reformulation strategy explored through the case study of Bangers and Mash would incur an additional cost to school meal providers, should it be implemented. Although the cost is relatively small compared to the large increase in folate provision, it remains to be explored whether this cost would be prohibitive, especially if reformation was conducted across a wider range of school dinners. Furthermore, additional factors such as palatability, environmental footprint, practicality, and potential nutritional trade-offs in reformulated recipes could present barriers to implementation of folate-optimised school meals in practice. Therefore, although significant potential has been identified to improve nutritional status through school meals, future works should seek to contextualise such optimisation strategies within the wider context of the school meal.

In this thesis, primary school meals were targeted as an intervention point. This decision was taken predominantly because primary school meals are relatively tightly regulated through the School Food Standards and have wide reach through the free school meal programme (Chapter 5). This makes them an effective and relatively simple point of intervention. However, primary school aged children had relatively small proportions of the population with poor micronutrient status compared to teenagers or women of childbearing age (Chapter 2). As childhood eating patterns often track into adolescence and adulthood (Mikkilä *et al.*, 2007; Craigie *et al.*, 2011; Simmonds *et al.*, 2016; Kim and Lim, 2019; McIntyre *et al.*, 2022), it was hypothesised that enhancing folate provision through primary school meals could contribute to longer-term

improvements in population food security as the affected children age (Chapter 5). Over time, therefore, if this intervention was effective it would also improve the folate status of adolescents and adults. However, there would be a significant delay between the administration of folate-enhanced school meals to primary school children and improvements in the folate status of adolescents and adults. Whilst this does not necessary diminish the effectiveness of the strategy, it is important to note as policy strategies that implemented such measures would need to be prepared for assessment of long-term effectiveness in the most vulnerable groups.

Beyond folate, it should be noted that several other micronutrients of public health concern were identified in Chapter 2. These included potassium and magnesium, which had large proportions of the population with poor nutrient intakes, but lacked biomarker data, and zinc, with poor nutrient intakes but conflicting results from the biomarker analysis (Chapter 2 Sections 2.3.6, 2.3.10, and 2.3.8, respectively). Additionally, riboflavin (vitamin B2), had both poor intakes and low biomarker levels relative to other micronutrients (Chapter 2 Section 2.3.11). In practice, school meal provision represents an equally valuable opportunity for improving intakes of multiple micronutrients simultaneously. Exploring these opportunities in future research could reveal co-benefits in dietary adequacy that extend beyond folate alone. At the same time, it may be challenging to optimise school meals to deliver sufficient quantities of several micronutrients concurrently. This raises a broader policy question of how best to prioritise and balance different nutritional goals. Addressing this challenge will require further research into optimisation strategies that can maximise synergies across micronutrients, while maintaining practicality and acceptability in institutional settings.

Together, these chapters illustrate the importance of linking epidemiological data with practical food system interventions. Population-level surveys provide the evidence base for identifying nutrients of concern, while institutional food programmes offer a tangible platform for intervention. By integrating these approaches, policymakers and practitioners can move beyond identifying deficiencies to actively designing food environments that reduce them.

6.2 Diet-based interventions can be identified to improve folate status in the UK

The work presented in Chapter 3 and Chapter 4 provide strong, complementary evidence that parsnips could deliver nutritionally significant amounts of folate to the UK population. With a mean folate content in Chapter 3 of 77.4 ± 7.14 µg/100 g, parsnips far exceed the threshold for being classed as ‘rich in’ folate (>60 µg/100 g FW) (DHSC, 2025). In fact, the lowest mean folate content of any variety was 72.0 ± 6.42 µg/100 g (variety 312), and the lowest folate content of

any individual was 61.0 µg/100 g. Therefore, even at the lowest concentrations, parsnips still exceeded the 'rich in' threshold (DHSC, 2025).

The folate content of parsnips was more variable in Chapter 4. The mean folate content of freshly harvested parsnips was 67.8 ± 7.89 µg/100 g FW. Across the experimental conditions, mean folate content ranged from 50.7 ± 5.44 µg/100 g FW (6 weeks field storage) to 72.0 ± 1.78 µg/100 g FW (4 weeks cold store storage), falling below the 'rich in' threshold at the lowest concentrations. In comparison, the mean folate content of raw parsnips in the cooking experiment in Chapter 4 was 83.7 ± 5.24 µg/100 g FW, ranging from 68.2 ± 4.09 µg/100 g FW (boiled) to 164.4 ± 5.26 µg/100 g FW (microwaved).

Notably, 5-methyltetrahydrofolate (5-CH_3-THF), a highly biologically active and relatively stable form of reduced folate (Indrawati *et al.*, 2004; Strandler *et al.*, 2015; Delchier *et al.*, 2016; Wusigale and Liang, 2020; Siatka *et al.*, 2025), was the main folate vitamer detected in parsnips across all assessments. This finding is important, as it indicates that the folate present in parsnips is not only quantitatively significant but also nutritionally valuable.

Together, these results suggest that parsnips are a reliable source of folate, which could be used as a diet-based intervention to improve folate status. Although significant variation was observed in the folate content of parsnips across chapters and experiments, parsnips under all conditions remained high in folate and always exceeded the threshold to be labelled as a 'source of' folate (>30 µg/100 g FW) (DHSC, 2025), and were resilient to storage and cooking conditions. However, the practical implications of improved utilisation of parsnips as a dietary source of folate remain to be explored. For example, the wider characteristics of parsnips as a crop, with a predisposition to poor germination and specific requirements for sandy, free draining soil (Chapter 1, Section 1.8.1), may limit the extent to which production could be expanded in the UK. In future, it would be interesting to explore grower perceptions of parsnips as a crop, and whether there would be capacity for increased production of parsnips in future that would allow for increased consumption of parsnips as a diet-based intervention for improving folate intakes.

More broadly, the results presented in this thesis suggest that valid diet-based options for improving folate, which may be used as an alternative or in addition to mandatory fortification of white flour with folic acid in the UK from December 2026, do exist. Given the co-benefits of diet-based interventions for public health and food security discussed in Chapter 1, this thesis is an important first step in underscoring both the importance and the undiscovered potential for UK-centric foods to support nutrition objectives, with co-benefits for wider food security where these foods are domestically produced, cheap, and widely available, as parsnips are. Furthermore, the methods used to explore the folate content of parsnips used in this thesis

could be used as a roadmap for the discovery and evaluation of other nutrient dense foods that could be better used to support food and nutrition security in the UK.

6.3 There is optimisation potential for folate in parsnips across the food supply chain

The research presented in this thesis has illustrated that there is optimisation potential for improving the folate content of parsnips across the food supply chain, but that the scope for optimisation differs across the various treatments from 'farm to fork'. In Chapter 3, varietal differences accounted for 15% variation in folate content. Similarly, Chapter 4 found variation of up to 23% over storage conditions. Although this variation is significant in both cases, the difference is small in comparison to the effect of cooking in Chapter 4, where variation of up to 83% was observed between cooking methods. Together, these findings indicate that improvements may be made in the production of parsnips to optimise folate delivery to consumers, but in fact, the treatment of parsnips by the consumers themselves may be much more influential in determining the impact of parsnips as a vehicle for folate delivery.

These findings also provide a foundation for potential biofortification of parsnips (Chapter 1 Section 1.7.3). Approaches to folate biofortification fall into two main categories – molecular breeding technology based approaches, or metabolic engineering/genetic modification approaches. The first approach relies on significant natural variation in folate levels being identified, from which enhanced folate profiles can be leveraged, whilst the second involves the introduction of genes or otherwise manipulation of gene expression to increase levels of folate in plant tissues. Although statistically significant, the amount of variation in folate content between varieties of parsnips was relatively low. In fact, the amount of variation was smaller than that observed multi-varieties studies in potato (Goyer and Navarre, 2007) and rice (Abilgos Ramos, 2010), which has been deemed insufficient for molecular breeding based approaches to be successful (Gorelova *et al.*, 2017). Therefore, biofortification of parsnips in future is likely to require genetic editing or genetic modification approaches.

The recent Genetic Technology (Precision Breeding) Act 2023 (UK Government, 2023) has relaxed some of the restrictions on using gene editing technologies to produce improved or novel crop lines, creating new avenues towards the production of genetically edited crops in the UK. However, significant barriers remain in the case of parsnips. Primarily, there are no genetic materials from which to identify target genes to edit to improve folate content. Additionally, although target genes have been identified in other crop species, there has only been moderate and inconsistent effects of editing expression of these genes on improving folate levels in target crops (Díaz de la Garza *et al.*, 2004; Naqvi *et al.*, 2009; Nunes, Kalkmann and Aragão, 2009; De

Lepeleire *et al.*, 2017; Strobbe and Van Der Straeten, 2017). Furthermore, the introduction of potentially effective genes from other crops into parsnips would fall outside the remit of allowable genetic editing technologies in the Genetic Technology Act (UK Government, 2023). Therefore, although scientifically interesting, such exercises would not progress parsnips towards a utilisable biofortified product under current legislative restrictions.

By defining the existing variation in folate content in parsnips, unknown prior to this research, a stronger platform for the exploration of enhancement of folate content by traditional breeding, agronomic treatment, or genetic engineering techniques has been provided. However, significant challenges remain on the pathway to the development and introduction of folate biofortified parsnips. Instead, the identified variation in folate content post-harvest should be leveraged to ensure parsnips are providing the maximum amount of folate to consumers within the current parameters of production and consumption. Overall, this thesis highlights the potential for optimisation of folate nutrition at multiple points: production (variety selection), supply chain (optimised storage), and consumption (cooking practices that preserve folate). By combining varietal selection with best-practice storage and cooking, parsnips have the potential to become a dependable and locally produced contributor to folate security.

6.4 Advances in the field

This thesis has been intentionally cross-disciplinary, with advancements being made across multiple fields within the broader umbrella of food systems research.

The work on folate content has provided new evidence that folate content of foods may differ across crops, with unique characteristics of different foods impacting their potential as dietary sources of folate. It has suggested that there may be unexplored potential in root crops, which may retain folate better on the pathway from farm to fork, than other more perishable crops.

The exploration of parsnips as a food has advanced knowledge of understudied crops in a UK setting. Parsnips are a domestically produced source of food that has not been explored in detail until now. This thesis has both provided evidence that parsnips warrant further study as an interesting, nutritious food crop that could contribute to improved food security in the UK, but also suggested that there may be other ‘forgotten’ crops, appropriate for growing in a UK setting, which have not yet been explored.

This thesis has brought together crop science and public health nutrition, illustrating the strong links between a good quality diet and desirable nutrition outcomes. The breaking down of silos between food, nutrition, and public health science in a single research outcome contributes to the unification of understandings of health under a food systems approach.

6.5 Future directions

Several avenues for future research arise from this work. In future, it would be valuable to extend upon the range of conditions for folate provision explored in this thesis. The work completed here provides important evidence of parsnips as a folate rich crop but also uncovered significant variation in folate content. It would be useful to explore this variation over a wider range of parsnip varieties, growing conditions, and cooking and storage conditions. In this way, the work could be expanded to have relevance beyond the UK context, exploring variables important on a global scale.

Similarly, the work on folate provision in school meals could be extended. This thesis has explored in detail the folate provided by school meals in the Summer 2023 menu supplied by a school meal provider (SMP) in Southampton, Hampshire, UK, but has not explored folate provision outside of this period. Additionally, school meal provision may vary with geography across the UK, as the sociodemographic characteristics change too. It would be interesting to explore how much the folate provided through school meals varies across England and the wider UK, and across different seasons, to be better able to comment on whether the English School Food Standards are fit for purpose in supporting sufficient folate, and other micronutrient, intakes.

The work in this thesis has centred around folate as a key micronutrient. However, folate is not the only micronutrient for which improvements in nutrient security are needed. Even for the subset of micronutrients identified in Chapter 2, suboptimal intakes and biomarker status were identified for many. In future, the exercises conducted in this thesis could be applied to a range of further micronutrients and corresponding micronutrient-dense foods, to identify possible option for foods that could be used as diet-based interventions to improve micronutrient security for other micronutrients.

It was noted that parsnips have particular promise for improving food security in the UK, as they can be domestically produced, are low cost and widely available, and are traditionally appropriate in UK dietary patterns. It would be interesting in future to explore other traditional foods to the UK, for example swedes, celeriac, and marrow, to see whether these similar, understudied, foods could also be better utilised to improve micronutrient security in the UK. By bringing domestically produced micronutrient dense foods back into mainstream diets, the security of micronutrient supply in the UK could be made more robust to global challenges that threaten micronutrients brought in through trade.

Equally, the population of the UK is not the same as it was when parsnips were most popular, with increasingly globalised, multicultural communities that bring their own dietary preferences

and patterns. In future, it would be interesting to explore the micronutrient content of foods traditional to a wide range of cultures that have been assimilated into the UK in modern times, with the aim of both generating an improved understanding of foods that might be key contributors to micronutrient intakes in different subpopulations, and also exploring whether there is any potential for shifting domestic production towards foods that are appropriate and tailored to the new shape of the UK population.

Finally, although this thesis has improved the knowledge base for parsnips, there is still much more that could be done. In particular, the molecular underpinning of phenotypes in parsnips is still largely unexplored, with little genetic information and no reference genome to work with. This is potentially limiting to future works that might aim to manipulate the folate content or other phenotypes in parsnips, and also limits the depth of understanding of valued phenotypes. Improved genetic tools, such as an annotated reference genome, could provide a platform from which to explore and potentially improve the characteristics in parsnips in a more informed and directed manor. Additionally, this thesis considered only a subset of the parsnip varieties that are available in the UK. There are over 30 cultivars of parsnip available in the UK, and many more in the global market that were not considered, including wild and ancestral cultivars that remain completely uncharacterised. Therefore, there remains a large pool of genetic and phenotypic potential for parsnips that remains open for exploration in future works.

6.6 Overall conclusions

This thesis has shown that parsnips, a traditionally overlooked yet widely consumed UK crop, represent a credible and underutilised source of dietary folate. By examining the nutrient from crop level through to its provision within school meals, the work provides a comprehensive analysis of folate across the food system, from production to consumption. Several novel contributions have been made: the first detailed characterisation of folate vitamers in parsnip; evidence that folate content is maintained through storage and is enhanced, rather than diminished, by certain cooking methods; and the demonstration that small, feasible changes to institutional meals can substantially improve folate provision. These findings highlight both the biological robustness of parsnip folate and the practical opportunities to integrate this crop into interventions designed to improve nutritional security. Overall, the research in this thesis lends strength to the idea that parsnips could contribute to folate security across all four pillars of food security, improving the availability (UK grown crop), accessibility (affordable, familiar, culturally accepted), utilisation (nutrient stability through storage and cooking), and sustainability (strengthening local supply chains) of folate provision in the UK.

The significance of this work extends beyond parsnips themselves. By uniting crop science, nutrition, and public health, this thesis demonstrates how UK-grown, nutrient-dense crops can strengthen food systems and address micronutrient deficiencies in a sustainable manner. The interdisciplinary approach taken - linking laboratory analysis with national survey data and applied case studies - provides a framework for developing diet-based interventions that can complement supplementation and fortification strategies.

Looking ahead, the research provides a platform for further work on varietal optimisation, biofortification, and the integration of additional micronutrient-rich crops into institutional and household diets. While there is more progress to be made, the findings presented here illustrate the potential impact of reconnecting traditional, affordable crops with contemporary nutritional needs. In doing so, this thesis contributes both new evidence and new pathways for advancing food and nutrition security in the UK.

Appendix A Thresholds for biomarker levels

Biomarker thresholds for a range of micronutrients, including those used in the above analysis, were sourced from the literature and compiled in Table 6-1. The summarised results from Chapter 2 in table form are shown in Table 6-2.

Table 6-1 Biomarker thresholds from the scientific literature for a range of micronutrients

Nutrient	Biomarker	Deficiency threshold	Categorisation	Source
Vitamin A	Plasma retinol	<1.05umol/L	High risk of deficiency	(de Carvalho *et al.*, 1996)
		<0.7umol/L	Deficiency	(WHO, 2009)
		<0.35umol/L	Severe deficiency	
		<0.7umol/L	Deficiency	(National Institutes of health Office of Dietary Supplements, 2022)
		<0.35umol/L	Severe deficiency	
		<0.7umol/L	Clinical deficiency	(Scottish Trace Element and Micronutrient Diagnostic and Research Laboratory, no date)
		<0.7umol/L	Deficiency in children	(Tanumihardjo *et al.*, 2016)
		<0.35umol/L	Severe deficiency in children	
		<1.05umol/L	Deficiency in adults	
		<1umol/L	Deficiency	(Johnson, 2022b)
Vitamin B1 (Thiamin)	ETKAC – Erythrocyte transketolase activity	>1.2	Clinical deficiency	(Jones *et al.*, 2021b)
		1.15-1.25	Low risk of clinical deficiency	
		>1.4	Beriberi disease	
		1.2-1.25	Marginal deficiency	(Institute of Medicine (US) Standing Committee on the Scientific Evaluation of Dietary Reference Intakes and its Panel on Folate, Other B Vitamins, and Choline, 1998)
		>1.25	Deficiency	
		1.2-1.25	Marginal deficiency	(Bates, Thurnham and Nelson, 1997; Gibson, 2021)
		>1.25	Deficiency	
		1.10-1.19	Moderate risk of deficiency	(de Carvalho *et al.*, 1996)
		>1.19	High risk of deficiency	
		1.2-1.4	Low vitamin status	

Vitamin B2 (Riboflavin)	EGRAC - erythrocyte glutathione reductase activity coefficient	>1.4	Deficient	(Institute of Medicine (US) Standing Committee on the Scientific Evaluation of Dietary Reference Intakes and its Panel on Folate, Other B Vitamins, and Choline, 1998); (McCormick and Greene, 1994)
		>1.34	Deficient	(Sadowski, 1992; Institute of Medicine (US) Standing Committee on the Scientific Evaluation of Dietary Reference Intakes and its Panel on Folate, Other B Vitamins, and Choline, 1998)
		>1.30	Deficient	(Hill *et al.*, 2009; University of Cambridge, MRC Epidemiology Unit, NatCen Social Research, 2023)
		>1.80	Deficient	(Bates, Thurnham and Nelson, 1997; Gibson, 2021)
		>1.4	Deficient adult and elderly	(Gibson, 1990; Wright *et al.*, 1995)
Vitamin B6 (pyridoxine)	Serum pyridoxal-5-phosphate (PLP)	<10nmol/L	Suboptimal concentration with clinical consequences	(Kretsch, Sauberlich and Newbrun, 1991; Institute of Medicine (US) Standing Committee on the Scientific Evaluation of Dietary Reference Intakes and its Panel on Folate, Other B Vitamins, and Choline, 1998)
		<20nmol/L	Inadequate	(Lui *et al.*, 1985; Institute of Medicine (US) Standing Committee on the Scientific Evaluation of Dietary Reference Intakes and its Panel on Folate, Other B Vitamins, and Choline, 1998)
		20-30nmol/L	Moderate risk of deficiency	(de Carvalho *et al.*, 1996)
		<20nmol/L	High risk of deficiency	
		<34.4nmol/L	Inadequate B6 status	(Rose *et al.*, 1976; Wright *et al.*, 1995)
Vitamin B9 (folate)	Red blood cell folate	<305nmol/L	inadequate status	(Institute of Medicine (US) Standing Committee on the Scientific Evaluation of Dietary Reference Intakes and its Panel on Folate, Other B Vitamins, and Choline, 1998)
		<305nmol/L	Deficient	(Institute of Medicine (US) Standing Committee on the Scientific Evaluation of Dietary Reference Intakes and its Panel on Folate, Other B Vitamins, and Choline, 1998; University of Cambridge, MRC Epidemiology

				Unit, NatCen Social Research, 2023)
		<317nmol/L	Deficiency	(Shin *et al.*, 1976; Lynn B Bailey *et al.*, 2015)
		<340nmol/L	Deficiency	(Bagley and Selhub, 1998; Lynn B Bailey *et al.*, 2015)
		<305nmol/L	Likely Deficiency	(Johnson, 2022a)
		<140nmol/L	Low RBC folate	(Pfeiffer *et al.*, 2009)
	Serum folate	<7nmol/L	Negative folate balance	(Herbert, 1987; Institute of Medicine (US) Standing Committee on the Scientific Evaluation of Dietary Reference Intakes and its Panel on Folate, Other B Vitamins, and Choline, 1998)
		<7nmol/L	Deficient	(WHO, 2015; University of Cambridge, MRC Epidemiology Unit, NatCen Social Research, 2023)
		<13nmol/L	Low	
		<10nmol/L	Deficiency cutoff	(Lynn B Bailey *et al.*, 2015)
		6.8 – 13.6nmol/L	Moderate risk of deficiency	(de Carvalho *et al.*, 1996)
		<6.8nmol/L	High risk of deficiency	
		<7nmol/L	Deficiency likely	(Johnson, 2022a)
		<3nmol/L	Low serum folate	(Pfeiffer *et al.*, 2009)
Vitamin B12	Serum Vitamin B12	<110.7pmol/L	Nearly always deficient in adults	(NHS Foundation Trust, 2023)
		<73/78pmol/L	Usually deficient	
		<140pmol/L	Lower threshold of normal	(Ratini, 2021)
		<147.6pmol/L	Low B12 is below this	(Leonard, 2020)
		<150pmol/L	Threshold for deficiency	(de Benoist, 2008; University of Cambridge, MRC Epidemiology Unit, NatCen Social Research, 2023)
		<145pmol/L	Deficiency	(Johnson, 2022c)
		<147.56pmol/L	Cut-off for deficiency	(Gibson, 1990; Pfeiffer *et al.*, 2009)
	Serum holotranscobalamin	<32pmol/L	Deficiency threshold	(Heil *et al.*, 2012; University of Cambridge, MRC Epidemiology Unit, NatCen Social Research, 2023)
		<21pmol/L	Lower limit of diagnostic test	
		<30pmol/L	Deficient	(Johnson, 2022c)

Vitamin C	Serum Vitamin C	<22.7umol/L	Marginal or frank deficiency	(Simon, 1992; Simon, Hudes and Tice, 2001)
		<23umol/L	Hypovitaminosis	(Levine *et al.*, 1996; Rowe and Carr, 2020)
		<11umol/L	Deficiency	(Johnston and Corte, 1999; Rowe and Carr, 2020)
		11.35-23umol/L	Low Vitamin C status	(Loria *et al.*, 1998)
		<11.35umol/L	Deficient	
		<11umol/L	Risk of deficiency	(Riemersma *et al.*, 2000)
		<20umol/L	Cut-off point for deficiency	(Rousseau *et al.*, 2004)
		<20umol/L	Low Status	(Gibson, 1990; Wright *et al.*, 1995)
		<34umol/L	Below the normal range	(Kraemer, 2022)
		<60umol/L	Below the healthy range	(Jacob, Pianalto and Agee, 1992; Levine *et al.*, 1996)
		<10umol/L	Scurvy	(Maxfield and Crane, 2023)
		<34umol/L	Marginal deficiency	(Johnson, 2022d)
		<11umol/L	Deficiency	
		<11umol/L	Scurvy	(Institute of Medicine (US) Panel on Dietary Antioxidants and Related Compounds, 2000)
		<22umol/L	Below normal range	
Vitamin D	Serum 25-Hydroxy Vitamin D	<25nmol/L	Deficiency	(Scientific Advisory Committee on Nutrition, 2016)
		<25nmol/L	High risk of deficiency	(de Carvalho *et al.*, 1996)
		<50-60nmol/L	Below target for maximal bone health	(Johnson, 2022e)
Vitamin E	Serum alpha-tocopherol	<9.3umol/L	Cut-off point for deficiency	(Rousseau *et al.*, 2004)
		<11.6umol/L	Deficiency suggested	(Johnson, 2022f)
		<12umol/L	Threshold for poor health outcomes	(Traber, 2014)
		<14umol/L	Inadequacy	(Institute of Medicine (US) Panel on Dietary Antioxidants and Related Compounds, 2000)
Iron	Plasma ferritin	<15ug/L	Depleted iron stores in people >5 years.	(Lynch *et al.*, 2018)

		<12ug/L	Depleted iron stores in people <5 years.	
		<15ug/L	Depleted iron stores in people >5 years.	(Lynch *et al.*, 2018; University of Cambridge, MRC Epidemiology Unit, NatCen Social Research, 2023)
		<12ug/L	Depleted iron stores in people <5 years.	
		<12ug/L	Deficient	(Cook, Baynes and Skikne, 1992; Wright *et al.*, 1995)
		12-24ug/L	Low body stores	
Selenium	Plasma selenium	<0.507umol/L	Deficiency	(Smith and Garg, 2017)
		<0.1umol/L	Lowest biologically normal amount	(Johnson, 2021)
		<0.8umol/L	Indicates limited selenium intake	(Institute of Medicine (US) Panel on Dietary Antioxidants and Related Compounds, 2000; Pfeiffer *et al.*, 2009)
Zinc	Plasma zinc	9umol/L	Lowest end of biologically normal range	(Smith and Garg, 2017)

Table 6-2 Summary table of the results from Chapter 2

		Population group									
		1 – 3-year-old		4 – 10-year-old		11 – 18-year-old		19 – 65-year-old		Over – 65-year-old	
Micronutrient	**Measure**	**Female**	**Male**	**Female**	**Male**	**Female**	**Male**	**Female**	**Male**	**Female**	**Male**
Vitamin C	% below RNI	14.0	11.9	12.1	7.1	22.0	22.3	20.9	21.2	22.3	20.8
	% below LRNI	0.0	0.0	0.5	0.0	0.9	0.3	1.2	0.7	0.6	0.6
	Avg intake (mg/day)	64.4	64.0	76.0	73.8	75.9	76.3	82.2	87.2	77.9	83.8
	Avg serum vitamin C (µmol/L)	-	-	73.7	73.5	57.4	55.0	57.9	50.3	56.9	48.5
	% below deficiency threshold	-	-	1.3	0.0	0.0	1.4	5.3	6.4	7.5	6.3
Folate	% below RNI	7.8	2.4	27.5	20.3	74.4	52.7	49.9	26.8	47.9	24.1
	% below LRNI	0.0	0.0	1.6	0.4	10.4	8.5	6.6	2.4	4.5	1.6
	Avg intake (µg/day)	128.2	139.8	163.5	178.4	171.5	205.6	210.9	264.9	211.1	262.1
	Avg RBC folate (nmol/L)	-	-	518.7	606.8	413.4	466.8	538.4	528.0	577.2	648.2
	% below deficiency threshold	-	-	2.3	6.7	15.8	17.1	14.3	10.0	12.4	9.7
Niacin	% below RNI	0.0	0.0	0.6	0.5	1.9	2.3	1.8	1.3	1.2	1.5
	% below LRNI	0.0	0.0	0.0	0.0	0.0	0.7	0.3	0.3	0.0	1.2
	Avg intake (mg/day)	16.5	18.6	22.3	25.3	27.0	33.6	30.8	40.6	26.9	35.2
Thiamin	% below RNI	0.5	0.0	4.4	1.7	11.9	19.0	9.1	10.8	7.5	0.5
	% below LRNI	0.0	0.0	0.0	0.3	0.5	2.5	1.1	1.5	0.5	0.0
	Avg intake (mg/day)	0.9	1.0	1.2	1.3	1.3	1.5	1.3	1.7	1.4	0.9

	Avg ETKAC value	-	-	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
	% below deficiency threshold	-	-	0.0	0.0	6.0	3.2	0.6	2.5	1.2	0.0
Potassium	% below RNI	4.7	1.9	27.7	16.2	96.6	85.9	90.0	71.0	90.1	74.3
	% below LRNI	0.0	0.0	1.1	0.3	37.2	22.3	23.7	10.2	20.2	8.3
	Avg intake (mg/day)	1566.1	1736.7	1950.8	2132.1	2083.7	2385.8	2560.8	3109.0	2578.0	3026.8
Phosphorus	% below RNI	0.0	0.0	0.6	0.3	9.7	14.6	3.4	0.8	3.2	1.8
	% below LRNI	0.0	0.0	0.0	0.0	0.5	0.0	0.2	0.0	0.0	0.0
	Avg intake (mg/day)	756.7	827.6	871.8	982.2	943.1	1152.1	1123.2	1375.2	1057.8	1265.2
Zinc	% below RNI	61.4	57.0	81.0	64.7	80.0	72.6	42.8	55.1	52.2	67.5
	% below LRNI	11.0	5.5	14.6	8.3	15.7	20.0	6.7	5.5	4.1	8.6
	Avg intake (mg/day)	4.6	5.0	5.6	6.2	6.5	7.8	7.6	9.5	7.1	8.6
	Avg plasma zinc level (µmol/L)	-	-	13.3	14.2	13.5	14.2	12.8	13.8	12.7	13.2
	% below deficiency threshold	-	-	0.0	0.0	0.0	0.0	0.8	0.3	1.0	2.3
Copper	% below RNI	22.7	18.3	44.1	26.3	53.4	51.0	64.8	49.6	71.0	53.8
	% below LRNI	-	-	-	-	-	-	-	-	-	-
	Avg intake (mg/day)	0.6	0.6	0.7	0.8	0.9	1.0	1.1	1.3	1.1	1.3
Magnesium	% below RNI	8.8	1.9	50.0	29.2	91.6	81.0	67.3	54.4	75.0	67.9
	% below LRNI	0.0	0.0	2.8	1.0	46.3	32.5	11.3	11.7	11.2	14.4
	Avg intake (mg/day)	139.5	152.1	171.7	194.9	196.4	223.8	243.7	300.9	235.2	277.6

Riboflavin	% below RNI	1.2	1.3	1.2	1.4	1.2	1.6	1.4	1.7	1.4	1.8
	% below LRNI	0.0	0.0	0.9	1.1	22.2	13.2	13.3	4.2	10.5	5.2
	Avg intake (mg/day)	1.2	1.3	1.2	1.4	1.2	1.6	1.4	1.7	1.4	1.8
	Avg ERGAC value	-	-	1.3	1.3	1.5	1.4	1.3	1.3	1.3	1.3
	% below deficiency threshold	-	-	46.3	49.0	75.1	69.0	54.8	53.2	32.6	31.1

Appendix B Unit and value conversion for Chapter 5

Various conversion factors were used to translate raw ingredients in recipes into the cooked form they would be served to children. Additionally, some unit conversions were needed to match recipe ingredients to the McCance and Widdowson Composition of Food Integrated Dataset listings, which are listed per 100 grams unless specified otherwise.

Ingredient	Original amount	Original unit	New amount	New unit	Formula or explanation	Reference or link
brown and white rice (uncooked weight)	40	grams	120	grams	weight * 3	Omni calculator
apple juice	60	millilitres	62	grams	volume * 1.04	(Charrondiere, Haytowitz and Stadlmayr, 2012)
macaroni	25	grams	75	grams	weight *3	Back of pack label
pasta wholewheat fusilli	45	grams	100	grams	weight * 2.22	Omni calculator
green apple	2	pieces	34	grams	(avg apple weight (135 g) / 8 segments) * 2	(Bender and Muller, 2015)
high fibre bun	1	unit	50	grams	product information	SMP recipe management software
jacket potato	1	unit	150	grams	portion size for child is 200 g raw. Potatoes lose ¼ weight when cooked	https://pkunews.org/cooked-versus-raw/
orange	2	pieces	25	grams	avg weight of a peeled orange is 100 to 150 g. There are usually 10 segments. (125/10) *2	https://weighschool.com/orange-weights/
egg	1	unit	58	grams	avg weight of a medium egg is 53-63 g	https://www.egginfo.co.uk/egg-facts-and-figures/industry-informatio

						n/egg-sizes
pear	1	pieces	25	grams	avg weight of a small pear – 100 g. 100/8*2 = 25 g	https://www.sainsburys.co.uk/gol-ui/product/sainsburys-conference-pear-single#:~:text=Description,Nutrition & (Tóth-Markus *et al.*, 2011)
pork sausage	3	units	84	grams	recipe instructions from SMP say 1 portion is 84 g	SMP recipe management software
red apple	2	pieces	34	grams	avg apple weight = 135 g. 135 g/8*2 = 34 g	(Bender and Muller, 2015)
semi skimmed milk	80	millilitres	83.2	grams	Density of milk is 1.04 g/ml	Omni calculator
small (28 cm) white baguette	0.5	unit	62.5	grams	recipe instructions from SMP say 1 baguette weighs 125 g	SMP recipe management software
sweet potato	35	grams	26.25	grams	potatoes lose 25% of weight when cooked	https://pkunews.org/cooked-versus-raw/
wheat flour tortilla	0.5	unit	30	grams	recipe instructions from SMP say 1 tortilla weighs 60 g	SMP recipe management software
vegetable oil	1	millilitres	0.89	grams	Density of vegetable oil is 0.92 g/ml	Omni calculator
lemon juice	1	millilitres	1.03	grams	Density of lemon juice is 1.03 g/ml	https://www.aqua-calc.com/page/density-table/substance/lemon-blank-juice-

						coma-and-blank-raw
Ice cream	60	millilitres	33	grams	Density of ice cream is 0.55 g/ml	Omni calculator
mayonnaise	1	millilitres	0.972	grams	Density of mayonnaise is 0.91 g/ml	The Calculator Site

List of References

Abilgos Ramos, R. (2010) *Folate profiling in wild and transgenic rice*. Thesis. Nottingham. Available at: https://eprints.nottingham.ac.uk/12870/ (Accessed: 5 June 2025).

Adamant, A. (2019) 'Old Fashioned Parsnip Wine', *Practical Self Reliance*, 26 January. Available at: https://practicalselfreliance.com/parsnip-wine/ (Accessed: 7 July 2025).

Adamson, A. *et al.* (2013) 'School food standards in the UK: implementation and evaluation', *Public Health Nutrition*, 16(6), pp. 968–981. Available at: https://doi.org/10.1017/S1368980013000621.

Afshin, A. *et al.* (2019) 'Health effects of dietary risks in 195 countries, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017', *The Lancet*, 393(10184), pp. 1958–1972. Available at: https://doi.org/10.1016/S0140-6736(19)30041-8.

A&G Lamattina & Sons Ptd Ltd (2017) 'A History of Parsnips', *Lamattina*, 20 October. Available at: https://lamattina.com.au/2017/10/20/a-history-of-parsnips/ (Accessed: 6 May 2025).

AG Pearce Ltd (no date) *Our Parsnips*, *Alfred G Pearce*. Available at: https://www.alfredgpearce.co.uk/parsnips (Accessed: 6 May 2025).

Akoglu, H. (2018) 'User's guide to correlation coefficients', *Turkish Journal of Emergency Medicine*, 18(3), pp. 91–93. Available at: https://doi.org/10.1016/j.tjem.2018.08.001.

Alamnia, T.T., Sargent, G.M. and Kelly, M. (2023) 'Dietary patterns and associations with metabolic risk factors for non-communicable disease', *Scientific Reports*, 13(1), p. 21028. Available at: https://doi.org/10.1038/s41598-023-47548-0.

AMETEK Inc (2007) *Texture Analysis Instruments*. Available at: https://www.tectra.hu/pdf-docs/Lloyd-TAPlus.pdf (Accessed: 7 May 2025).

Andersson, J. *et al.* (2022) 'Comparison of steaming and boiling of root vegetables for enhancing carbohydrate content and sensory profile', *Journal of Food Engineering*, 312, p. 110754. Available at: https://doi.org/10.1016/j.jfoodeng.2021.110754.

Ashraf, S.A. (2025) 'Food fortification as a sustainable global strategy to mitigate micronutrient deficiencies and improve public health', *Discover Food*, 5(1), p. 201. Available at: https://doi.org/10.1007/s44187-025-00512-5.

Baddam, S., Khan, K.M. and Jialal, I. (2025) 'Folic Acid Deficiency', *StatPearls*. Treasure Island (FL): StatPearls Publishing. Available at: http://www.ncbi.nlm.nih.gov/books/NBK535377/ (Accessed: 7 August 2025).

Baggott, J.E. *et al.* (1992) 'Effects of folate deficiency and supplementation on methylnitrosourea-induced rat mammary tumors', *Journal of the National Cancer Institute*, 84(22), pp. 1740–1744. Available at: https://doi.org/10.1093/jnci/84.22.1740.

Bagley, P.J. and Selhub, J. (1998) 'A common mutation in the methylenetetrahydrofolate reductase gene is associated with an accumulation of formylated tetrahydrofolates in red blood cells', *Proceedings of the National Academy of Sciences of the United States of America*, 95(22), pp. 13217–13220.

Bailey, L.B. (1994) *Folate in Health and Disease*. CRC Press.

Bailey, Lynn B *et al.* (2015) 'Biomarkers of Nutrition for Development—Folate Review', *The Journal of Nutrition*, 145(7), pp. 1636S-1680S. Available at: https://doi.org/10.3945/jn.114.206599.

Bailey, Lynn B. *et al.* (2015) 'Biomarkers of Nutrition for Development-Folate Review', *The Journal of Nutrition*, 145(7), pp. 1636S-1680S. Available at: https://doi.org/10.3945/jn.114.206599.

Bailey, R.L. *et al.* (2017) 'Correspondence of folate dietary intake and biomarker data1, 2, 3', *The American Journal of Clinical Nutrition*, 105(6), pp. 1336–1343. Available at: https://doi.org/10.3945/ajcn.116.148775.

Bailey, R.L. (2021) 'Overview of Dietary Assessment Methods for Measuring Intakes of Foods, Beverages, and Dietary Supplements in Research Studies', *Current opinion in biotechnology*, 70, pp. 91–96. Available at: https://doi.org/10.1016/j.copbio.2021.02.007.

Bates, B. *et al.* (2014) *National Diet and Nutrition Survey. Results from Years 1, 2, 3 and 4 (combined) of the Rolling Programme (2008/2009-2011/2012)*. London: Public Health England, p. 160. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/594361/NDNS_Y1_to_4_UK_report_full_text_revised_February_2017.pdf (Accessed: 22 May 2022).

Bates, C., Thurnham, D. and Nelson, M. (1997) 'Biochemical Markers of Nutrient Status', *Design Concepts in Nutritional Epidemiology*. 2nd edn. Oxford: Oxford University Press, pp. 170–240.

Bationo, F., Savadogo, B. and Goubgou, M. (2022) 'Folates in various African foods: Contents, food processing and matrix effects', *International Journal for Vitamin and Nutrition Research*, 93(5), pp. 459–470. Available at: https://doi.org/10.1024/0300-9831/a000759.

BBC News (2015) 'Folic acid to fortify flour "would cut birth defects"', 18 December. Available at: https://www.bbc.com/news/health-35122699 (Accessed: 2 June 2025).

Bechoff, A. *et al.* (2023) 'Exploring the Complementarity of Fortification and Dietary Diversification to Combat Micronutrient Deficiencies: A Scoping Review', *Current Developments in Nutrition*, 7(2), p. 100033. Available at: https://doi.org/10.1016/j.cdnut.2023.100033.

Beck, K.L. *et al.* (2021) 'Micronutrients and athletic performance: A review', *Food and Chemical Toxicology*, 158, p. 112618. Available at: https://doi.org/10.1016/j.fct.2021.112618.

Beck, L. (no date) *Parsnips*, *Leslie Beck RD*. Available at: https://lesliebeck.com/foods/parsnips (Accessed: 7 July 2025).

Bekaert, S. *et al.* (2008) 'Folate biofortification in food plants', *Trends in plant science*, 13, pp. 28–35. Available at: https://doi.org/10.1016/j.tplants.2007.11.001.

Bender, R.J. and Muller, I. (2015) 'After harvest mechanical injuries on apples.' UFRGS (Federal University of Rio Grande do Sul). Available at: https://doi.org/10.13140/RG.2.1.2287.8569.

Bennett, G. and Gibney, E.R. (2024) 'An investigation of diet quality across racial groups in the United Kingdom and United States considering nutritional adequacy, disease risk, and environmental sustainability: a secondary analysis of NDNS and NHANES datasets', *Journal of Nutritional Science*, 13, p. e93. Available at: https://doi.org/10.1017/jns.2024.64.

de Benoist, B. (2008) ‘Conclusions of a WHO Technical Consultation on folate and vitamin B12 deficiencies’, *Food and Nutrition Bulletin*, 29(2 Suppl), pp. S238-244. Available at: https://doi.org/10.1177/15648265080292S129.

Berenbaum, M.R., Zangerl, A.R. and Nitao, J.K. (1984) ‘Furanocoumarins in seeds of wild and cultivated parsnip’, *Phytochemistry*, 23(8), pp. 1809–1810. Available at: https://doi.org/10.1016/S0031-9422(00)83503-7.

Berenbaum, M.R., Zangerl, A.R. and Nitao, J.K. (1986) ‘CONSTRAINTS ON CHEMICAL COEVOLUTION: WILD PARSNIPS AND THE PARSNIP WEBWORM’, *Evolution*, 40(6), pp. 1215–1228. Available at: https://doi.org/10.1111/j.1558-5646.1986.tb05746.x.

Berry Ottaway, P. (2010) ‘19 - Stability of vitamins during food processing and storage’, in L.H. Skibsted, J. Risbo, and M.L. Andersen (eds) *Chemical Deterioration and Physical Instability of Food and Beverages*. Woodhead Publishing (Woodhead Publishing Series in Food Science, Technology and Nutrition), pp. 539–560. Available at: https://doi.org/10.1533/9781845699260.3.539.

Bhardwaj, R.L. *et al.* (2024) ‘An Alarming Decline in the Nutritional Quality of Foods: The Biggest Challenge for Future Generations’ Health’, *Foods*, 13(6), p. 877. Available at: https://doi.org/10.3390/foods13060877.

Bianchi, E. *et al.* (2024) ‘Impact of the Mediterranean Diet on Athletic Performance, Muscle Strength, Body Composition, and Antioxidant Markers in Both Athletes and Non-Professional Athletes: A Systematic Review of Intervention Trials’, *Nutrients*, 16(20), p. 3454. Available at: https://doi.org/10.3390/nu16203454.

Bilenka, I. *et al.* (2018) ‘Effect of Pre-Treatment On Qualitative Indices of White Roots’, *Food Science and Technology*, 12(1). Available at: https://doi.org/10.15673/fst.v12i1.838.

Bite Back (2025) *Fuel Us Don’t Fool Us: Advertising. Are food giants bombarding young people on our streets?*, p. 22.

Bjørke-Monsen, A.-L. and Ueland, P.M. (2023) ‘Folate – a scoping review for Nordic Nutrition Recommendations 2023’, *Food & Nutrition Research*, 67, p. 10.29219/fnr.v67.10258. Available at: https://doi.org/10.29219/fnr.v67.10258.

Blancquaert, D. *et al.* (2013) ‘Enhancing pterin and para-aminobenzoate content is not sufficient to successfully biofortify potato tubers and Arabidopsis thaliana plants with folate’, *Journal of experimental botany*, 64(12). Available at: https://doi.org/10.1093/jxb/ert224.

Blancquaert, D. *et al.* (2015) ‘Improving folate (vitamin B9) stability in biofortified rice through metabolic engineering’, *Nature Biotechnology*, 33(10), pp. 1076–1078. Available at: https://doi.org/10.1038/nbt.3358.

Bloom, I. *et al.* (2018) ‘Diet Quality and Sarcopenia in Older Adults: A Systematic Review’, *Nutrients*, 10(3), p. 308. Available at: https://doi.org/10.3390/nu10030308.

Bo, Y. *et al.* (2020) ‘Association Between Folate and Health Outcomes: An Umbrella Review of Meta-Analyses’, *Frontiers in Public Health*, 8. Available at: https://doi.org/10.3389/fpubh.2020.550753.

Bo, Y. *et al.* (2022) ‘Intakes of Folate, Vitamin B6, and Vitamin B12 in Relation to All-Cause and Cause-Specific Mortality: A National Population-Based Cohort’, *Nutrients*, 14(11), p. 2253. Available at: https://doi.org/10.3390/nu14112253.

Boswell, V.R. (1923) *Changes in quality and chemical composition of parsnips under various storage conditions*. University of Maryland, Agricultural Experiment Station. Available at: https://scholar.google.com/scholar_lookup?title=Changes+in+quality+and+chemical+composition+of+parsnips+under+various+storage+conditions&author=Boswell%2C+Victor+R.+%28Victor+Rickman%29&publication_year=1923 (Accessed: 23 June 2022).

Bouzari, A., Holstege, D. and Barrett, D.M. (2015) 'Vitamin Retention in Eight Fruits and Vegetables: A Comparison of Refrigerated and Frozen Storage', *Journal of Agricultural and Food Chemistry*, 63(3), pp. 957–962. Available at: https://doi.org/10.1021/jf5058793.

Brandt, K. (2015) *Carrot and Parsnip: Intervention study to assess the effect of consumption on biomarkers of human health | AHDB*. AHDB. Available at: https://ahdb.org.uk/fv-420-carrot-and-parsnip-intervention-study-to-assess-the-effect-of-consumption-on-biomarkers-of-human-health (Accessed: 23 October 2021).

Breitling-Utzmann, C.M. and Hankele, S. (2019) 'Formation of acrylamide in vegetable crisps – Influence of processing conditions and reducing sugars'.

Brown, B. and Wright, C. (2020) 'Safety and efficacy of supplements in pregnancy', *Nutrition Reviews*, 78(10), pp. 813–826. Available at: https://doi.org/10.1093/nutrit/nuz101.

Brown, L. *et al.* (eds) (2010) *Preserve it! bottled fruits, jams & jellies, pickles, cured meats*. 1st American ed. New York, N.Y: DK Publishing.

Brownson, E. *et al.* (2024) 'Micronutrient Status and Prediction of Disease Outcome in Adults With Inflammatory Bowel Disease Receiving Biologic Therapy', *Inflammatory Bowel Diseases*, 30(8), pp. 1233–1240. Available at: https://doi.org/10.1093/ibd/izad174.

Brubacher, G., Müller-Mulot, W. and Southgate, D.A.T. (eds) (1985) *Methods for the Determination of Vitamins in Food*. Dordrecht: Springer Netherlands. Available at: https://doi.org/10.1007/978-94-009-4944-7.

Bufler, G. and Horneburg, B. (2013) 'Changes in sugar and starch concentrations in parsnip (*Pastinaca sativa* L.) during root growth and development and in cold storage', *The Journal of Horticultural Science and Biotechnology*, 88(6), pp. 756–761. Available at: https://doi.org/10.1080/14620316.2013.11513035.

Burgoine, T. *et al.* (2018) 'Examining the interaction of fast-food outlet exposure and income on diet and obesity: evidence from 51,361 UK Biobank participants', *International Journal of Behavioral Nutrition and Physical Activity*, 15(1), p. 71. Available at: https://doi.org/10.1186/s12966-018-0699-8.

CALU (2007) *Parsnips*. Centre for Alternative Land Use: Bangor University, p. 2.

Cardoso, R.V.C. *et al.* (2019) 'Flour fortification for nutritional and health improvement: A review', *Food Research International*, 125, p. 108576. Available at: https://doi.org/10.1016/j.foodres.2019.108576.

Carlson, B. (2023) 'When World War II Meant No Bananas For The UK, People Made "Mock Bananas" Out Of Parsnips', *Brady Carlson*, 19 April. Available at: https://www.bradycarlson.com/when-world-war-ii-meant-no-bananas-for-the-uk-people-made-mock-bananas-out-of-parsnips-cool-weird-awesome-991/ (Accessed: 6 May 2025).

Carrillo-Alvarez, E. *et al.* (2025) 'Diet-Related Health Inequalities in High-Income Countries: A Scoping Review of Observational Studies', *Advances in Nutrition*, 16(6), p. 100439. Available at: https://doi.org/10.1016/j.advnut.2025.100439.

de Carvalho, M.J.C. *et al.* (1996) 'Vitamin Status of Healthy Subjects in Burgundy (France)', *Annals of Nutrition & Metabolism*, 40(1), pp. 24–51.

Castillo-Lancellotti, C., Tur, J.A. and Uauy, R. (2013) 'Impact of folic acid fortification of flour on neural tube defects: a systematic review', *Public Health Nutrition*, 16(5), pp. 901–911. Available at: https://doi.org/10.1017/S1368980012003576.

Castro, A., Bergenståhl, B. and Tornberg, E. (2012) 'Parsnip (*Pastinaca sativa* L.): Dietary fibre composition and physicochemical characterization of its homogenized suspensions', *Food Research International*, 48(2), pp. 598–608. Available at: https://doi.org/10.1016/j.foodres.2012.05.023.

Cena, H. and Calder, P.C. (2020) 'Defining a Healthy Diet: Evidence for the Role of Contemporary Dietary Patterns in Health and Disease', *Nutrients*, 12(2), p. 334. Available at: https://doi.org/10.3390/nu12020334.

Chandra, R. (1997) 'Nutrition and the immune system: an introduction', *The American Journal of Clinical Nutrition*, 66(2), pp. 460S-463S. Available at: https://doi.org/10.1093/ajcn/66.2.460S.

Chapman, J. and Wentworth, J. (2024) 'Inequalities in diets'. Available at: https://post.parliament.uk/inequalities-in-diets/ (Accessed: 6 August 2025).

Chappell, L.H.K. and Dunford, A.J. (2021) 'Parsnip (*Pastinaca sativa* L.) Breeding for the Future', in J.M. Al-Khayri, S.M. Jain, and D.V. Johnson (eds) *Advances in Plant Breeding Strategies: Vegetable Crops: Volume 8: Bulbs, Roots and Tubers*. Cham: Springer International Publishing, pp. 239–273. Available at: https://doi.org/10.1007/978-3-030-66965-2_6.

Charrondiere, R., Haytowitz, D. and Stadlmayr, B. (2012) 'FAO / INFOODS Density Database Version 2.0 (2012)'. FAO.

Chaudhary, V., Saraswathy, K.N. and Sarwal, R. (2022) 'Dietary diversity as a sustainable approach towards micronutrient deficiencies in India', *The Indian Journal of Medical Research*, 156(1), pp. 31–45. Available at: https://doi.org/10.4103/ijmr.ijmr_3314_21.

Chen, W.-J. *et al.* (2023) 'Dietary Folate Deficiency Promotes Lactate Metabolic Disorders to Sensitize Lung Cancer Metastasis through MTOR-Signaling-Mediated Druggable Oncotargets', *Nutrients*, 15(6), p. 1514. Available at: https://doi.org/10.3390/nu15061514.

Childs, C.E., Calder, P.C. and Miles, E.A. (2019) 'Diet and Immune Function', *Nutrients*, 11(8), p. 1933. Available at: https://doi.org/10.3390/nu11081933.

Conner, M. *et al.* (2003) 'Environmental influences: factors influencing a woman's decision to use dietary supplements', *The Journal of Nutrition*, 133(6), pp. 1978S-1982S. Available at: https://doi.org/10.1093/jn/133.6.1978S.

Cook, J.D., Baynes, R.D. and Skikne, B.S. (1992) 'Iron Deficiency and the Measurement of Iron Status', *Nutrition Research Reviews*, 5(1), pp. 198–202. Available at: https://doi.org/10.1079/NRR19920014.

Costa, T.S. (2020) 'Parsnip Stir Fry – Parsnip Bhaji (পারস্নিপ ভাজি)', *Vegan Bangla*, 3 October. Available at: https://veganbangla.com/2020/10/03/parsnip-stir-fry-parsnip-bhaji-%e0%a6%aa%e0%a6%be%e0%a6%b0%e0%a6%b8%e0%a7%8d%e0%a6%a8%e0%a6%bf%e0%a6%aa-%e0%a6%ad%e0%a6%be%e0%a6%9c%e0%a6%bf/ (Accessed: 7 July 2025).

Craigie, A.M. *et al.* (2011) 'Tracking of obesity-related behaviours from childhood to adulthood: A systematic review', *Maturitas*, 70(3), pp. 266–284. Available at: https://doi.org/10.1016/j.maturitas.2011.08.005.

Crawley, H. (2005) *Nutrient-based standards for school food: a summary of the standards and recommendations of the Caroline Walker Trust and the National Heart Forum*. St Austell: National Heart Forum/Caroline Walker Trust.

Crider, K.S., Bailey, L.B. and Berry, R.J. (2011) 'Folic Acid Food Fortification—Its History, Effect, Concerns, and Future Directions', *Nutrients*, 3(3), pp. 370–384. Available at: https://doi.org/10.3390/nu3030370.

Croll, J.K., Neumark-Sztainer, D. and Story, M. (2001) 'Healthy Eating: What Does It Mean to Adolescents?', *Journal of Nutrition Education*, 33(4), pp. 193–198. Available at: https://doi.org/10.1016/S1499-4046(06)60031-6.

Czarnowska-Kujawska, M., Draszanowska, A. and Starowicz, M. (2022) 'Effect of different cooking methods on the folate content, organoleptic and functional properties of broccoli and spinach', *LWT*, 167, p. 113825. Available at: https://doi.org/10.1016/j.lwt.2022.113825.

Czarnowska-Kujawska, M., Gujska, E. and Michalak, J. (2017) 'Testing of different extraction procedures for folate HPLC determination in fresh fruits and vegetables', *Journal of Food Composition and Analysis*, 57, pp. 64–72. Available at: https://doi.org/10.1016/j.jfca.2016.12.019.

Czeizel, A.E. *et al.* (2013) 'Folate Deficiency and Folic Acid Supplementation: The Prevention of Neural-Tube Defects and Congenital Heart Defects', *Nutrients*, 5(11), pp. 4760–4775. Available at: https://doi.org/10.3390/nu5114760.

Davis, J. (no date) *Japanese-Style Parsnip & Carrot Stir-Fry Recipe | Abel & Cole*. Available at: https://www.abelandcole.co.uk/recipes/-japanese-style-parsnip--carrot-stir-fry (Accessed: 7 July 2025).

De Lepeleire, J. *et al.* (2017) 'Folate Biofortification of Potato by Tuber-Specific Expression of Four Folate Biosynthesis Genes', *Molecular Plant*, 11. Available at: https://doi.org/10.1016/j.molp.2017.12.008.

Delchier, N. *et al.* (2016) 'Folates in Fruits and Vegetables: Contents, Processing, and Stability', *Comprehensive Reviews in Food Science and Food Safety*, 15(3), pp. 506–528. Available at: https://doi.org/10.1111/1541-4337.12193.

Department for Education (2025a) *Over half a million more children to get free school meals*, *GOV.UK*. Available at: https://www.gov.uk/government/news/over-half-a-million-more-children-to-get-free-school-meals (Accessed: 29 July 2025).

Department for Education (2025b) *School food standards practical guide*, *GOV.UK*. Available at: https://www.gov.uk/government/publications/school-food-standards-resources-for-schools/school-food-standards-practical-guide (Accessed: 29 July 2025).

Department for Education (2025c) *Schools, pupils and their characteristics, Academic year 2024/25*. Available at: https://explore-education-statistics.service.gov.uk/find-statistics/school-pupils-and-their-characteristics/2024-25 (Accessed: 29 July 2025).

Department for Environment, Food & Rural Affairs (2024a) *Horticulture statistics - 2023*, *GOV.UK*. Available at: https://www.gov.uk/government/statistics/latest-horticulture-statistics (Accessed: 9 June 2025).

Department for Environment, Food & Rural Affairs (2024b) *United Kingdom Food Security Report 2024*. Available at: https://www.gov.uk/government/statistics/united-kingdom-food-security-report-2024/united-kingdom-food-security-report-2024-introduction (Accessed: 16 May 2025).

Department for Levelling Up, Housing and Communities (2022) *Levelling Up the United Kingdom*, *GOV.UK*. Available at: https://www.gov.uk/government/publications/levelling-up-the-united-kingdom (Accessed: 24 February 2022).

Department of Health (ed.) (1991) *Dietary reference values for food energy and nutrients for the United Kingdom: report*. 18. impression. London: TSO (Report on health and social subjects, 41).

Department of Health (2000) *Folic acid and the prevention of disease: report of the Committee on Medical Aspects of Food and Nutrition Policy*. London: The Stationery Office (Report on health and social subjects, 50).

Department of Health and Social Care *et al.* (2024) *Birth defects prevented by fortifying flour with folic acid*, *GOV.UK*. Available at: https://www.gov.uk/government/news/birth-defects-prevented-by-fortifying-flour-with-folic-acid (Accessed: 2 June 2025).

De-Regil, L.M. *et al.* (2015) 'Effects and safety of periconceptional oral folate supplementation for preventing birth defects - De-Regil, LM - 2015 | Cochrane Library'. Available at: https://doi.org/10.1002/14651858.CD007950.pub3.

DHSC (2025) *Great Britain nutrition and health claims (NHC) register*, *GOV.UK*. Available at: https://www.gov.uk/government/publications/great-britain-nutrition-and-health-claims-nhc-register (Accessed: 11 July 2025).

Díaz de la Garza, R. *et al.* (2004) 'Folate biofortification in tomatoes by engineering the pteridine branch of folate synthesis', *Proceedings of the National Academy of Sciences of the United States of America*, 101(38), pp. 13720–13725. Available at: https://doi.org/10.1073/pnas.0404208101.

Díaz de la Garza, R.I., Gregory, J.F. and Hanson, A.D. (2007) 'Folate biofortification of tomato fruit', *Proceedings of the National Academy of Sciences*, 104(10), pp. 4218–4222. Available at: https://doi.org/10.1073/pnas.0700409104.

Dickinson, A. and MacKay, D. (2014) 'Health habits and other characteristics of dietary supplement users: a review', *Nutrition Journal*, 13, p. 14. Available at: https://doi.org/10.1186/1475-2891-13-14.

Distéfano, A.M. *et al.* (2017) 'Heat stress induces ferroptosis-like cell death in plants', *The Journal of Cell Biology*, 216(2), pp. 463–476. Available at: https://doi.org/10.1083/jcb.201605110.

Dong, W. *et al.* (2014) 'Overexpression of Folate Biosynthesis Genes in Rice (Oryza sativa L.) and Evaluation of Their Impact on Seed Folate Content', *Plant Foods for Human Nutrition*, 69(4), pp. 379–385. Available at: https://doi.org/10.1007/s11130-014-0450-9.

Dorninger, C. *et al.* (2020) 'Leverage points for sustainability transformation: a review on interventions in food and energy systems', *Ecological Economics*, 171, p. 106570. Available at: https://doi.org/10.1016/j.ecolecon.2019.106570.

Downie, S.R., Katz-Downie, D.S. and Watson, M.F. (2000) 'A phylogeny of the flowering plant family Apiaceae based on chloroplast DNA rpl16 and rpoC1 intron sequences: towards a suprageneric classification of subfamily Apioideae', *American Journal of Botany*, 87(2), pp. 273–292. Available at: https://doi.org/10.2307/2656915.

Dresen, E. *et al.* (2023) 'History of scurvy and use of vitamin C in critical illness: A narrative review', *Nutrition in Clinical Practice*, 38(1), pp. 46–54. Available at: https://doi.org/10.1002/ncp.10914.

Dwyer, J.T. *et al.* (2015) 'Fortification and Health: Challenges and Opportunities', *Advances in Nutrition*, 6(1), pp. 124–131. Available at: https://doi.org/10.3945/an.114.007443.

Dyson, E. *et al.* (2023) 'Impacts of the Ukraine–Russia Conflict on the Global Food Supply Chain and Building Future Resilience', *EuroChoices*, 22(1). Available at: https://doi.org/10.1111/1746-692X.12380.

Education and Skills Funding Agency and Department for Education (2025) *Universal infant free school meals (UIFSM): 2024 to 2025*, *GOV.UK*. Available at: https://www.gov.uk/government/publications/universal-infant-free-school-meals-uifsm-2024-to-2025 (Accessed: 29 July 2025).

Ellis, G.F. and Schneider, B. (2024) *srvyr: 'dplyr'-Like Syntax for Summary Statistics of Survey Data*. Available at: https://CRAN.R-project.org/package=srvyr.

English, L.K. *et al.* (2024) 'Dietary Patterns and Health: Insights From NESR Systematic Reviews to Inform the *Dietary Guidelines for Americans*', *Journal of Nutrition Education and Behavior*, 56(1), pp. 75–87. Available at: https://doi.org/10.1016/j.jneb.2023.10.001.

Espinosa-Salas, S. and Gonzalez-Arias, M. (2025) 'Nutrition: Micronutrient Intake, Imbalances, and Interventions', *StatPearls*. Treasure Island (FL): StatPearls Publishing. Available at: http://www.ncbi.nlm.nih.gov/books/NBK597352/ (Accessed: 7 August 2025).

Fabbri, A.D.T. and Crosby, G.A. (2016) 'A review of the impact of preparation and cooking on the nutritional quality of vegetables and legumes', *International Journal of Gastronomy and Food Science*, 3, pp. 2–11. Available at: https://doi.org/10.1016/j.ijgfs.2015.11.001.

Fallah, M. *et al.* (2025) 'Folate Biomarkers, Folate Intake, and Risk of Death From All Causes, Cardiovascular Disease, and Cancer: A Systematic Review and Dose-Response Meta-Analysis of Prospective Cohort Studies', *Nutrition Reviews*, 83(3), pp. e801–e813. Available at: https://doi.org/10.1093/nutrit/nuae077.

Falsafi, S.R. *et al.* (2025) 'Recent trends in fortifying bread with nutrients: Comprehensive insights into chemical, physical, functional, and nutritional attributes', *Future Foods*, 11, p. 100674. Available at: https://doi.org/10.1016/j.fufo.2025.100674.

Fanzo, J. *et al.* (2021) 'Sustainable food systems and nutrition in the 21st century: a report from the 22nd annual Harvard Nutrition Obesity Symposium', *The American Journal of Clinical Nutrition*, 115(1), pp. 18–33. Available at: https://doi.org/10.1093/ajcn/nqab315.

FAO (1996) *Declaration on world food security*. Rome, FAO. Available at: https://www.fao.org/4/w3548e/w3548e00.htm (Accessed: 27 January 2025).

FAO (2002) *The world food summit - five years later*. Available at: https://www.fao.org/4/y1780e/y1780e00.htm#TopOfPage (Accessed: 27 January 2025).

FAO *et al.* (2024) *The State of Food Security and Nutrition in the World 2024 – Financing to end hunger, food insecurity and malnutrition in all its forms*. Rome, Italy: FAO ; IFAD ; UNICEF ; WFP ; WHO ; (The State of Food Security and Nutrition in the World (SOFI), 2024). Available at: https://openknowledge.fao.org/handle/20.500.14283/cd1254en (Accessed: 27 January 2025).

FAO (2025) ‘Food and Agriculture Organization of the United Nations - Production: Crops and livestock products (2025).’ Available at: https://www.fao.org/faostat/en/#data/QCL (Accessed: 12 August 2025).

FAO *et al.* (2025) *The State of Food Security and Nutrition in the World 2025 - Addressing high food price inflation for food security and nutrition*. Rome. Available at: https://doi.org/10.4060/cd6008en.

Fardous, A.M. and Heydari, A.R. (2023) ‘Uncovering the Hidden Dangers and Molecular Mechanisms of Excess Folate: A Narrative Review’, *Nutrients*, 15(21), p. 4699. Available at: https://doi.org/10.3390/nu15214699.

Federal Food Safety and Vetinary Office FSVO (2021) *Swiss food composition database version 6.3*, *The Swiss Food Composition Database*. Available at: https://valorinutritivi.ch/en/versions-and-updates/ (Accessed: 11 January 2022).

Fisher, D. (2025) ‘Dataset in support of the thesis “An Investigation of Overlooked Complexities Affecting UK Vitamin C Security and the Potential for Local Crops to Address Insecurities: A Case of UK Strawberries”.’ University of Southampton. Available at: https://doi.org/10.5258/SOTON/D3582.

Flynn, A.N. *et al.* (2025) ‘Dish swap across a weekly menu can deliver health and sustainability gains’, *Nature Food*, pp. 1–5. Available at: https://doi.org/10.1038/s43016-025-01218-8.

Food Foundation (2025) *Food Insecurity Tracking*. Round 16. Available at: https://foodfoundation.org.uk/initiatives/food-insecurity-tracking (Accessed: 5 August 2025).

Food Standards Agency (2022) ‘Chapter 1: The nation’s plate, our diet and food choices today’, *Our Food 2021: An annual review of food standards across the UK*. 1.7. Food Standards Agency, p. 127. Available at: https://www.food.gov.uk/our-work/chapter-1-the-nations-plate-our-diet-and-food-choices-today (Accessed: 27 May 2025).

Garnett, E.E. *et al.* (2020) ‘Order of meals at the counter and distance between options affect student cafeteria vegetarian sales’, *Nature Food*, 1(8), pp. 485–488. Available at: https://doi.org/10.1038/s43016-020-0132-8.

George, K. (2019) *Folate Deficiency: Causes, Complications, and Prevention*, *ActiveBeat - Your Daily Dose of Health Headlines*. Available at: https://activebeat.com/your-health/folate-deficiency-causes-complications-and-prevention/ (Accessed: 2 June 2025).

Gibson, R. (2021) ‘Biomarkers’, *Principles of Nutritional Assessment*. 3rd edn. Available at: https://nutritionalassessment.org/bio-markers/.

Gibson, R.S. (1990) *Principles of Nutritional Assessment*. Oxford: Oxford University Press.

Gilson, T. (2017) ‘Parsnip Crisps’, *Food Meanderings*, 7 October. Available at: https://foodmeanderings.com/parsnip-crisps/ (Accessed: 7 July 2025).

van Ginkel, M. and Cherfas, J. (2023) ‘What is wrong with biofortification’, *Global Food Security*, 37, p. 100689. Available at: https://doi.org/10.1016/j.gfs.2023.100689.

Gmelch, L. *et al.* (2020) ‘Comprehensive Vitamer Profiling of Folate Mono- and Polyglutamates in Baker’s Yeast (Saccharomyces cerevisiae) as a Function of Different Sample Preparation Procedures’, *Metabolites*, 10(8), p. 301. Available at: https://doi.org/10.3390/metabo10080301.

Golley, R., Pearce, J. and Nelson, M. (2011) 'Children's lunchtime food choices following the introduction of food-based standards for school meals: observations from six primary schools in Sheffield', *Public Health Nutrition*, 14(2), pp. 271–278. Available at: https://doi.org/10.1017/S1368980010002120.

Gombart, A.F., Pierre, A. and Maggini, S. (2020) 'A Review of Micronutrients and the Immune System–Working in Harmony to Reduce the Risk of Infection', *Nutrients*, 12(1), p. 236. Available at: https://doi.org/10.3390/nu12010236.

Good Food (no date) *Parsnip | Good Food*. Available at: https://www.bbcgoodfood.com/glossary/parsnip-glossary (Accessed: 7 July 2025).

Gorelova, V. *et al.* (2017) 'Folates in Plants: Research Advances and Progress in Crop Biofortification', *Frontiers in Chemistry*, 5. Available at: https://doi.org/10.3389/fchem.2017.00021.

Goyer, A. and Navarre, D.A. (2007) 'Determination of folate concentrations in diverse potato germplasm using a trienzyme extraction and a microbiological assay', *Journal of Agricultural and Food Chemistry*, 55(9), pp. 3523–3528. Available at: https://doi.org/10.1021/jf063647x.

Graves, S., Piepho, H.-P. and Dorai-Raj, L.S. with help from S. (2024) *multcompView: Visualizations of Paired Comparisons*. Available at: https://CRAN.R-project.org/package=multcompView.

Green, R. and Datta Mitra, A. (2017) 'Megaloblastic Anemias: Nutritional and Other Causes', *The Medical Clinics of North America*, 101(2), pp. 297–317. Available at: https://doi.org/10.1016/j.mcna.2016.09.013.

Greene, K. (2016) 'Apiaceae Agronomy', *farmersmarketinstitute.org* [Preprint].

Grimaccia, E. and Naccarato, A. (2022) 'Food Insecurity in Europe: A Gender Perspective', *Social Indicators Research*, 161(2), pp. 649–667. Available at: https://doi.org/10.1007/s11205-020-02387-8.

Gross, K.C., Wang, C.Y. and Saltveit, M. (2016) *The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks* [pdf]. USDA, p. 3.8 MB. Available at: https://doi.org/10.22004/AG.ECON.348552.

Grosse, S.D. *et al.* (2005) 'Reevaluating the Benefits of Folic Acid Fortification in the United States: Economic Analysis, Regulation, and Public Health', *American Journal of Public Health*, 95(11), pp. 1917–1922. Available at: https://doi.org/10.2105/AJPH.2004.058859.

Grosso, G. (2019) 'Impact of nutritional risk factors on chronic non-communicable diseases', *European Journal of Public Health*, 29(Supplement_4), p. ckz185.197. Available at: https://doi.org/10.1093/eurpub/ckz185.197.

Gunter, E. (2020) 'National Diet and Nutrition Survey: Years 9 to 11 of the Rolling Programe (2016/2017 to 2018/2019)'.

Guys and St Thomas' Charity (2020) *Serving up children's health*. Available at: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://urbanhealth.org.uk/wp-content/uploads/2020/12/Serving-up-childrens-health.pdf (Accessed: 5 August 2025).

Hammond, R.A. and Dubé, L. (2012) 'A systems science perspective and transdisciplinary models for food and nutrition security', *Proceedings of the National Academy of Sciences of the*

United States of America, 109(31), pp. 12356–12363. Available at: https://doi.org/10.1073/pnas.0913003109.

Han, X. *et al.* (2022) 'Global, regional, and national burdens of common micronutrient deficiencies from 1990 to 2019: A secondary trend analysis based on the Global Burden of Disease 2019 study', *EClinicalMedicine*, 44, p. 101299. Available at: https://doi.org/10.1016/j.eclinm.2022.101299.

Haney, E. *et al.* (2023) 'Dietary quality of school meals and packed lunches: a national study of primary and secondary schoolchildren in the UK', *Public Health Nutrition*, 26(2), pp. 425–436. Available at: https://doi.org/10.1017/S1368980022001355.

Harris, S. (no date) *Oxford University Plants 400: Pastinaca sativa*. Available at: https://herbaria.plants.ox.ac.uk/bol/plants400/Profiles/op/Pastinaca (Accessed: 6 May 2025).

Harrison, R.A. *et al.* (2004) 'Are those in need taking dietary supplements? A survey of 21 923 adults', *The British Journal of Nutrition*, 91(4), pp. 617–623. Available at: https://doi.org/10.1079/BJN20031076.

Hawkesworth, S. *et al.* (2017) 'Investigating the importance of the local food environment for fruit and vegetable intake in older men and women in 20 UK towns: a cross-sectional analysis of two national cohorts using novel methods', *International Journal of Behavioral Nutrition and Physical Activity*, 14(1), p. 128. Available at: https://doi.org/10.1186/s12966-017-0581-0.

Health, C.F. (2022) *Lacto-fermented Carrot and Parsnip Pickles Recipe*, *Cultures For Health*. Available at: https://culturesforhealth.com/blogs/recipes/fermentation-recipe-lacto-fermented-carrot-parsnip-pickles (Accessed: 7 July 2025).

Hefni, M.E., Shalaby, M.T. and Witthöft, C.M. (2015) 'Folate content in faba beans (Vicia faba L.)—effects of cultivar, maturity stage, industrial processing, and bioprocessing', *Food Science & Nutrition*, 3(1), pp. 65–73. Available at: https://doi.org/10.1002/fsn3.192.

Heil, S.G. *et al.* (2012) 'Screening for metabolic vitamin B12 deficiency by holotranscobalamin in patients suspected of vitamin B12 deficiency: a multicentre study', *Annals of Clinical Biochemistry*, 49(Pt 2), pp. 184–189. Available at: https://doi.org/10.1258/acb.2011.011039.

Hendrick, U.P. (1919) *Sturtevant's Notes on Edible Plants*. Albany, New York: JB Lyon State Printer.

Henríquez-Sánchez, P. *et al.* (2009) 'Dietary assessment methods for micronutrient intake: a systematic review on vitamins', *British Journal of Nutrition*, 102(S1), pp. S10–S37. Available at: https://doi.org/10.1017/S0007114509993126.

Herbert, V. (1987) 'Making sense of laboratory tests of folate status: folate requirements to sustain normality', *American Journal of Hematology*, 26(2), pp. 199–207. Available at: https://doi.org/10.1002/ajh.2830260211.

Hill & Vale (no date) *Pickled Carrots and Parsnips*, *Hill & Vale*. Available at: https://www.hillvale.co.uk/blogs/recipes/pickled-carrots-and-parsnips (Accessed: 7 July 2025).

Hill, M.H.E. *et al.* (2009) 'Effects of methodological variation on assessment of riboflavin status using the erythrocyte glutathione reductase activation coefficient assay', *The British Journal of Nutrition*, 102(2), pp. 273–278. Available at: https://doi.org/10.1017/S0007114508162997.

Hinkle, D.E., Wiersma, W. and Jurs, S.G. (2003) *Applied statistics for the behavioral sciences*. 5. Aufl. Boston: Houghton Mifflin Company.

Hirschler, R. (2016) 'Whiteness, Yellowness, and Browning in Food Colorimetry. A Critical Review', *Color in Food: technological and Psychophysical Aspects*. 1st edn. CRC Press, p. 478.

Hotti, H. *et al.* (2015) 'Polyketide synthases from poison hemlock (Conium maculatum L.)', *The FEBS journal*, 282(21), pp. 4141–4156. Available at: https://doi.org/10.1111/febs.13410.

HPLE (2017) *Nutrition and Food Systems. A Report by The High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security*. Rome.

Huey, S.L. *et al.* (2023) 'A systematic review of the impacts of post-harvest handling on provitamin A, iron and zinc retention in seven biofortified crops', *Nature Food*, 4(11), pp. 978–985. Available at: https://doi.org/10.1038/s43016-023-00874-y.

Ilić, Z. *et al.* (2013) 'Effect of Postharvest Treatments and Storage Conditions on Quality Parameters of Carrots', *Journal of Agricultural Science*, 5(5), p. p100. Available at: https://doi.org/10.5539/jas.v5n5p100.

Ilić, Z.S. *et al.* (2016) 'Quality of Root Vegetables during Prolonged Storage', *Agriculturae Conspectus Scientificus*, 81(2), pp. 115–122.

Ilić, Z.S. and Sunić, L. (2015) 'Carbohydrate Changes in Parsnip (Pastinaca sativa L.) during Long-Term Cold Storage', *Acta Horticulturae*, (1079), pp. 667–674. Available at: https://doi.org/10.17660/ActaHortic.2015.1079.91.

Imhoff-Kunsch, B. *et al.* (2007) 'Wheat Flour Fortification Is Unlikely to Benefit the Neediest in Guatemala', *The Journal of Nutrition*, 137(4), pp. 1017–1022. Available at: https://doi.org/10.1093/jn/137.4.1017.

Indrawati *et al.* (2004) 'Comparative study on pressure and temperature stability of 5-methyltetrahydrofolic acid in model systems and in food products', *JOURNAL OF AGRICULTURAL AND FOOD CHEMISTRY*, 52(3), pp. 485–492. Available at: https://doi.org/10.1021/jf0349432.

Iniesta, M. *et al.* (2009) 'Folate Content in Tomato (Lycopersicon esculentum). Influence of Cultivar, Ripeness, Year of Harvest, and Pasteurization and Storage Temperatures', *JOURNAL OF AGRICULTURAL AND FOOD CHEMISTRY*, 57(11), pp. 4739–4745. Available at: https://doi.org/10.1021/jf900363r.

Institute of Medicine (US) Panel on Dietary Antioxidants and Related Compounds (2000) *Dietary Reference Intakes for Vitamin C, Vitamin E, Selenium, and Carotenoids*. Washington (DC): National Academies Press (US). Available at: http://www.ncbi.nlm.nih.gov/books/NBK225483/ (Accessed: 10 May 2023).

Institute of Medicine (US) Standing Committee on the Scientific Evaluation of Dietary Reference Intakes and its Panel on Folate, Other B Vitamins, and Choline (1998) *Dietary Reference Intakes for Thiamin, Riboflavin, Niacin, Vitamin B6, Folate, Vitamin B12, Pantothenic Acid, Biotin, and Choline*. Washington (DC): National Academies Press (US) (The National Academies Collection: Reports funded by National Institutes of Health). Available at: http://www.ncbi.nlm.nih.gov/books/NBK114310/ (Accessed: 24 April 2023).

Islam, M. *et al.* (2021) 'Folate content in fresh corn: Effects of harvest time, storage and cooking methods', *Journal of Food Composition and Analysis*, 103, p. 104123. Available at: https://doi.org/10.1016/j.jfca.2021.104123.

Ismail, S., Eljazzar, S. and Ganji, V. (2023) ‘Intended and Unintended Benefits of Folic Acid Fortification—A Narrative Review’, *Foods*, 12(8), p. 1612. Available at: https://doi.org/10.3390/foods12081612.

Jacob, R.A., Pianalto, F.S. and Agee, R.E. (1992) ‘Cellular ascorbate depletion in healthy men’, *The Journal of Nutrition*, 122(5), pp. 1111–1118. Available at: https://doi.org/10.1093/jn/122.5.1111.

James, L.F., Ralphs, M.H. and Nielsen, D.B. (2019) *The Ecology And Economic Impact Of Poisonous Plants On Livestock Production*. Boca Raton: CRC Press. Available at: https://doi.org/10.1201/9780429310225.

Jelena, M.S. *et al*. (2014) ‘Antimicrobial potential of essential oil from Pastinaca sativa L.’, *Biologica Nyssana*, 5(1). Available at: https://journal.pmf.ni.ac.rs/bionys/index.php/bionys/article/view/43 (Accessed: 24 June 2025).

Johnson, A. (2024) ‘Universal infant free school meal policy helps children eat less ultra-processed foods’, *NIHR School for Public Health Research*, 1 November. Available at: https://sphr.nihr.ac.uk/news-and-events/news/universal-infant-free-school-meal-policy-helps-children-eat-less-ultra-processed-foods/ (Accessed: 13 August 2025).

Johnson, L.E. (2021) *Selenium Deficiency - Nutritional Disorders*, *MSD Manual Professional Edition*. Available at: https://www.msdmanuals.com/professional/nutritional-disorders/mineral-deficiency-and-toxicity/selenium-deficiency (Accessed: 10 May 2023).

Johnson, L.E. (2022a) *Folate Deficiency - Nutritional Disorders - MSD Manual Professional Edition*, *MSD Manual Professional Version*. Available at: https://www.msdmanuals.com/en-gb/professional/nutritional-disorders/vitamin-deficiency,-dependency,-and-toxicity/folate-deficiency (Accessed: 9 May 2023).

Johnson, L.E. (2022b) *Vitamin A Deficiency - Nutritional Disorders*, *MSD Manual Professional Edition*. Available at: https://www.msdmanuals.com/en-gb/professional/nutritional-disorders/vitamin-deficiency,-dependency,-and-toxicity/vitamin-a-deficiency (Accessed: 9 May 2023).

Johnson, L.E. (2022c) *Vitamin B12 Deficiency - Nutritional Disorders*, *MSD Manual Professional Edition*. Available at: https://www.msdmanuals.com/en-gb/professional/nutritional-disorders/vitamin-deficiency,-dependency,-and-toxicity/vitamin-b12-deficiency (Accessed: 10 May 2023).

Johnson, L.E. (2022d) *Vitamin C Deficiency - Nutritional Disorders*, *MSD Manual Professional Edition*. Available at: https://www.msdmanuals.com/professional/nutritional-disorders/vitamin-deficiency,-dependency,-and-toxicity/vitamin-c-deficiency (Accessed: 10 May 2023).

Johnson, L.E. (2022e) *Vitamin D Deficiency and Dependency - Nutritional Disorders*, *MSD Manual Professional Edition*. Available at: https://www.msdmanuals.com/en-gb/professional/nutritional-disorders/vitamin-deficiency,-dependency,-and-toxicity/vitamin-d-deficiency-and-dependency (Accessed: 10 May 2023).

Johnson, L.E. (2022f) *Vitamin E Deficiency - Nutritional Disorders*, *MSD Manual Professional Edition*. Available at: https://www.msdmanuals.com/professional/nutritional-disorders/vitamin-deficiency,-dependency,-and-toxicity/vitamin-e-deficiency (Accessed: 10 May 2023).

Johnston, C.S. and Corte, C. (1999) 'People with Marginal Vitamin C Status are at High Risk of Developing Vitamin C Deficiency', *Journal of the American Dietetic Association*, 99(7), pp. 854–856. Available at: https://doi.org/10.1016/S0002-8223(99)00203-5.

Johnstone, A.M. and Lonnie, M. (2024) 'Tackling diet inequalities in the UK food system: is food insecurity driving the obesity epidemic? (The FIO Food project)', *Proceedings of the Nutrition Society*, 83(3), pp. 133–141. Available at: https://doi.org/10.1017/S0029665123004871.

Jones, K.S. *et al.* (2021a) 'Erythrocyte transketolase activity coefficient (ETKAC) assay protocol for the assessment of thiamine status', *Annals of the New York Academy of Sciences*, 1498(1), pp. 77–84. Available at: https://doi.org/10.1111/nyas.14547.

Jones, K.S. *et al.* (2021b) 'Erythrocyte transketolase activity coefficient (ETKAC) assay protocol for the assessment of thiamine status', *Annals of the New York Academy of Sciences*, 1498(1), pp. 77–84. Available at: https://doi.org/10.1111/nyas.14547.

Jones, K.S. *et al.* (2023) 'National Diet and Nutrition Survey data reveal a decline in folate status in the United Kingdom population between 2008 and 2019', *The American Journal of Clinical Nutrition*, 118(6), pp. 1182–1191. Available at: https://doi.org/10.1016/j.ajcnut.2023.10.006.

Kaganov, B. *et al.* (2015) 'Suboptimal Micronutrient Intake among Children in Europe', *Nutrients*, 7(5), pp. 3524–3535. Available at: https://doi.org/10.3390/nu7053524.

Kaim, U. and Goluch, Z.S. (2023) 'Health Benefits of Bread Fortification: A Systematic Review of Clinical Trials according to the PRISMA Statement', *Nutrients*, 15(20), p. 4459. Available at: https://doi.org/10.3390/nu15204459.

Kandel, S. (2019) 'An Evidence-based Look at the Effects of Diet on Health', *Cureus*, 11(5). Available at: https://doi.org/10.7759/cureus.4715.

Kariluoto, S., Edelmann, M. and Piironen, V. (2010) 'Effects of Environment and Genotype on Folate Contents in Wheat in the HEALTHGRAIN Diversity Screen', *Journal of Agricultural and Food Chemistry*, 58(17), pp. 9324–9331. Available at: https://doi.org/10.1021/jf100251j.

Kassambara, A. (2023a) *ggpubr: 'ggplot2' Based Publication Ready Plots*. Available at: https://CRAN.R-project.org/package=ggpubr.

Kassambara, A. (2023b) *rstatix: Pipe-Friendly Framework for Basic Statistical Tests*. Available at: https://CRAN.R-project.org/package=rstatix.

Kenari, H.M. *et al.* (2021) 'Review of Pharmacological Properties and Chemical Constituents of Pastinaca sativa', *Journal of Pharmacopuncture*, 24(1), pp. 14–23. Available at: https://doi.org/10.3831/KPI.2021.24.1.14.

Khadivi, A., Mirheidari, F. and Moradi, Y. (2023) 'Morphological characterizations of parsnip (Pastinaca sativa L.) to select superior genotypes', *Food Science & Nutrition*, 11(7), pp. 3858–3874. Available at: https://doi.org/10.1002/fsn3.3371.

Khan, K.M. and Jialal, I. (2023) 'Folic Acid Deficiency', *StatPearls*. Treasure Island (FL): StatPearls Publishing. Available at: http://www.ncbi.nlm.nih.gov/books/NBK535377/ (Accessed: 2 June 2025).

Kim, J. and Lim, H. (2019) 'Nutritional Management in Childhood Obesity', *Journal of Obesity & Metabolic Syndrome*, 28(4), pp. 225–235. Available at: https://doi.org/10.7570/jomes.2019.28.4.225.

Kim, Y.-I. (2004) ‘Folate, colorectal carcinogenesis, and DNA methylation: Lessons from animal studies’, *Environmental and Molecular Mutagenesis*, 44(1), pp. 10–25. Available at: https://doi.org/10.1002/em.20025.

Kim, Y.-I. (2018) ‘Folate and cancer: a tale of Dr. Jekyll and Mr. Hyde?’, *The American Journal of Clinical Nutrition*, 107(2), pp. 139–142. Available at: https://doi.org/10.1093/ajcn/nqx076.

Koontz, J.L. *et al.* (2005) ‘Comparison of Total Folate Concentrations in Foods Determined by Microbiological Assay at Several Experienced U.S. Commercial Laboratories’, *Journal of AOAC INTERNATIONAL*, 88(3), pp. 805–813. Available at: https://doi.org/10.1093/jaoac/88.3.805.

Kraemer, C.M. (2022) ‘Vitamin C (Ascorbic Acid): Reference Range, Interpretation, Collection and Panels’. Available at: https://emedicine.medscape.com/article/2088649-overview (Accessed: 10 May 2023).

Kretsch, M.J., Sauberlich, H.E. and Newbrun, E. (1991) ‘Electroencephalographic changes and periodontal status during short-term vitamin B-6 depletion of young, nonpregnant women’, *The American Journal of Clinical Nutrition*, 53(5), pp. 1266–1274. Available at: https://doi.org/10.1093/ajcn/53.5.1266.

Kumar, M. *et al.* (2024) ‘Micronutrients throughout the Life Cycle: Needs and Functions in Health and Disease’, *Current Nutrition & Food Science*, 20(1), pp. 62–84. Available at: https://doi.org/10.2174/1573401319666230420094603.

Lamers, Y. (2019) ‘Approaches to improving micronutrient status assessment at the population level’, *Proceedings of the Nutrition Society*, 78(2), pp. 170–176. Available at: https://doi.org/10.1017/S0029665118002781.

Laws, B. (2006) *The Curious History of Vegetables: The Curious History of Vegetables*. 1st ed. London: History Press Limited, The.

Lee, S. *et al.* (2017) ‘Effect of different cooking methods on the content of vitamins and true retention in selected vegetables’, *Food Science and Biotechnology*, 27(2), pp. 333–342. Available at: https://doi.org/10.1007/s10068-017-0281-1.

Leeming, E.R. *et al.* (2019) ‘Effect of Diet on the Gut Microbiota: Rethinking Intervention Duration’, *Nutrients*, 11(12), p. 2862. Available at: https://doi.org/10.3390/nu11122862.

Lehner, M., Mont, O. and Heiskanen, E. (2016) ‘Nudging – A promising tool for sustainable consumption behaviour?’, *Journal of Cleaner Production*, 134, pp. 166–177. Available at: https://doi.org/10.1016/j.jclepro.2015.11.086.

Lemmens, E. *et al.* (2019) ‘Steeping and germination of wheat (*Triticum aestivum* L.). I. Unlocking the impact of phytate and cell wall hydrolysis on bio-accessibility of iron and zinc elements’, *Journal of Cereal Science*, 90, p. 102847. Available at: https://doi.org/10.1016/j.jcs.2019.102847.

Lemmens, L. *et al.* (2014) ‘Carotenoid bioaccessibility in fruit- and vegetable-based food products as affected by product (micro)structural characteristics and the presence of lipids: A review’, *Trends in Food Science & Technology*, 38(2), pp. 125–135. Available at: https://doi.org/10.1016/j.tifs.2014.05.005.

Leonard, J. (2020) *Vitamin B-12 level test: Uses, normal ranges, and results*. Available at: https://www.medicalnewstoday.com/articles/322286 (Accessed: 10 May 2023).

Levine, M. *et al.* (1996) 'Vitamin C pharmacokinetics in healthy volunteers: evidence for a recommended dietary allowance.', *Proceedings of the National Academy of Sciences of the United States of America*, 93(8), pp. 3704–3709.

Li, X. *et al.* (2025) 'Recent advances in detection techniques for vitamin analysis: A comprehensive review', *Food Chemistry: X*, 26, p. 102226. Available at: https://doi.org/10.1016/j.fochx.2025.102226.

Liang, Q. *et al.* (2020) 'Folate content and retention in wheat grains and wheat-based foods: Effects of storage, processing, and cooking methods', *FOOD CHEMISTRY*, 333. Available at: https://doi.org/10.1016/j.foodchem.2020.127459.

Lin, F. *et al.* (2023) 'The impact of Russia-Ukraine conflict on global food security', *Global Food Security*, 36, p. 100661. Available at: https://doi.org/10.1016/j.gfs.2022.100661.

Linus Pauling Institute (2014) *Folate*, *Linus Pauling Institute*. Available at: https://lpi.oregonstate.edu/mic/vitamins/folate (Accessed: 2 May 2022).

Linus Pauling Institute (2024) *Micronutrients for Health*. Oregon, USA: Oregon State University. Available at: https://lpi.oregonstate.edu/publications/micronutrients-health (Accessed: 7 August 2025).

Liu, F. *et al.* (2022) 'The bioaccessibility of folate in breads and the stability of folate vitamers during in vitro digestion', *Food & Function* [Preprint]. Available at: https://doi.org/10.1039/D1FO03352B.

Livingstone, K.M. *et al.* (2021) 'Diet quality indices, genetic risk and risk of cardiovascular disease and mortality: a longitudinal analysis of 77 004 UK Biobank participants', *BMJ Open*, 11(4), p. e045362. Available at: https://doi.org/10.1136/bmjopen-2020-045362.

Liwinski, T. and Lang, U.E. (2023) 'Folate and Its Significance in Depressive Disorders and Suicidality: A Comprehensive Narrative Review', *Nutrients*, 15(17), p. 3859. Available at: https://doi.org/10.3390/nu15173859.

Loria, C.M. *et al.* (1998) 'Agreement among indicators of vitamin C status', *American Journal of Epidemiology*, 147(6), pp. 587–596. Available at: https://doi.org/10.1093/oxfordjournals.aje.a009491.

Ložnjak Švarc, P. and Jakobsen, J. (2023) 'Folate retention in nuts and seeds – Effects of household cooking', *Journal of Food Composition and Analysis*, 122, p. 105428. Available at: https://doi.org/10.1016/j.jfca.2023.105428.

Lui, A. *et al.* (1985) 'Relationship between body store of vitamin B6 and plasma pyridoxal-P clearance: metabolic balance studies in humans', *The Journal of Laboratory and Clinical Medicine*, 106(5), pp. 491–497.

Lupu, C.E. *et al.* (2025) 'Adolescent Nutritional Patterns and Health Behaviors in Romania: A Cross-Sectional Analysis', *Nutrients*, 17(9), p. 1448. Available at: https://doi.org/10.3390/nu17091448.

Lynch, S. *et al.* (2018) 'Biomarkers of Nutrition for Development (BOND)—Iron Review', *The Journal of Nutrition*, 148, pp. 1001S-1067S. Available at: https://doi.org/10.1093/jn/nxx036.

Macdiarmid, J.I. *et al.* (2018) 'Assessing national nutrition security: The UK reliance on imports to meet population energy and nutrient recommendations', *PLOS ONE*, 13(2), p. e0192649. Available at: https://doi.org/10.1371/journal.pone.0192649.

MacDougall, D.B. (2002) *Colour in food: improving quality*. Cambridge Boca Raton Boston New York: Woodhead Publishing CRC Press (Woodhead Publishing in Food Science and Technology, 2002).

Maguire, E.R. *et al.* (2017) 'Does exposure to the food environment differ by socioeconomic position? Comparing area-based and person-centred metrics in the Fenland Study, UK', *International Journal of Health Geographics*, 16(1), p. 33. Available at: https://doi.org/10.1186/s12942-017-0106-8.

Malapit, H.J.L. *et al.* (2013) *Women's Empowerment in Agriculture Production Diversity, and Nutrition: Evidence from Nepal*. report. The Institute of Development Studies and Partner Organisations. Available at: https://opendocs.ids.ac.uk/articles/report/Women_s_Empowerment_in_Agriculture_Production_Diversity_and_Nutrition_Evidence_from_Nepal/26473465/1 (Accessed: 9 June 2025).

Malézieux, E. *et al.* (2024) 'Biofortification versus diversification to fight micronutrient deficiencies: an interdisciplinary review', *Food Security*, 16(1), pp. 261–275. Available at: https://doi.org/10.1007/s12571-023-01422-z.

Malnutrition Task Force (2024) *Malnutrition in England Factsheet*, *malnutritiontaskforce.co.uk*. Available at: https://www.malnutritiontaskforce.org.uk/malnutrition-england-factsheet (Accessed: 2 June 2025).

Martin, C.J. *et al.* (2021) 'Genome-Wide Association Study of Seed Folate Content in Common Bean', *FRONTIERS IN PLANT SCIENCE*, 12, p. 696423. Available at: https://doi.org/10.3389/fpls.2021.696423.

Mason, J.B. *et al.* (2007) 'A Temporal Association between Folic Acid Fortification and an Increase in Colorectal Cancer Rates May Be Illuminating Important Biological Principles: A Hypothesis', *Cancer Epidemiology, Biomarkers & Prevention*, 16(7), pp. 1325–1329. Available at: https://doi.org/10.1158/1055-9965.EPI-07-0329.

Mason, P. *et al.* (2019) *State of the Nation: Dietary Trends in the UK 20 Years On. Where are we and where are we going?* The Health and Food Supplements Information Service, p. 36. Available at: https://www.hsis.org/wp-content/uploads/2019/08/HSIS-report-2019-artwork-screen-res.pdf (Accessed: 27 May 2025).

Maxfield, L. and Crane, J.S. (2023) 'Vitamin C Deficiency', *StatPearls*. Treasure Island (FL): StatPearls Publishing. Available at: http://www.ncbi.nlm.nih.gov/books/NBK493187/ (Accessed: 4 May 2023).

McCormick, D. and Greene, H. (1994) 'Vitamins', *Tietz Textbook of Clinical Chemistry*. Philidelphia: Saunders, pp. 366–375.

McIntyre, R.L. *et al.* (2022) 'Changes and differences in school food standards (2010–2021) and free school meal provision during COVID-19 across the UK: Potential implications for children's diets', *Nutrition Bulletin*, 47(2), pp. 230–245. Available at: https://doi.org/10.1111/nbu.12556.

McKillop, D.J. *et al.* (2002) 'The effect of different cooking methods on folate retention in various foods that are amongst the major contributors to folate intake in the UK diet', *British Journal of Nutrition*, 88(6), pp. 681–688. Available at: https://doi.org/10.1079/BJN2002733.

McNaughton, S.A. *et al.* (2005) 'Supplement Use Is Associated with Health Status and Health-Related Behaviors in the 1946 British Birth Cohort, ', *The Journal of Nutrition*, 135(7), pp. 1782–1789. Available at: https://doi.org/10.1093/jn/135.7.1782.

McPherson, G.M. (no date) *Parsnip: An Improved understanding of root blemishes and their prevention*. Annual Report Year 2 FV 366. Cambridgeshire, UK: AHDB. Available at: https://archive.ahdb.org.uk/fv-366-parsnip-an-improved-understanding-of-root-blemishes-and-their-prevention (Accessed: 9 June 2025).

Meadows, D.H. and Wright, D. (2011) *Thinking in systems: a primer*. Nachdr. White River Junction, Vt: Chelsea Green Pub.

Meadows, J. *et al.* (2024) 'The impact of the cost-of-living crisis on population health in the UK: rapid evidence review', *BMC Public Health*, 24(1), p. 561. Available at: https://doi.org/10.1186/s12889-024-17940-0.

Melough, M.M., Cho, E. and Chun, O.K. (2018) 'Furocoumarins: A review of biochemical activities, dietary sources and intake, and potential health risks', *Food and Chemical Toxicology*, 113, pp. 99–107. Available at: https://doi.org/10.1016/j.fct.2018.01.030.

Melse-Boonstra, A. *et al.* (2002) 'Influence of processing on total, monoglutamate and polyglutamate folate contents of leeks, cauliflower, and green beans', *Journal of Agricultural and Food Chemistry*, 50(12), pp. 3473–3478. Available at: https://doi.org/10.1021/jf0112318.

Micha, R. *et al.* (2018) 'Effectiveness of school food environment policies on children's dietary behaviors: A systematic review and meta-analysis', *PLOS ONE*, 13(3), p. e0194555. Available at: https://doi.org/10.1371/journal.pone.0194555.

Mikkilä, V. *et al.* (2007) 'Major dietary patterns and cardiovascular risk factors from childhood to adulthood. The Cardiovascular Risk in Young Finns Study', *British Journal of Nutrition*, 98(1), pp. 218–225. Available at: https://doi.org/10.1017/S0007114507691831.

Miller, R., Spiro, A. and Stanner, S. (2016) 'Micronutrient status and intake in the UK – where might we be in 10 years' time?', *Nutrition Bulletin*, 41(1), pp. 14–41. Available at: https://doi.org/10.1111/nbu.12187.

Moazzen, S. *et al.* (2018) 'Folic acid intake and folate status and colorectal cancer risk: A systematic review and meta-analysis', *Clinical Nutrition*, 37(6), pp. 1926–1934. Available at: https://doi.org/10.1016/j.clnu.2017.10.010.

Molani-Gol, R., Kheirouri, S. and Alizadeh, M. (2023) 'Does the high dietary diversity score predict dietary micronutrients adequacy in children under 5 years old? A systematic review', *Journal of Health, Population and Nutrition*, 42(1), p. 2. Available at: https://doi.org/10.1186/s41043-022-00337-3.

Molloy, A.M. *et al.* (2009) 'The Search for Genetic Polymorphisms in the Homocysteine/Folate Pathway That Contribute to the Etiology of Human Neural Tube Defects', *Birth defects research. Part A, Clinical and molecular teratology*, 85(4), pp. 285–294. Available at: https://doi.org/10.1002/bdra.20566.

Motegaonkar, S. *et al.* (2024) 'A comprehensive review on carrot (Daucus carota L.): the effect of different drying methods on nutritional properties and its processing as value-added foods', *Sustainable Food Technology*, 2(3), pp. 667–688. Available at: https://doi.org/10.1039/d3fb00162h.

Mukherjee, A. *et al.* (2020) 'Impacts of Organic and Conventional Management on the Nutritional Level of Vegetables', *Sustainability*, 12(21), p. 8965. Available at: https://doi.org/10.3390/su12218965.

Munteanu, C. and Schwartz, B. (2022) 'The relationship between nutrition and the immune system', *Frontiers in Nutrition*, 9, p. 1082500. Available at: https://doi.org/10.3389/fnut.2022.1082500.

Munyaka, A.W. *et al.* (2010) 'Influence of Thermal Processing on Hydrolysis and Stability of Folate Poly-γ-glutamates in Broccoli (Brassica oleracea var. italica), Carrot (Daucus carota) and Tomato (Lycopersicon esculentum)', *Journal of Agricultural and Food Chemistry*, 58(7), pp. 4230–4240. Available at: https://doi.org/10.1021/jf100004w.

Mutombo Arcel, M. *et al.* (2025) 'Optimizing nutrient retention in carrots during storage: A hyperspectral imaging approach', *Journal of Food Composition and Analysis*, 146, p. 107899. Available at: https://doi.org/10.1016/j.jfca.2025.107899.

Naderi, N. and House, J.D. (2018) 'Chapter Five - Recent Developments in Folate Nutrition', in N.A.M. Eskin (ed.) *Advances in Food and Nutrition Research*. Academic Press (New Research and Developments of Water-Soluble Vitamins), pp. 195–213. Available at: https://doi.org/10.1016/bs.afnr.2017.12.006.

Nair, M.K., Augustine, L.F. and Konapur, A. (2016) 'Food-Based Interventions to Modify Diet Quality and Diversity to Address Multiple Micronutrient Deficiency', *Frontiers in Public Health*, 3. Available at: https://doi.org/10.3389/fpubh.2015.00277.

Naqvi, S. *et al.* (2009) 'Transgenic multivitamin corn through biofortification of endosperm with three vitamins representing three distinct metabolic pathways', *Proceedings of the National Academy of Sciences of the United States of America*, 106(19), pp. 7762–7767. Available at: https://doi.org/10.1073/pnas.0901412106.

National Institute for Health and Welfare (2019) *Fineli Finnish food composition database*. Release 20. Helsinki: National Institute for Health and Welfare, Public Health Promotion Unit. Available at: https://fineli.fi (Accessed: 11 January 2022).

National Institutes of health Office of Dietary Supplements (2022) *Office of Dietary Supplements - Vitamin A and Carotenoids*. Available at: https://ods.od.nih.gov/factsheets/VitaminA-HealthProfessional/ (Accessed: 9 May 2023).

Nayak, M.U. *et al.* (2001) 'Nutrition Communication Using Social-Marketing Techniques to Combat Vitamin A Deficiency: Results of Summative Evaluation', *Food and Nutrition Bulletin*, 22(4), pp. 454–465. Available at: https://doi.org/10.1177/156482650102200419.

Nepper, M.J. and Chai, W. (2016) 'Parents' barriers and strategies to promote healthy eating among school-age children', *Appetite*, 103, pp. 157–164. Available at: https://doi.org/10.1016/j.appet.2016.04.012.

Nestel, P. *et al.* (2006) 'Biofortification of Staple Food Crops', *The Journal of Nutrition*, 136(4), pp. 1064–1067. Available at: https://doi.org/10.1093/jn/136.4.1064.

Neufeld, L.M. *et al.* (2022) 'Food choice in transition: adolescent autonomy, agency, and the food environment', *The Lancet*, 399(10320), pp. 185–197. Available at: https://doi.org/10.1016/S0140-6736(21)01687-1.

Ng, A. and Waldron, K.W. (1997) 'Effect of Cooking and Pre-Cooking on Cell-Wall Chemistry in Relation to Firmness of Carrot Tissues', *Journal of the Science of Food and Agriculture*, 73(4), pp. 503–512. Available at: https://doi.org/10.1002/(SICI)1097-0010(199704)73:4<503::AID-JSFA762>3.0.CO;2-Z.

NHS England (2022) *Common questions about folic acid*, *nhs.uk*. Available at: https://www.nhs.uk/medicines/folic-acid/common-questions-about-folic-acid/ (Accessed: 5 June 2025).

NHS Foundation Trust (2023) *Vitamin B12 and Serum Folate*, *Gloucestershire Hospitals NHS Foundation Trust*. Available at: https://www.gloshospitals.nhs.uk/our-services/services-we-offer/pathology/tests-and-investigations/vitamin-b12-and-serum-folate/ (Accessed: 10 May 2023).

Nunes, A.C.S., Kalkmann, D.C. and Aragão, F.J.L. (2009) 'Folate biofortification of lettuce by expression of a codon optimized chicken GTP cyclohydrolase I gene', *Transgenic Research*, 18(5), pp. 661–667. Available at: https://doi.org/10.1007/s11248-009-9256-1.

Octavia, L. and Choo, W. (2017) 'Folate, ascorbic acid, anthocyanin and colour changes in strawberry (Fragaria x annanasa) during refrigerated storage', *LWT-FOOD SCIENCE AND TECHNOLOGY*, 86, pp. 652–659. Available at: https://doi.org/10.1016/j.lwt.2017.08.049.

Oddbox (2022) *Five delicious ways to cook parsnips*. Available at: https://www.oddbox.co.uk/blog/five-delicious-ways-to-cook-parsnips (Accessed: 7 July 2025).

Office for Health Improvement and Disparities (2024) *The Eatwell Guide*. gov.uk. Available at: https://www.gov.uk/government/publications/the-eatwell-guide (Accessed: 5 August 2025).

Ogundijo, D.A., Tas, A.A. and Onarinde, B.A. (2021) 'Exploring the Impact of COVID-19 Pandemic on Eating and Purchasing Behaviours of People Living in England', *Nutrients*, 13(5), p. 1499. Available at: https://doi.org/10.3390/nu13051499.

O'Hare, T. *et al.* (2012) 'Impact of low temperature storage on active and storage forms of folate in choy sum (Brassica rapa subsp parachinensis)', *POSTHARVEST BIOLOGY AND TECHNOLOGY*, 74, pp. 85–90. Available at: https://doi.org/10.1016/j.postharvbio.2012.06.020.

Olson, R. *et al.* (2021) 'Food Fortification: The Advantages, Disadvantages and Lessons from Sight and Life Programs', *Nutrients*, 13(4), p. 1118. Available at: https://doi.org/10.3390/nu13041118.

O'Neil, A. *et al.* (2014) 'Relationship Between Diet and Mental Health in Children and Adolescents: A Systematic Review', *American Journal of Public Health*, 104(10), pp. e31–e42. Available at: https://doi.org/10.2105/AJPH.2014.302110.

Osman, A.M.G., Chittiboyina, A.G. and Khan, I.A. (2013) 'Chapter 32 - Plant Toxins', in J.G. Morris and M.E. Potter (eds) *Foodborne Infections and Intoxications (Fourth Edition)*. San Diego: Academic Press (Food Science and Technology), pp. 435–451. Available at: https://doi.org/10.1016/B978-0-12-416041-5.00032-9.

Osterhues, A., Holzgreve, W. and Michels, K.B. (2009) 'Shall we put the world on folate?', *The Lancet*, 374(9694), pp. 959–961. Available at: https://doi.org/10.1016/S0140-6736(09)61646-9.

Ostertag, E. *et al.* (2002) 'Effects of storage conditions on furocoumarin levels in intact, chopped, or homogenized parsnips', *Journal of Agricultural and Food Chemistry*, 50(9), pp. 2565–2570. Available at: https://doi.org/10.1021/jf011426f.

Otsu, Y., Ae, R. and Kuwabara, M. (2023) 'Folate and cardiovascular disease', *Hypertension Research*, 46(7), pp. 1816–1818. Available at: https://doi.org/10.1038/s41440-023-01307-w.

Parnham, J.C. *et al.* (2020) 'Half of children entitled to free school meals did not have access to the scheme during COVID-19 lockdown in the UK', *Public Health*, 187, pp. 161–164. Available at: https://doi.org/10.1016/j.puhe.2020.08.019.

Parnham, J.C. *et al.* (2024) 'Evaluating the impact of the universal infant free school meal policy on the ultra-processed food content of children's lunches in England and Scotland: a natural experiment', *International Journal of Behavioral Nutrition and Physical Activity*, 21(1), p. 124. Available at: https://doi.org/10.1186/s12966-024-01656-w.

Patil, I. (2021) 'Visualizations with statistical details: The "ggstatsplot" approach', *Journal of Open Source Software*, 6(61), p. 3167. Available at: https://doi.org/10.21105/joss.03167.

Paul, K.V. *et al.* (2025) 'Analysis of folate (vitamin B9) composition and accumulation pattern in developing kernels of specialty and biofortified maize genotypes', *Journal of Food Composition and Analysis*, 141, p. 107259. Available at: https://doi.org/10.1016/j.jfca.2025.107259.

Pautz, H. and Dempsey, D. (2020) *Food Insecurity, In-Work Poverty and Gender: a Literature Review*. UWS-Oxfam Partnership (Collaborative Research Reports Series). Available at: https://www.uws.ac.uk/research/research-institutes-centres-groups/uws-oxfam-partnership/ (Accessed: 20 August 2025).

Payne, A. *et al.* (2023) 'Nutritional-environmental trade-offs in potato storage and processing for a sustainable healthy diet', *Npj Science of Food*, 7(1), p. 63. Available at: https://doi.org/10.1038/s41538-023-00237-8.

(PDF) Structural Changes in Foods Caused by High-Pressure Processing (no date) *ResearchGate*. Available at: https://www.researchgate.net/publication/306060829_Structural_Changes_in_Foods_Caused_by_High-Pressure_Processing (Accessed: 27 February 2026).

Pedersen, T.L. (2024) *patchwork: The Composer of Plots*. Available at: https://CRAN.R-project.org/package=patchwork.

Penberthy, W.T. and Kirkland, J.B. (2020) 'Chapter 12 - Niacin', in B.P. Marriott et al. (eds) *Present Knowledge in Nutrition (Eleventh Edition)*. Academic Press, pp. 209–224. Available at: https://doi.org/10.1016/B978-0-323-66162-1.00012-3.

Peters, G.J. *et al.* (2013) 'Folate homeostasis of cancer cells affects sensitivity to not only antifolates but also other non-folate drugs: effect of MRP expression', *Pteridines*, 24(1), pp. 81–86. Available at: https://doi.org/10.1515/pterid-2013-0019.

Pfeiffer, C.M. *et al.* (2009) 'National Report on Biochemical Indicators of Diet and Nutrition in the U.S. Population 1999-2002', *The FASEB Journal*, 23(S1). Available at: https://doi.org/10.1096/fasebj.23.1_supplement.551.26.

Pfeiffer, C.M. *et al.* (2019) 'Folate status in the US population 20 y after the introduction of folic acid fortification', *The American Journal of Clinical Nutrition*, 110(5), pp. 1088–1097. Available at: https://doi.org/10.1093/ajcn/nqz184.

Phipps, R. (2024) 'Yes, you can eat parsnips raw: a recipe for Parsnip Remoulade.', *ingredient by Rachel Phipps*, 23 January. Available at: https://ingredientbyrachelphipps.substack.com/p/yes-you-can-eat-parsnips-raw-a-recipe (Accessed: 7 July 2025).

Pineda, E. *et al.* (2024) 'Food environment and obesity: a systematic review and meta-analysis', *BMJ Nutrition, Prevention & Health* [Preprint]. Available at: https://doi.org/10.1136/bmjnph-2023-000663.

Pinela, J. *et al.* (2019) 'Stability of total folates/vitamin B-9 in irradiated watercress and buckler sorrel during refrigerated storage', *FOOD CHEMISTRY*, 274, pp. 686–690. Available at: https://doi.org/10.1016/j.foodchem.2018.09.042.

Polegato, B.F. *et al.* (2019) 'Role of Thiamin in Health and Disease', *Nutrition in Clinical Practice*, 34(4), pp. 558–564. Available at: https://doi.org/10.1002/ncp.10234.

Poppy, G.M., Baverstock-Poppy, J.J. and Baverstock, J. (2022) 'Trade and dietary preferences can determine micronutrient security in the United Kingdom', *Nature Food*, 3(7), pp. 512–522. Available at: https://doi.org/10.1038/s43016-022-00538-3.

Posit team (2025) *RStudio: Integrated Development Environment for R.* Boston, MA: Posit Software, PBC. Available at: http://www.posit.co/.

Prakash, S. (2015) *12 Vegetables That Just Might Be Better Raw*, *Epicurious*. Available at: https://www.epicurious.com/ingredients/12-vegetables-you-didnt-know-you-could-eat-raw-article (Accessed: 7 July 2025).

Public Health England (2016) 'Government Dietary Recommendations'. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/618167/government_dietary_recommendations.pdf (Accessed: 9 January 2023).

Public Health England (2017) *Nutrient analysis of fruits and vegetables*. Available at: https://www.gov.uk/government/publications/nutrient-analysis-of-fruits-and-vegetables (Accessed: 14 September 2025).

Public Health England (2018) *Health matters: reproductive health and pregnancy planning*, *GOV.UK*. Available at: https://www.gov.uk/government/publications/health-matters-reproductive-health-and-pregnancy-planning/health-matters-reproductive-health-and-pregnancy-planning (Accessed: 2 June 2025).

Public Health England (2020) *National Diet and Nutrition Survey: Results from the Rolling programme Years 9 to 11 (2016/2017 to 2018/2019)*.

Public Health England (2021) *McCance and Widdowson's Composition of foods integrated dataset (CoFID)*. Available at: https://www.gov.uk/government/publications/composition-of-foods-integrated-dataset-cofid (Accessed: 11 January 2022).

Quinlivan, E.P., Hanson, A.D. and Gregory, J.F. (2006) 'The analysis of folate and its metabolic precursors in biological samples', *Analytical Biochemistry*, 348(2), pp. 163–184. Available at: https://doi.org/10.1016/j.ab.2005.09.017.

Quinn, M. *et al.* (2024) 'Global heterogeneity in folic acid fortification policies and implications for prevention of neural tube defects and stroke: a systematic review', *eClinicalMedicine*, 67. Available at: https://doi.org/10.1016/j.eclinm.2023.102366.

R Core Team (2024) *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing. Available at: https://www.R-project.org/.

Ramírez Rivera, N.G. *et al.* (2016) 'Metabolic engineering of folate and its precursors in Mexican common bean (Phaseolus vulgaris L.)', *Plant Biotechnology Journal*, 14(10), pp. 2021–2032. Available at: https://doi.org/10.1111/pbi.12561.

Ramos, M.I. *et al.* (2005) 'Low folate status is associated with impaired cognitive function and dementia in the Sacramento Area Latino Study on Aging2', *The American Journal of Clinical Nutrition*, 82(6), pp. 1346–1352. Available at: https://doi.org/10.1093/ajcn/82.6.1346.

Ratini, M. (2021) *Vitamin B12 Test & Normal Levels*, *WebMD*. Available at: https://www.webmd.com/a-to-z-guides/vitamin-b12-test (Accessed: 10 May 2023).

Rayner, M. and Scarborough, P. (2005) 'The burden of food related ill health in the UK', *Journal of Epidemiology & Community Health*, 59(12), pp. 1054–1057. Available at: https://doi.org/10.1136/jech.2005.036491.

Razzak, A. *et al.* (2023) 'Effect of cooking methods on the nutritional quality of selected vegetables at Sylhet City', *Heliyon*, 9(11), p. e21709. Available at: https://doi.org/10.1016/j.heliyon.2023.e21709.

Rébeillé, F. *et al.* (2006) 'Folates in plants: biosynthesis, distribution, and enhancement', *Physiologia Plantarum*, 126(3), pp. 330–342. Available at: https://doi.org/10.1111/j.1399-3054.2006.00587.x.

Reynolds, E.H. (2002) 'Folic acid, ageing, depression, and dementia', *BMJ : British Medical Journal*, 324(7352), pp. 1512–1515. Available at: https://doi.org/10.1136/bmj.324.7352.1512.

Reynolds, E.H. (2016) 'What is the safe upper intake level of folic acid for the nervous system? Implications for folic acid fortification policies', *European Journal of Clinical Nutrition*, 70(5), pp. 537–540. Available at: https://doi.org/10.1038/ejcn.2015.231.

Riaz, B. *et al.* (2019) 'Folate content analysis of wheat cultivars developed in the North China Plain', *Food Chemistry*, 289, pp. 377–383. Available at: https://doi.org/10.1016/j.foodchem.2019.03.028.

Rickerby, A. and Green, R. (2024) 'Barriers to Adopting a Plant-Based Diet in High-Income Countries: A Systematic Review', *Nutrients*, 16(6), p. 823. Available at: https://doi.org/10.3390/nu16060823.

Riemersma, R.A. *et al.* (2000) 'Vitamin C and the risk of acute myocardial infarction', *The American Journal of Clinical Nutrition*, 71(5), pp. 1181–1186. Available at: https://doi.org/10.1093/ajcn/71.5.1181.

Rigillo, N. (2025) *New SDG indicator on Minimum Dietary Diversity adopted by UN Statistical Commission*, *FAO*. Available at: https://www.fao.org/newsroom/detail/new-sdg-indicator-on-minimum-dietary-diversity-adopted-by-un-statistical-commission/en (Accessed: 9 June 2025).

Ringling, C. and Rychlik, M. (2017) 'Origins of the difference between food folate analysis results obtained by LC-MS/MS and microbiological assays', *Analytical and Bioanalytical Chemistry*, 409(7), pp. 1815–1825. Available at: https://doi.org/10.1007/s00216-016-0126-4.

Rinninella, E. *et al.* (2023) 'The role of diet in shaping human gut microbiota', *Best Practice & Research Clinical Gastroenterology*, 62–63, p. 101828. Available at: https://doi.org/10.1016/j.bpg.2023.101828.

Rivington, M. *et al.* (2021) 'UK food and nutrition security during and after the COVID-19 pandemic', *Nutrition Bulletin*, 46(1), pp. 88–97. Available at: https://doi.org/10.1111/nbu.12485.

RIVM, B. (2021) *NEVO online version 2021/7.0*. Available at: https://www.rivm.nl/en/dutch-food-composition-database/questions-and-remarks (Accessed: 11 January 2022).

Roberts, K. *et al.* (2018) 'Empirically Derived Dietary Patterns in UK Adults Are Associated with Sociodemographic Characteristics, Lifestyle, and Diet Quality', *Nutrients*, 10(2), p. 177. Available at: https://doi.org/10.3390/nu10020177.

Robinson, S., Granic, A. and Sayer, A.A. (2019) 'Nutrition and Muscle Strength, As the Key Component of Sarcopenia: An Overview of Current Evidence', *Nutrients*, 11(12), p. 2942. Available at: https://doi.org/10.3390/nu11122942.

Rodrigues, V.B., da Silva, E.N. and Santos, M.L.P. (2021) 'Cost-effectiveness of mandatory folic acid fortification of flours in prevention of neural tube defects: A systematic review', *PLoS ONE*, 16(10), p. e0258488. Available at: https://doi.org/10.1371/journal.pone.0258488.

Roe, M. *et al.* (2017a) *Nutrient analysis survey of fresh and processed fruit and vegetables with respect to fibre: Analytical Report*. Analytical Report 2016707. UK: Public Health England, p. 94.

Roe, M. *et al.* (2017b) *Nutrient analysis survey of fresh and processed fruit and vegetables with respect to fibre: Sampling Report*. Analytical Report 2016707. UK: Public Health England, p. 94.

Rose, C.S. *et al.* (1976) 'Age differences in vitamin B6 status of 617 men', *The American Journal of Clinical Nutrition*, 29(8), pp. 847–853. Available at: https://doi.org/10.1093/ajcn/29.8.847.

Rose, K. *et al.* (2019) 'School food provision in England: A historical journey', *Nutrition Bulletin*, 44(3), pp. 283–291. Available at: https://doi.org/10.1111/nbu.12394.

Rosenberg, I.H. (2012) 'A history of the isolation and identification of folic acid (folate)', *Annals of Nutrition & Metabolism*, 61(3), pp. 231–235. Available at: https://doi.org/10.1159/000343112.

Ross, F.C. *et al.* (2024) 'The interplay between diet and the gut microbiome: implications for health and disease', *Nature Reviews Microbiology*, 22(11), pp. 671–686. Available at: https://doi.org/10.1038/s41579-024-01068-4.

Rotstein, A. *et al.* (2022) 'Serum folate deficiency and the risks of dementia and all-cause mortality: a national study of old age', *Evidence Based Mental Health*, 25(2). Available at: https://doi.org/10.1136/ebmental-2021-300309.

Rousseau, A.-S. *et al.* (2004) 'Antioxidant vitamin status in high exposure to oxidative stress in competitive athletes', *The British Journal of Nutrition*, 92(3), pp. 461–468. Available at: https://doi.org/10.1079/bjn20041222.

Rowe, S. and Carr, A.C. (2020) 'Global Vitamin C Status and Prevalence of Deficiency: A Cause for Concern?', *Nutrients*, 12(7), p. 2008. Available at: https://doi.org/10.3390/nu12072008.

Rucklidge, J.J. *et al.* (2025) 'Annual Research Review: Micronutrients and their role in the treatment of paediatric mental illness', *Journal of Child Psychology and Psychiatry*, 66(4), pp. 477–497. Available at: https://doi.org/10.1111/jcpp.14091.

Rusakov, D.A. (2023) 'A misadventure of the correlation coefficient', *Trends in Neurosciences*, 46(2), pp. 94–96. Available at: https://doi.org/10.1016/j.tins.2022.09.009.

Rutherford, P.P. (1977) *Carbohydrate changes in stored vegetables with special reference to red beet and parsnip*. 85. Bath: Bath University, pp. 440–444. Available at: https://www.cabidigitallibrary.org/doi/full/10.5555/19770351841 (Accessed: 8 July 2025).

Ruthsatz, M. and Candeias, V. (2020) 'Non-communicable disease prevention, nutrition and aging', *Acta Bio Medica : Atenei Parmensis*, 91(2), pp. 379–388. Available at: https://doi.org/10.23750/abm.v91i2.9721.

Rydenheim, L. (2008) *Effects of storage on the visual quality, ascorbic acid and total phenolic content of fresh-cut rutabaga, kohlrabi and parsnip*. Alnarp: Swedish University of Agricultural Sciences.

Sadowski, J. (1992) ‘Riboflavin’, *Nutrition in the Elderly The Boston Nutritional Status Survey*. London: Smith-Gordon, pp. 119–125.

Saini, R.K., Nile, S.H. and Keum, Y.-S. (2016) ‘Folates: Chemistry, analysis, occurrence, biofortification and bioavailability’, *Food Research International*, 89, pp. 1–13. Available at: https://doi.org/10.1016/j.foodres.2016.07.013.

Sánchez-Mata, M.C., Cámara, M. and Díez-Marqués, C. (2003) ‘Extending shelf-life and nutritive value of green beans (Phaseolus vulgaris L.), by controlled atmosphere storage: micronutrients’, *Food Chemistry*, 80(3), pp. 317–322. Available at: https://doi.org/10.1016/S0308-8146(02)00266-2.

Saubade, F. (2016) *Potentiel nutritionnel du microbiote d’aliments fermentés à base de céréales : le cas des folates*. Université Montpellier. Available at: https://theses.hal.science/tel-01688503v1 (Accessed: 9 July 2025).

Schalla, J. *et al.* (2024) ‘Is there a beneficial effect of a high-protein diet on body composition and strength capacity in physical active middle-aged individuals?—An eight-week randomized controlled trial’, *Frontiers in Sports and Active Living*, 6. Available at: https://doi.org/10.3389/fspor.2024.1346637.

Scheelbeek, P. *et al.* (2020) ‘Health impacts and environmental footprints of diets that meet the Eatwell Guide recommendations: analyses of multiple UK studies’, *BMJ Open*, 10(8), p. e037554. Available at: https://doi.org/10.1136/bmjopen-2020-037554.

Schoenaker, D.A.J.M. *et al.* (2023) ‘Women’s preconception health in England: a report card based on cross-sectional analysis of national maternity services data from 2018/2019’, *BJOG: an international journal of obstetrics and gynaecology*, 130(10), pp. 1187–1195. Available at: https://doi.org/10.1111/1471-0528.17436.

Scientific Advisory Committee on Nutrition (2006) *Folate and disease prevention*. London: TSO. Available at: http://www.sacn.gov.uk/pdfs/folate_and_disease_prevention_report.pdf (Accessed: 10 January 2022).

Scientific Advisory Committee on Nutrition (2016) *SACN vitamin D and health report*, *GOV.UK*. Available at: https://www.gov.uk/government/publications/sacn-vitamin-d-and-health-report (Accessed: 10 May 2023).

Scientific Advisory Committee on Nutrition (2017) *Folic acid: updated SACN recommendations*, *GOV.UK*. Available at: https://www.gov.uk/government/publications/folic-acid-updated-sacn-recommendations (Accessed: 29 July 2025).

Scott, J., Rébeillé, F. and Fletcher, J. (2000) ‘Folic acid and folates: the feasibility for nutritional enhancement in plant foods’, *Journal of the Science of Food and Agriculture*, 80(7), pp. 795–824. Available at: https://doi.org/10.1002/(SICI)1097-0010(20000515)80:7<795::AID-JSFA599>3.0.CO;2-K.

Scottish Government (2021) *Healthy eating in schools: a guide to implementing the nutritional requirements for Food and drink in Schools (Scotland) Regulations 2020*. Edinburgh: The Scottish Government.

Scottish Trace Element and Micronutrient Diagnostic and Research Laboratory (no date) *Scottish Trace Element and Micronutrient Diagnostic and Research Laboratory - Vitamin A*. Available at: https://www.trace-elements.co.uk/vitamin-a.asp?term=Vitamin+A (Accessed: 9 May 2023).

Searle, F. *et al.* (2023) 'Fresh Produce Journal Magazine 2023 - BIG 50 Products', *Fruitnet*, 21 July. Available at: https://issuu.com/fruitnetmedia/docs/fpj_issue_6_big_50 (Accessed: 9 June 2025).

Selvakumar, R. and Kalia, P. (2025) 'Genetic Resources, Biodiversity, Conservation, and Utilization in the Improvement of Parsnip (Pastinaca sativa L.)', *Vegetable Crops*. 1st ed. 2025. Singapore: Springer Nature Singapore (Handbooks of Crop Diversity: Conservation and Use of Plant Genetic Resources), pp. 899–929. Available at: https://doi.org/10.1007/978-981-97-8949-8.

Shattuck, V.I., Kakuda, Y. and Yada, R. (1989) 'Sweetening of Parsnip Roots During Short-Term Cold Storage', *Canadian Institute of Food Science and Technology Journal*, 22(4), pp. 378–382. Available at: https://doi.org/10.1016/S0315-5463(89)70432-6.

Shenkin, A. (2006) 'The key role of micronutrients', *Clinical Nutrition*, 25(1), pp. 1–13. Available at: https://doi.org/10.1016/j.clnu.2005.11.006.

Sheoran, S. *et al.* (2022) 'Current Status and Potential of Biofortification to Enhance Crop Nutritional Quality: An Overview', *Sustainability*, 14(6), p. 3301. Available at: https://doi.org/10.3390/su14063301.

Shergill-Bonner, R. (2017) 'Micronutrients', *Paediatrics and Child Health*, 27(8), pp. 357–362. Available at: https://doi.org/10.1016/j.paed.2017.04.002.

Shewry, P.R. *et al.* (2010) 'Effects of Genotype and Environment on the Content and Composition of Phytochemicals and Dietary Fiber Components in Rye in the HEALTHGRAIN Diversity Screen', *Journal of Agricultural and Food Chemistry*, 58(17), pp. 9372–9383. Available at: https://doi.org/10.1021/jf100053d.

Shim, H., Kim, Y.-J. and Shin, Y. (2024) 'Physicochemical Properties, Organic Acid, and Sugar Profiles in Edible and Inedible Parts of Parsnip (Pastinaca sativa) Cultivars Harvested in Korea', *Applied Sciences*, 14(19), p. 9095. Available at: https://doi.org/10.3390/app14199095.

Shin, Y.S. *et al.* (1976) 'Subcellular localization of gamma-glutamyl carboxypeptidase and of folates', *Biochimica Et Biophysica Acta*, 444(3), pp. 794–801. Available at: https://doi.org/10.1016/0304-4165(76)90326-3.

Shinwell, J. *et al.* (2022) 'Food insecurity and patterns of dietary intake in a sample of UK adults', *British Journal of Nutrition*, 128(4), pp. 770–777. Available at: https://doi.org/10.1017/S0007114521003810.

Siatka, T. *et al.* (2025) 'Biological, dietetic and pharmacological properties of vitamin B9', *npj Science of Food*, 9(1), p. 30. Available at: https://doi.org/10.1038/s41538-025-00396-w.

Silver, C. (2025) *The Top 25 Economies in the World*, *Investopedia*. Available at: https://www.investopedia.com/insights/worlds-top-economies/ (Accessed: 5 August 2025).

Simmonds, M. *et al.* (2016) 'Predicting adult obesity from childhood obesity: a systematic review and meta-analysis', *Obesity Reviews: An Official Journal of the International Association for the Study of Obesity*, 17(2), pp. 95–107. Available at: https://doi.org/10.1111/obr.12334.

Simon, J.A. (1992) 'Vitamin C and cardiovascular disease: a review', *Journal of the American College of Nutrition*, 11(2), pp. 107–125.

Simon, J.A., Hudes, E.S. and Tice, J.A. (2001) 'Relation of Serum Ascorbic Acid to Mortality Among US Adults', *Journal of the American College of Nutrition*, 20(3), pp. 255–263. Available at: https://doi.org/10.1080/07315724.2001.10719040.

Sinai, T. *et al.* (2021) 'Dietary Patterns among Adolescents Are Associated with Growth, Socioeconomic Features, and Health-Related Behaviors', *Foods*, 10(12), p. 3054. Available at: https://doi.org/10.3390/foods10123054.

Singh, R.K. *et al.* (2017) 'Influence of diet on the gut microbiome and implications for human health', *Journal of Translational Medicine*, 15(1), p. 73. Available at: https://doi.org/10.1186/s12967-017-1175-y.

Sjoberg, D.D. *et al.* (2021) 'Reproducible Summary Tables with the gtsummary Package', *The R Journal*, 13(1), pp. 570–580. Available at: https://doi.org/10.32614/RJ-2021-053.

Smith, L. D. and Garg, U. (2017) 'Disorders of trace metals', in Uttam Garg and Laurie D. Smith (eds) *Biomarkers in Inborn Errors of Metabolism*. San Diego: Elsevier (Clinical Aspects and Laboratory Determination), pp. 399–426. Available at: https://doi.org/10.1016/B978-0-12-802896-4.00015-8.

Smith-Ryan, A.E., Cabre, H.E. and Moore, S.R. (2022) 'Active Women Across the Lifespan: Nutritional Ingredients to Support Health and Wellness', *Sports Medicine (Auckland, N.z.)*, 52(Suppl 1), pp. 101–117. Available at: https://doi.org/10.1007/s40279-022-01755-3.

Spence, S. *et al.* (2013) 'The impact of food and nutrient-based standards on primary school children's lunch and total dietary intake: a natural experimental evaluation of government policy in England', *PloS One*, 8(10), p. e78298. Available at: https://doi.org/10.1371/journal.pone.0078298.

Spence, S. *et al.* (2014) 'Did school food and nutrient-based standards in England impact on 11-12Y olds nutrient intake at lunchtime and in total diet? Repeat cross-sectional study', *PloS One*, 9(11), p. e112648. Available at: https://doi.org/10.1371/journal.pone.0112648.

Springmann, M. *et al.* (2020) 'The healthiness and sustainability of national and global food based dietary guidelines: modelling study', *BMJ (Clinical research ed.)*, 370, p. m2322. Available at: https://doi.org/10.1136/bmj.m2322.

Stannard, J. (1982) 'Medicinal plants and folk remedies in Pliny, Historia naturalis', *History and Philosophy of the Life Sciences*, 4(1), pp. 3–23.

Steel, N. *et al.* (2018) 'Changes in health in the countries of the UK and 150 English Local Authority areas 1990–2016: a systematic analysis for the Global Burden of Disease Study 2016', *The Lancet*, 392(10158), pp. 1647–1661. Available at: https://doi.org/10.1016/S0140-6736(18)32207-4.

Stevenson, C. *et al.* (2007) 'Adolescents' views of food and eating: Identifying barriers to healthy eating', *Journal of Adolescence*, 30(3), pp. 417–434. Available at: https://doi.org/10.1016/j.adolescence.2006.04.005.

Stiebahl, S. (2025) *Obesity Statistics*. Research Briefing. House of Commons Library.

Stipanuk, M.H. and Caudill, M.A. (2018) *Biochemical, Physiological, and Molecular Aspects of Human Nutrition - E-Book: Biochemical, Physiological, and Molecular Aspects of Human Nutrition - E-Book*. Elsevier Health Sciences.

Stone, R.A. *et al.* (2024) 'The impact of the cost of living crisis and food insecurity on food purchasing behaviours and food preparation practices in people living with obesity', *Appetite*, 196, p. 107255. Available at: https://doi.org/10.1016/j.appet.2024.107255.

Storozhenko, S. *et al.* (2007) 'Folate fortification of rice by metabolic engineering', *Nature Biotechnology*, 25(11), pp. 1277–1279. Available at: https://doi.org/10.1038/nbt1351.

Strandler, H.S. *et al.* (2015) 'Challenges in the Determination of Unsubstituted Food Folates: Impact of Stabilities and Conversions on Analytical Results', *Journal of Agricultural and Food Chemistry*, 63(9), pp. 2367–2377. Available at: https://doi.org/10.1021/jf504987n.

Strandler, H.S. and Jastrebova, J. (2011) 'Comparison of UPLC and HPLC for Analysis of Dietary Folates', *Chromatographia* [Preprint]. Available at: https://www.academia.edu/6541140/Comparison_of_UPLC_and_HPLC_for_Analysis_of_Dietary_Folates (Accessed: 12 April 2022).

Strobbe, S. and Van Der Straeten, D. (2017) 'Folate biofortification in food crops', *Current Opinion in Biotechnology*, 44, pp. 202–211. Available at: https://doi.org/10.1016/j.copbio.2016.12.003.

Swinburn, B. *et al.* (2013) 'INFORMAS (International Network for Food and Obesity/non-communicable diseases Research, Monitoring and Action Support): overview and key principles', *Obesity Reviews*, 14(S1), pp. 1–12. Available at: https://doi.org/10.1111/obr.12087.

Talsma, E. and Pachón, H. (2017) *Biofortification of crops with minerals and vitamins*, *World Health Organisation*. Available at: https://www.who.int/tools/elena/bbc/biofortification (Accessed: 5 June 2025).

Talukder, A. *et al.* (2010) 'Homestead food production model contributes to improved household food security and nutrition status of young children and women in poor populations', *Field Actions Science Reports. The journal of field actions* [Preprint], (Special Issue 1). Available at: https://journals.openedition.org/factsreports/404 (Accessed: 9 June 2025).

Tanumihardjo, S.A. *et al.* (2016) 'Biomarkers of Nutrition for Development (BOND)—Vitamin A Review', *The Journal of Nutrition*, 146(9), pp. 1816S-1848S. Available at: https://doi.org/10.3945/jn.115.229708.

The Department for Environment & Rural Affairs (2021a) *The National Food Strategy - The Plan, part 2*, *National Food Strategy*. Available at: https://www.nationalfoodstrategy.org/ (Accessed: 20 October 2021).

The Department for Environment & Rural Affairs (2021b) *UK Food Security Report 2021*.

The Food Foundation (2023) *Food Insecurity Tracking | Food Foundation*. Available at: https://foodfoundation.org.uk/initiatives/food-insecurity-tracking (Accessed: 25 May 2023).

The World Bank (2025) *World Development Indicators | DataBank*. Available at: https://databank.worldbank.org/reports.aspx?source=2&series=NY.GDP.MKTP.CD&country=# (Accessed: 5 August 2025).

Thomas, M. *et al.* (2022) 'The Impact of the COVID-19 Pandemic on the Food Security of UK Adults Aged 20–65 Years (COVID-19 Food Security and Dietary Assessment Study)', *Nutrients*, 14(23), p. 5078. Available at: https://doi.org/10.3390/nu14235078.

Tian, P. *et al.* (2025) 'Exploration of folate and its derivatives in grains of wheat with different colors', *Frontiers in Genetics*, 16. Available at: https://doi.org/10.3389/fgene.2025.1549122.

Tóth-Markus, M. *et al.* (2011) 'Composition and storage of pear cultivars from Nagykanizsa', *International Journal of Horticultural Science*, 17(1–2), pp. 63-68. Available at: https://doi.org/10.31421/IJHS/17/1-2./947.

Tozer Seeds Ltd (2017) *Parsnip*. Tozer Seeds Ltd, p. 4. Available at: https://www.tozerseeds.com/wp-content/uploads/2017/01/Parsnips-Brochure.pdf (Accessed: 15 May 2025).

Traber, M.G. (2014) 'Vitamin E Inadequacy in Humans: Causes and Consequences', *Advances in Nutrition*, 5(5), pp. 503–514. Available at: https://doi.org/10.3945/an.114.006254.

Tridge (2025) *United Kingdom Parsnip market overview 2024*, *Tridge*. Available at: https://www.tridge.com/intelligences/parsnip/GB (Accessed: 9 June 2025).

Uk Flour Millers (no date) *Bread and Flour Regulations*, *UK Flour Millers*. Available at: https://www.ukflourmillers.org/bread-and-flour-regulations (Accessed: 4 June 2025).

UK Government (1998) *The Bread and Flour Regulations 1998*, *SI 1998/141*. The Stationary Office. Available at: https://www.legislation.gov.uk/uksi/1998/141/regulation/1 (Accessed: 8 August 2025).

UK Government (2023) *Genetic Technology (Precision Breeding) Act 2023*. King's Printer of Acts of Parliament. Available at: https://www.legislation.gov.uk/ukpga/2023/6/contents (Accessed: 8 August 2025).

Ulrich, C.M. and Potter, J.D. (2006) 'Folate Supplementation: Too Much of a Good Thing?', *Cancer Epidemiology, Biomarkers & Prevention*, 15(2), pp. 189–193. Available at: https://doi.org/10.1158/1055-9965.EPI-06-0054.

United Nations Development Programme (2025) *Human Development Index*, *Human Development Reports*. United Nations. Available at: https://hdr.undp.org/data-center/human-development-index (Accessed: 5 August 2025).

University of Cambridge, MRC Epidemiology Unit, NatCen Social Research (2023) 'National Diet and Nutrition Survey Years 1-11, 2008-2019.' UK Data Service. Available at: https://doi.org/10.5255/UKDA-SN-6533-19.

Vahteristo, L. *et al.* (1997) 'Application of an HPLC assay for the determination of folate derivatives in some vegetables, fruits and berries consumed in Finland', *Food Chemistry*, 59(4), pp. 589–597. Available at: https://doi.org/10.1016/S0308-8146(96)00318-4.

Vancoillie, F. *et al.* (2024) 'Impact of refrigerated storage on (bio)chemical conversions of health-related compounds in pretreated, pasteurized Brussels sprouts and leek', *Food Research International*, 175, p. 113764. Available at: https://doi.org/10.1016/j.foodres.2023.113764.

Vollset, S.E. *et al.* (2013) 'Effects of folic acid supplementation on overall and site-specific cancer incidence during the randomised trials: meta-analyses of data on 50 000 individuals', *The Lancet*, 381(9871), pp. 1029–1036. Available at: https://doi.org/10.1016/S0140-6736(12)62001-7.

Wald, N. and Sneddon, J. (1991) *Prevention of neural tube defects: Results of the Medical Research Council Vitamin Study*. Volume 338 Issue 8760. Lancet, p. 7. Available at: https://pdp.sjsu.edu/faculty/gerstman/hs261/Lancet1991-338-8760-131-137.htm (Accessed: 3 June 2025).

Wald, N.J. (2022) ‘Folic acid and neural tube defects: Discovery, debate and the need for policy change’, *Journal of Medical Screening*, 29(3), pp. 138–146. Available at: https://doi.org/10.1177/09691413221102321.

Wald, N.J. *et al.* (2025) ‘Blood folate level needed for fully effective fortification in the prevention of neural tube defects’, *Archives of Disease in Childhood*, 110(8), pp. 651–656. Available at: https://doi.org/10.1136/archdischild-2024-328115.

Wald, N.J., Morris, J.K. and Blakemore, C. (2018) ‘Public health failure in the prevention of neural tube defects: time to abandon the tolerable upper intake level of folate’, *Public Health Reviews*, 39(1), p. 2. Available at: https://doi.org/10.1186/s40985-018-0079-6.

Wang, C. *et al.* (2011) ‘Influence of High-Pressure Processing on the Profile of Polyglutamyl 5-Methyltetrahydrofolate in Selected Vegetables’, *Journal of Agricultural and Food Chemistry*, 59(16), pp. 8709–8717. Available at: https://doi.org/10.1021/jf201120n.

Wang, C., Riedl, K.M. and Schwartz, S.J. (2013) ‘Fate of folates during vegetable juice processing — Deglutamylation and interconversion’, *Food Research International*, 53(1), pp. 440–448. Available at: https://doi.org/10.1016/j.foodres.2013.05.011.

Wang, X.-J. *et al.* (2022) ‘Origin, evolution, breeding, and omics of Apiaceae: a family of vegetables and medicinal plants’, *Horticulture Research*, 9, p. uhac076. Available at: https://doi.org/10.1093/hr/uhac076.

Welsh Government (2014) *Healthy eating in maintained schools. Statutory guidance for local authorities and governing bodies*.

West, P.C. *et al.* (2014) ‘Leverage points for improving global food security and the environment’, *Science*, 345(6194), pp. 325–328. Available at: https://doi.org/10.1126/science.1246067.

WHO (2009) *Vitamin A deficiency*, *Nutrition Landscap Information System (NLiS)*. Available at: https://www.who.int/data/nutrition/nlis/info/vitamin-a-deficiency (Accessed: 9 May 2023).

WHO (2015) ‘Serum and red blood cell folate concentrations for assessing folate in populations.’, *Vitamin and Mineral Nutrition Information System* [Preprint]. Available at: http://apps.who.int/iris/bitstream/handle/10665/162114/WHO_NMH_NHD_EPG_15.01.pdf;jsessionid=6FACBE6271001D4C1A2E0B3C0DEF879D?sequence=1 (Accessed: 10 May 2023).

WHO (no date) *Micronutrients*. Available at: https://www.who.int/health-topics/micronutrients (Accessed: 27 May 2025).

Wibowo, S. *et al.* (2019) ‘Thermal processing of kale purée: The impact of process intensity and storage on different quality related aspects’, *Innovative Food Science & Emerging Technologies*, 58, p. 102213. Available at: https://doi.org/10.1016/j.ifset.2019.102213.

Wickham, H. (2016) *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York. Available at: https://ggplot2.tidyverse.org.

Wickham, H. *et al.* (2019) ‘Welcome to the tidyverse’, *Journal of Open Source Software*, 4(43), p. 1686. Available at: https://doi.org/10.21105/joss.01686.

Wickham, H. *et al.* (2023) *dplyr: A Grammar of Data Manipulation*. Available at: https://CRAN.R-project.org/package=dplyr.

Wilke, C.O. (2024) *cowplot: Streamlined Plot Theme and Plot Annotations for 'ggplot2'*. Available at: https://CRAN.R-project.org/package=cowplot.

Willett, W. *et al.* (2019) 'Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems', *The Lancet*, 393(10170), pp. 447–492. Available at: https://doi.org/10.1016/S0140-6736(18)31788-4.

Williams, S.N. and Dienes, K. (2022) 'The "Cost of Living Crisis" and its effects on health: A qualitative study from the UK'. Available at: https://doi.org/10.31234/osf.io/tr4xf.

Woodside, J.V. *et al.* (2021) 'Opportunities for intervention and innovation in school food within UK schools', *Public Health Nutrition*, 24(8), pp. 2313–2317. Available at: https://doi.org/10.1017/S1368980020004668.

World Bank Group (2024) *What is Food Security? There are Four Dimensions*, *World Bank*. Available at: https://www.worldbank.org/en/topic/agriculture/brief/food-security-update/what-is-food-security (Accessed: 27 January 2025).

Wright, A.J. *et al.* (1995) 'Nutrient intake and biochemical status of non-instutionalized elderly subjects in Norwich: comparison with younger adults and adolescents from the same general community', *The British Journal of Nutrition*, 74(4), pp. 453–475. Available at: https://doi.org/10.1079/bjn19950151.

Wright, J. (2011) 'How to make parsnip wine', *The Guardian*, 9 November. Available at: https://www.theguardian.com/lifeandstyle/wordofmouth/2011/nov/09/how-to-make-parsnip-wine (Accessed: 7 July 2025).

Wusigale and Liang, L. (2020) 'Folates: Stability and interaction with biological molecules', *Journal of Agriculture and Food Research*, 2, p. 100039. Available at: https://doi.org/10.1016/j.jafr.2020.100039.

Xu, J. *et al.* (2023) 'Non-linear associations of serum and red blood cell folate with risk of cardiovascular and all-cause mortality in hypertensive adults', *Hypertension Research*, 46(6), pp. 1504–1515. Available at: https://doi.org/10.1038/s41440-023-01249-3.

Yang, T.C. *et al.* (2022) 'Are free school meals failing families? Exploring the relationship between child food insecurity, child mental health and free school meal status during COVID-19: national cross-sectional surveys', *BMJ Open*, 12(6), p. e059047. Available at: https://doi.org/10.1136/bmjopen-2021-059047.

Yau, A. *et al.* (2020) 'Socio-demographic characteristics, diet and health among food insecure UK adults: cross-sectional analysis of the International Food Policy Study', *Public Health Nutrition*, 23(14), pp. 2602–2614. Available at: https://doi.org/10.1017/S1368980020000087.

Your Choice Primary Care (2014) *Folate*, *Your Choice Primary Care (You Choi MD, Internal Medicine)*. Available at: http://www.youchoimd.com/folate.html (Accessed: 2 June 2025).

Yuan, G. *et al.* (2009) 'Effects of different cooking methods on health-promoting compounds of broccoli', *Journal of Zhejiang University SCIENCE B*, 10(8), pp. 580–588. Available at: https://doi.org/10.1631/jzus.B0920051.

Zhang, P. (2022) 'Influence of Foods and Nutrition on the Gut Microbiome and Implications for Intestinal Health', *International Journal of Molecular Sciences*, 23(17), p. 9588. Available at: https://doi.org/10.3390/ijms23179588.

Zhang, X. *et al.* (2021) 'The Association Between Folate and Alzheimer's Disease: A Systematic Review and Meta-Analysis', *Frontiers in Neuroscience*, 15, p. 661198. Available at: https://doi.org/10.3389/fnins.2021.661198.

Zheng, J. *et al.* (2022) 'Folate (vitamin B9) content analysis in bread wheat (Triticum aestivum L.)', *Frontiers in Nutrition*, 9. Available at: https://www.frontiersin.org/articles/10.3389/fnut.2022.933358 (Accessed: 30 January 2023).

Zor, M. *et al.* (2022) 'Changes caused by different cooking methods in some physicochemical properties, antioxidant activity, and mineral composition of various vegetables', *Journal of Food Processing and Preservation*, 46(11), p. e16960. Available at: https://doi.org/10.1111/jfpp.16960.