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Fruit and vegetable consumption as a preventative strategy for non-communicable diseases

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A high intake of fruit and vegetables (FV) has consistently been associated with a reduced risk of a number of non-communicable diseases. This evidence base is largely from prospective cohort studies, with meta-analyses demonstrating an association between increased FV intake and reduced risk of both CHD and stroke, although the evidence is less certain for cancer and diabetes. Controlled intervention trials examining either clinical or intermediate risk factor endpoints are more scarce. Therefore, evidence that FV consumption reduces the risk of disease is so far largely confined to observational epidemiology, which is hampered by some methodological uncertainties. Although increased FV intake is promoted across all dietary guidelines, national surveys confirm that dietary intakes are suboptimal and are not increasing over time. A range of barriers to increasing FV intake exist, including economic, physical and behavioural barriers that must be considered when exploring potential opportunities to change this, considering the feasibility of different approaches to encourage increased FV consumption. Such interventions must include consideration of context, for example, challenges and uncertainties which exist with the whole food system.

Fruit: Vegetables: Dietary intake: Non-communicable disease risk: Prevention: Behaviour change: Food system: Socio-economic inequalities

A diet rich in fruit and vegetables (FV) is considered healthy and FV feature in most dietary guidelines worldwide[1,2]. Despite this, population dietary intakes of FV in the UK and Ireland are low. Trends over time from the National Diet and Nutrition Survey in the UK highlight that, since 2008, adult intake has remained at approximately four portions daily. In children aged 11–18 years, intake has remained approximately three portions daily over the same timeframe, despite the public health advice to consume five portions daily[3].

In the most recently released data from the National Diet and Nutrition Survey, adults aged 19–64 years consumed on average 4·3 portions of FV daily. This figure was 4·5 portions in older adults aged 65–74 years, 3·9 portions in older adults aged 75 years and over and 2·9 portions daily in children aged 11–18 years. Thirty-three per cent of adults, 40 % of older

Abbreviations: FV, fruit and vegetables; NCD, non-communicable disease.
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adults (65–74 years), 27 % of older adults (>75 years) and 12 % of children (11–18 years) met the 5-a-day recommendation[3]. Mean FV consumption (2016–2019) was unchanged compared with 2014–2016 in all age groups, except for the 11–18 years age group, where there was a 0·2 portions/d increase and the proportion meeting 5-a-day increased from 8 to 12 %. Adults aged ≥65 years also had an 8 percentage point increase in the proportion meeting 5-a-day between 2014–2016 and 2016–2019. Since 2008 there has been a 7 percentage point increase in the proportion of women (19–64 years) meeting 5-a-day but no change for other age groups[4].

In Ireland the most recent data available are from the National Adult Nutrition Survey, conducted in 2011, when average combined FV intake was 192 g/d and the 400 g/d recommendation was met by only 9 % of those aged 18–64 years and 15 % of those aged more than 65 years[5]. These low levels of intake observed in Ireland and the UK are similar to what has also been observed globally[6,7], including in children[8].

Against this background of low-FV intake, it has been consistently demonstrated that there are socio-economic differentials in intake. For example, Maguire and Monsivais[9] used UK National Diet and Nutrition Survey data (2008–2011, adults aged >19 years) to explore socio-economic differences, focusing on the consumption of food groups and nutrients of public health concern including FV. As socio-economic differentials can be challenging to capture comprehensively, they analysed data for three socio-economic indicators – household income, occupational social class and highest educational qualification. Using general linear models to produce covariate-adjusted estimates, there were consistent socio-economic gradients in the consumption of FV as estimated by all three indicators, with the highest socio-economic groups consuming up to 128 g/d more FV than the lowest groups ($P < 0·05$).

Evidence supporting increasing fruit and vegetables consumption and reduced non-communicable disease risk

A range of studies have explored the association between FV intake and non-communicable disease (NCD) risk; these range from ecological studies through prospective cohort studies to randomised controlled trials, although the evidence is dominated by observational data.

One of the largest analyses carried out to date is from the global burden of disease study, with an analysis of the health effects of dietary risks in 195 countries between 1990 and 2017[10]. This analysis suggests that dietary risk factors significantly contribute to NCD, particularly CVD and type 2 diabetes. When the dietary risk factors with the greatest contributions to mortality were ranked, fruit intake was ranked third and vegetable intake fifth and, for each, CVD made up the majority of the causes of mortality. See Fig. 1.

Many individual smaller studies have explored the associations between FV intake and NCD outcomes, and these have now been subject to systematic review and meta-analysis; two of the most recent and comprehensive analyses will be reported here.

Yip *et al.* recently summarised the previously published meta-analyses exploring the global burden of diseases attributable to low-FV intakes, and produced the best estimates of relative risks[11]. They were able to include data from sixty-four reports that investigated a total of ninety-eight risk–disease pairs. Fifty-six of these sixty-four pairs were statistically significant, and dose responses were observed for thirty-one negative and two positive associations. The largest linear dose responses for each 100 g/d increase in fruit intakes was 0·56 (95 % CI 0·42, 0·74) for oesophageal cancer, and 0·72 (95 % CI 0·59, 0·87) for mouth, pharynx and larynx cancer. Some non-linear dose responses for the first 100 g/d of fruit intakes were also observed and were 0·86 (95 % CI 0·84, 0·88) for stroke and 0·89 (95 % CI 0·88, 0·90) for all-cause mortality. The largest linear dose response for each 100 g/d increase in vegetable intakes was 0·88 (95 % CI 0·80, 0·95) for renal cell cancer, and 0·89 (95 % CI 0·84, 0·95) for non-Hodgkin lymphoma. Again non-linear dose responses for the first 100 g/d of vegetable intake were observed and were 0·86 (95 % CI 0·84, 0·89) for CHD and 0·87 (95 % CI 0·84, 0·90) for all-cause mortality. There were obvious increases in non-linear protective associations for the first 200 g/d of intakes, but little further increase or even a decrease in protective associations beyond intakes of 300 g/d. There was some indication of variation according to type of FV; for example, canned fruit intake was positively associated with all-cause and CVD mortality, and pickled vegetable intake was positively associated with stomach cancer. Therefore, this comprehensive systematic review, pooling previous meta-analyses using a novel methodology, supported the existing dietary recommendations for FV intakes, but also suggested that current comparative risk assessments might significantly underestimate the observed protective associations between FV intake and disease outcomes.

That novel approach has since been followed by Wang *et al.*, who initially conducted primary analysis of data from the nurses' health study (1984–2014; *n* 66 719 women) and the health professionals follow-up study (1986–2014; *n* 42 016 men)[12]. Their analysis was specifically focused on establishing the optimal intake levels of FV in order to maintain long-term health. This primary analysis was followed by the conduct of a dose–response meta-analysis, which included results from their own two cohorts, but also twenty-four other prospective cohort studies.

In the analysis of primary data, a total of 33 898 deaths occurred during the follow-up period. Non-linear inverse associations of FV intake with both total mortality and cause-specific mortality (i.e. mortality attributable to cancer, CVD and respiratory disease) (all $P < 0·001$) were observed in adjusted models. Intake of approximately five servings daily of FV (two servings of fruit and three servings of vegetables) was associated with the lowest mortality. Above that level of intake, which reflects most dietary guidelines, higher intake was not associated with further risk reduction. When compared with the reference level (set at two servings/d), a daily intake of five servings of FV was

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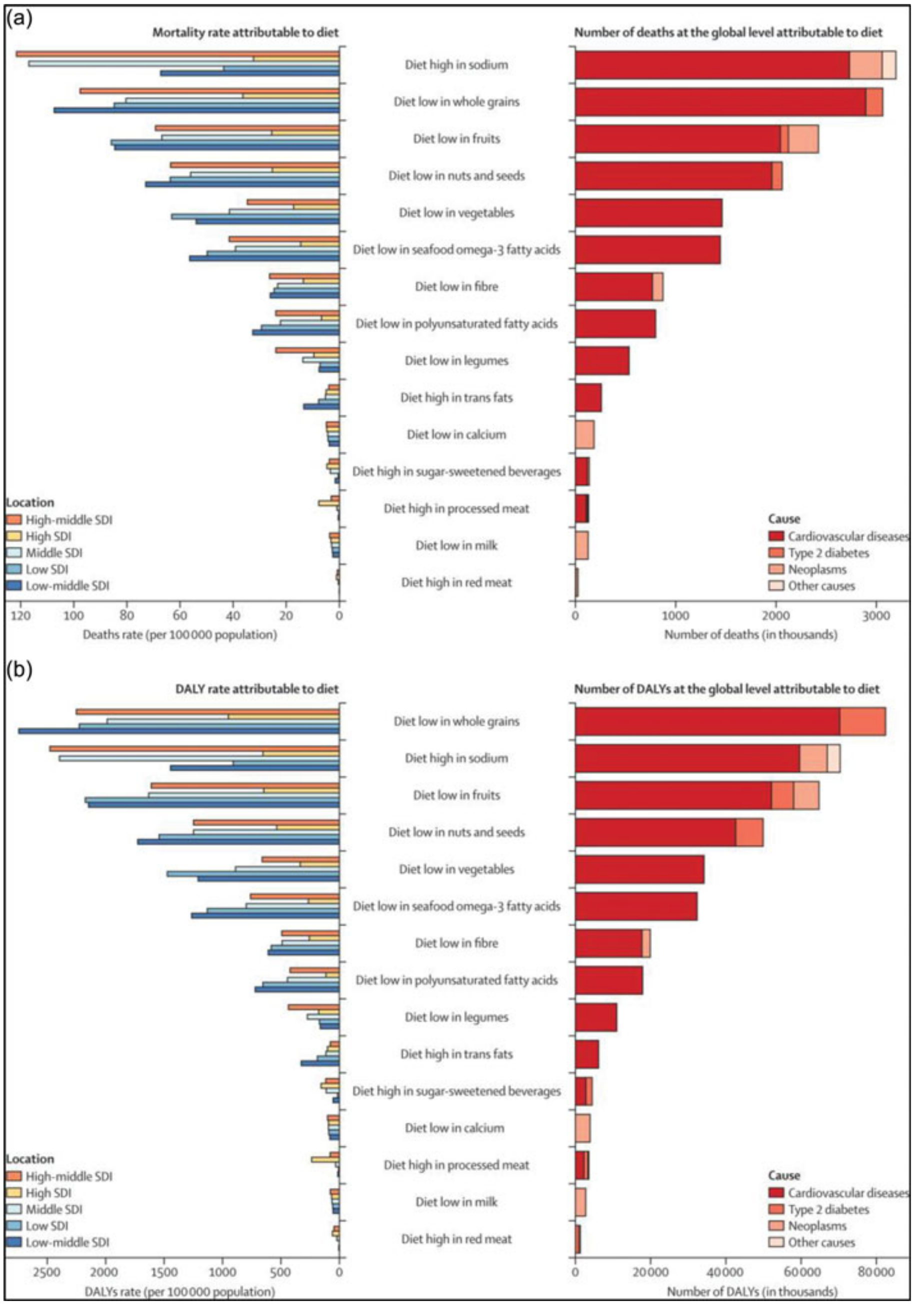

Fig. 1. Number of deaths and disability-adjusted life-years (DALY) and age-standardised mortality rate and disability-adjusted life-year rate (per 100 000 population) attributable to individual dietary risks at the global and Socio-demographic index (SDI) level in 2017: (a) mortality rate attributable to diet for each disease outcome and (b) disability-adjusted life-years attributable to diet for each disease outcome[10].

associated with reductions in risk with hazard ratios (95 % CI) of 0·87 (0·85, 0·90) for total mortality, 0·88 (0·83–0·94) for CVD mortality, 0·90 (0·86–0·95) for cancer mortality and 0·65 (0·59–0·72) for respiratory disease mortality.

The dose–response meta-analysis was then conducted, including the new primary analysis already described. This produced similar results (risk ratio of mortality for five servings/d (non-linear) = 0·87 (95 % CI 0·85, 0·88); $P < 0{\cdot}001$). Higher intakes of most FV sub-types were associated with lower mortality; exceptions to this were starchy vegetables such as peas and corn, and, furthermore, fruit juice and potato intake were not associated with total and cause-specific mortality.

The authors concluded from these two sets of analyses that higher intakes of FV were associated with lower mortality, which is not novel, but they also illustrated that the risk reduction plateaued at ≈5 servings of FV

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daily. This is of note, as there has been previous debate as to whether the 5-a-day recommendation should be increased, particularly given that it is a target that is not currently being met[13]. As for the previous analysis[11], findings supported current dietary recommendations to increase intake of FV, but not fruit juice and potatoes (considered a vegetable in the USA where the analysis was conducted).

Issues with evidence linking fruit and vegetables and non-communicable disease risk

While the observational evidence summarised within systematic reviews and meta-analyses afore-mentioned appears to be robust and reproducible, it is largely based on observational epidemiology, with relatively few randomised intervention studies being conducted[14]. Such trials with hard clinical outcomes are challenging to conduct over the time period required with food-focused interventions that require significant and sustained dietary behaviour change[15,16].

The meta-analyses afore-mentioned explore overall FV intake, but also start to explore fruit alone, vegetable intake alone and individual FV types. Dietary guidelines for FV vary in terms of what is considered a fruit or vegetable. Key examples include potatoes (considered a vegetable in the USA but not in the UK or Ireland), fruit juice (only one glass counted as a portion in the UK and Ireland) and legumes (only one serving counted as a portion daily), with potatoes then being considered as starchy foods and legumes as protein-rich foods. The impact of individual FV on NCD outcomes may differ, perhaps due to differences in bioactive content or due to how they are commonly cooked and consumed, and literature on this is still accruing[17–19]. Another concept that has received attention is that of FV variety and whether consuming a variety of FV is important in terms of maximising health impact, which also reflects the broader dietary diversity literature[20]. The interest in diversity largely arises from the suggestion that achieving the requirements for a range of nutrients is likely to come from eating a more diverse range of foods rather than consuming a more restricted diet with a limited variety of foods. Although early analysis suggested an association of FV variety with inflammatory outcomes[21], an analysis exploring more robust CHD outcomes suggested that absolute quantity, rather than variety, in FV intake was associated with a significantly lower risk of CHD[22] and this has been confirmed in a recent meta-analysis[20].

The earlier-reported observational studies rely on accurate reporting of usual dietary intake. Self-reported dietary intake is known to be affected by measurement error, but it has been suggested that misreporting might be more of an issue for FV than other foods. Respondents, knowing of the perceived health benefits of FV, may be more likely to over-report intake, as an example of social desirability response bias. For example, Michels *et al.*[23] reported substantial differences in the classification of fruit consumption and vegetable consumption when comparing a 7-d diary with a FFQ, with resulting differences how individuals were ranked in terms of FV intake. When intakes were classified into quintiles there was no substantial impact on the association observed with plasma vitamin C, but the magnitude of association differed[23]. In a further analysis, Bingham *et al.*[24] demonstrated that risk of IHD in the EPIC Norfolk cohort study was associated with concentrations of plasma vitamin C ($P < 0{\cdot}001$) and reported intake of vitamin C and FV when these were assessed by food diary (P quintile trends = 0·001 and 0·001 respectively), but this was not the case when intakes were assessed by FFQ. Given that many of the studies included in the systematic reviews and meta-analyses outlined earlier include cohort studies that have gathered intake data via FFQ, the potential impact on demonstrated associations has to remain a concern. One reason for the disparity may be that FFQ do not adequately account for intake from composite dishes[25].

Biomarkers, as objective measures of dietary intake, may help in testing the association of usual FV intake with NCD and other health outcomes, and a number of approaches have been used to develop biomarker approaches, either using more traditional or newly developed biomarkers[26–29], but also combinations of biomarkers to reflect the complexity of this food group[30,31], or a combination of biomarker and food intake data[32–34]. Innovation in this area will help to improve the robustness of the observational epidemiological evidence supported increased FV intake and reduced NCD risk.

What happens to overall diet when fruit and vegetables intake is increased?

FV are a source of vitamins, minerals, fibre and phytochemicals/bioactives as well as carbohydrate (sugars and starches) and therefore consumption of these foods is likely to be directly related to functional effects linked to this content. In addition to the direct effect of FV on nutrient intake, increasing FV intake may have indirect impacts on overall diet quality, as increasing intake of one food group is likely to lead to changes in other food groups, particularly if FV are substituted for other foods (e.g. having an apple instead of a chocolate biscuit as a snack). This has been explored to a limited extent, looking at pooled analysis of FV interventions and also via meta-analysis of published literature, although only at nutrient level[35,36]. In both analyses, intake of carbohydrate, fibre, carotene, vitamin C increased and fat decreased when FV intake increased. The two approaches did, however, lead to different findings in terms of energy intake. In the meta-analysis there was no impact of increased FV intake on energy intake, yet in the pooled analysis of interventions from a single-study centre there was an increase in energy intake of approximately 209 kJ per extra portion of FV consumed. This contrast may be due to different dietary assessment methods or, more likely, differences in how dietary advice was given; importantly there was no effect of increased FV intake on body weight in this analysis of

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the multiple interventions from a single centre. This contrast does serve to indicate that advice to increase FV intake should specifically mention substitution, as substitution rather than addition will maximise positive effects of increased FV intake on diet quality. The food choices made by participants within FV intervention studies when asked to increase intake could also be more fully explored to determine how choices made impact on dietary intake and health outcomes.

Challenge of/opportunities to increase fruit and vegetables intake

Given that worldwide FV intakes are low and are static, that certain population groups are at particular risk of low intakes, and that we have relatively robust and reproducible evidence (at least from observational studies and with the usual caveats about dietary assessment) that increasing FV intake is associated with reduced NCD risk, how policymakers might effectively promote FV intake, and where are the challenges and opportunities needs to be considered. Current context, including cost of food, issues around food supply and the impact of climate change on dietary choices also needs to be taken into consideration.

To explore interventions that are likely to increase FV it is useful to draw on the social ecological framework which has been applied to nutrition by the United States Department of Agriculture[37] (see Fig. 2). The framework considers that, when thinking about food and beverage intake, there will be a range of factors that influence intake and these can be categorised as individual factors (e.g. age, sex, psychosocial), environmental settings (homes, schools, workplaces, retail and out of home eating environments), a range of sectoral interests (government policy, agriculture, marketing and media) and, finally, social and cultural norms and values (belief systems, priorities, other aspects of lifestyle, body image). Such a multi-factor approach starts to capture the complexity of dietary choice and means that, when designing interventions that aim to change behaviour, considering this complexity may help encourage longer-term and more sustainable behaviour change.

Studies that have explored barriers to FV intake have identified factors that fit with this model of influencers of behaviour. For example, Appleton *et al.*[38] explored barriers to FV intake in a telephone survey of older adults (*n* 426) and found that greater ‘liking’ for FV, greater ‘awareness of current recommendations’ for consumption and greater ‘willingness to change’ were associated with higher intake. ‘Ease of consumption’ and ‘difficulties in achieving consumption’ were not associated with FV intake. Similar associations between FV intakes and ‘liking’ and ‘awareness’ were also found when population sub-groups were considered, for example, in those with low-FV intakes or those at risk of low intakes. Other commonly reported barriers related to environmental difficulties, such as cost and access,

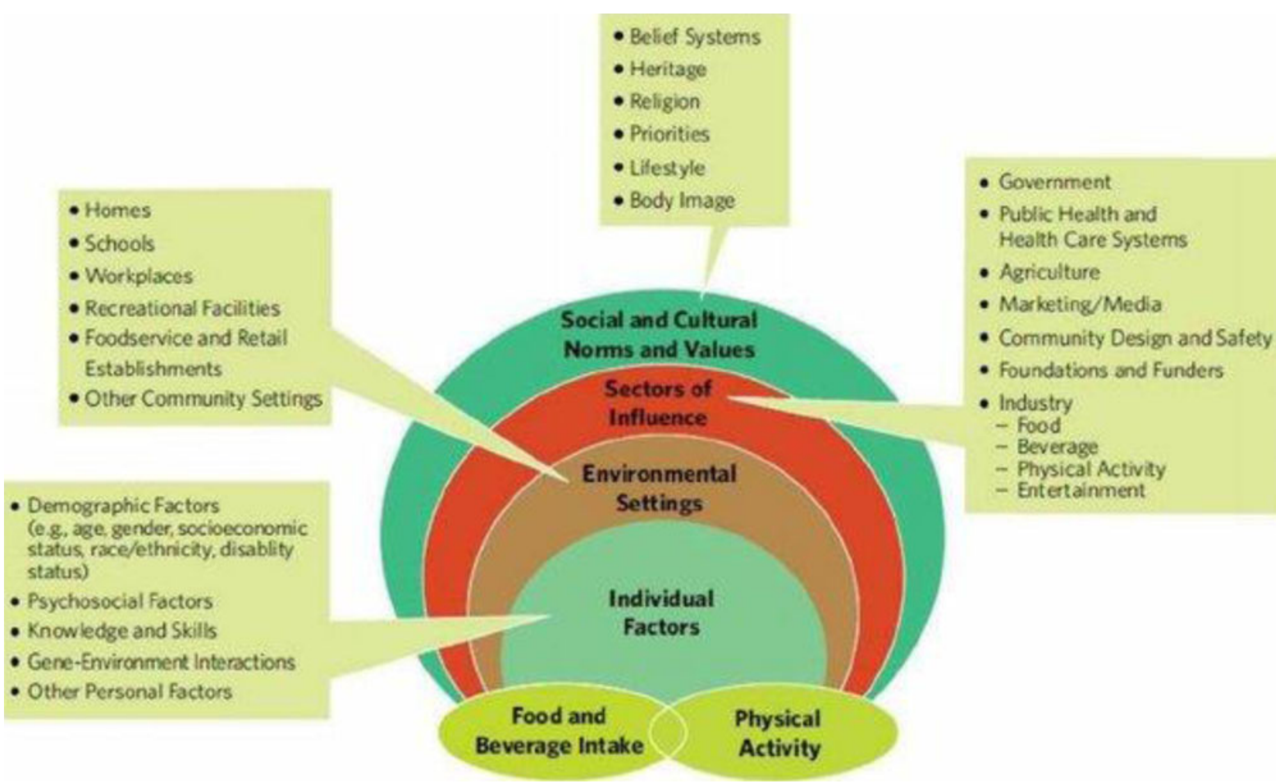

Fig. 2. Social ecological framework for nutrition and physical activity decisions.*Source*: Reproduced by Herforth *et al*. and United States Department of Agriculture (USDA)[37,94].

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were mentioned but not as frequently and these were not associated with FV intake.

More recent analysis, which also used a rather different methodology, was conducted by Hornsby and Ensaff[39]. They utilised online comments from news websites with the aim of exploring public perspectives on FV intake and related government dietary guidelines. A total of *n* 2696 web user comments made in response to the online reporting of a meta-analysis examining FV consumption and NCD and overall mortality risk were used. An inductive thematic approach was taken and four overarching themes emerged: personal factors (e.g. having children, taste, time, effort and skill), rejection (e.g. scepticism, quality *v*. quantity of life debate), lack of knowledge (e.g. what counts as FV and what is a portion) and food landscape (e.g. cost and availability). The authors highlighted gaps in understanding of dietary guidelines, which may be linked to poorer adherence to guidelines. It was suggested that further work is needed to examine this lack of understanding but also the rejection issue and the possibility of message fatigue in the general population related to diet/health information and news. The authors also suggested a need for targeted interventions to increase FV intake with a specific emphasis on health literacy.

The issue of awareness of FV dietary guidelines has also been explored in more detail in two studies in UK populations[40,41]. In a first study in low-FV consumers (*n* 28), focus group discussions highlighted that, although participants were aware of FV intake guidelines, they lacked deep insight into the meaning of the '5-a-day' message, including what FV contributed to the guideline, as well as understanding re: what constitutes a portion of FV[41]. There was also a sense of confusion regarding the concept of variety when considering FV intake. The participants highlighted a lack of previous education or available information on FV portion sizes, but also put forward suggestions for improving knowledge, including increasing information included on food packaging and through health campaigns. The second study included a face-to-face survey (*n* 507) followed by a postal questionnaire asking similar questions (*n* 247)[40]. Again, the majority of individuals in both parts of the overall study were aware of the 5-a-day message and could recount this correctly. However, specific knowledge of the details of the message was low, and, importantly, lower knowledge was associated with lower FV consumption. As previously, respondents had lowest knowledge of the details of the message related to portion sizes and the need for variety. However, FV consumption was not independently associated with knowledge of any one aspect of the message. These studies all suggest that strategies to increase FV consumption would benefit from including elements focused on increasing UK consumers' detailed knowledge of the 5-a-day FV message.

Involvement in a short-term FV intervention that included removal to known barriers to FV intake (access and cost by providing home deliveries) resulted in longer-term behaviour change. In a follow-up of a randomised controlled FV trial in eighty-three older adults (habitually consuming ≤2 portions/d) conducted 18 months post-intervention, mean FV intakes in both intervention (five portions FV daily over 16 weeks) and control (continue on ≤2 portions FV daily) groups were greater than baseline. At 18 months, both groups reported changes in barriers such as greater liking and ease in consuming FV while difficulties with consuming FV decreased. Those originally in the control group reported significantly greater awareness of FV recommendations at 18 months compared to baseline[42]. Therefore, participating in an FV intervention which provided FV and educational material about intake can lead to longer-term increases in FV consumption even if participants originally allocated to the control group.

Food literacy and cooking skill barriers to fruit and vegetables intake

Food literacy describes the proficiency an individual has in relation to food-related skills and knowledge which directly correlates to food choice. The concept is complex and can be influenced by numerous factors including, but not limited to, education related to the origin of food, selection, planning, language, food safety and preparation[43,44].

Cooking skills are a component of food literacy and a systematic review[45] has been conducted which focused on community interventions aimed at improving cooking skills and evaluating the effects of such interventions on outcomes including confidence and eating behaviour. The review concluded that cooking skill interventions can have a positive effect on food literacy, particularly in terms of improvements in confidence in cooking and in FV consumption. Vulnerable, low socio-economic groups tended to benefit more from such interventions. The authors concluded that cooking skill interventions are a potential vehicle to improve dietary quality, but that positive outcomes may be more likely to be realised if interventions include nutrition promotion and incorporating behaviour change techniques.

A matrix to define cooking skill intervention development has recently been developed and published[46]. This will be of real value, firstly in appreciating the complexity of the various required skills and helping to decide on content priorities within culinary education programmes that target improved diet quality and health. The matrix has six sections including skill focus points for: (1) kitchen safety, (2) food safety, (14) general food skills, (47) food group specific food skills, (47) general cooking skills and (6) food group-specific cooking skills; the final Cook-Ed™ matrix includes 117 skills on which to focus. Available resources, participant needs and sustainable nutrition principles are considered with the result that the matrix can be adapted based on these and also to suit regional food-based dietary guidelines and food cultures. In terms of FV, skills specific to this food group are given (the concept of seasonality, storage life and techniques appropriate for stage of ripeness and nutrient retention, preparation in terms of cleaning and washing, how to use food that is approaching end of life or, e.g. bruised, how to incorporate more vegetables into snacks or by adapting recipes). Furthermore, adaptations of

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skills where there is limited access to fresh produce due to finances, availability or ability to safely store, no access to certain preparation equipment (e.g. blender), or where there have to be adaptations to preparation methods to suit, for example, young children, are included.

Eating foods between meals is an opportunity for specific interventions to encourage increased FV intake. Indeed, while FV are listed as recommended snack foods in many national food-based dietary guidelines[37,48–52] they can often feature as less popular choices in studies examining snacking behaviours[53,54]. Beyond this, The Centers for Disease Control and Prevention advise replacing high-energy snacks with FV as well as substituting higher-energy ingredients in meals with FV[55]. A systematic review by Skoczek-Rubińska and Bajerska agreed, concluding that to prevent obesity (which was the purpose of the review)[56], community efforts should focus on planning eating occasions, eating mindfully, promoting more morning snacks and, finally, replacing energy-dense snacks with more nutritious ones, such as FV.

Food environment and settings-based interventions

So far, this review has described a range of barriers and facilitators to increased FV intake, possibilities for intervention in a range of settings and factors reported to influence FV intake, and how these align with parts of the social ecological framework. It is also the case that the majority of interventions focused on increasing FV considered so far have focused on individual level behaviour change. Other approaches, including considering settings and food environment-based interventions, are also likely to be of value. A range of systematic reviews have looked at workplace settings and schools as places where healthier dietary choices can be encouraged[47,57–60]. Many of these conclude that the evidence is strongest for FV intake positively influencing diet and health outcomes. It is uncertain as to whether the conclusions regarding FV are at least partly due to the fact that FV as a food group has been the subject of most attention within the research so far conducted. Such focus may be explained by the FV health-promoting properties or that it is considered easier to quantify intake of this food group. Alternatively it may simply be true that the evidence regarding achieving dietary change for FV does demonstrate greater effectiveness than for other food groups.

A separate setting for potential intervention is in the retail sector and supermarkets. A systematic review of interventions in these settings suggested that most interventions used a combination of information (e.g. awareness raising through food labelling, promotions, campaigns, etc.) and increasing availability, but relatively few used pricing interventions[61]. The authors also noted that the quality of included papers tended to be medium. The majority of studies reported that retail/supermarket-based interventions were effective in promoting increased purchase of healthy foods. The authors recommend a focus on increasing methodological quality and considering risk of bias in the design of future studies. However, even considering the methodological quality of currently available studies they concluded that interventions which combine price, information and easy access to and availability of healthy foods with interactive and engaging nutrition information, if carefully designed, could help customers in retail settings buy and consume more healthy foods[61].

Policy frameworks

There is now increasing effort to more formally look at policy actions across a range of intervention levels and domains. The NOURISHING framework for reporting, categorising and monitoring policy actions around the world has been developed by World Cancer Research Fund International and is outlined in Fig. 3[62].

Focusing entirely on FV and considering the NOURISHING framework, Wolfenden *et al.*[63] conducted an umbrella review to pull together evidence of the effectiveness of interventions to promote FV consumption. The use of this framework allowed the authors to identify strategies that may, to date, have been underutilised. A total of thirty-two different interventions were identified, included in nineteen reviews. When strategies were mapped across the three nourishing domains, these previously conducted and reported interventions only covered fourteen of the framework's sixty-five sub-policy areas. Of the thirty-two interventions, nineteen intervention strategies were suggested as effective; these tended to be (1) strategies implemented within schools, childcare services, homes, workplaces and primary care, (2) eHealth strategies, (14) mass media campaigns, (47) household food production strategies and (47) pricing/fiscal interventions. The authors concluded that a range of effective options are available for policy makers and practitioners who are aiming to improve FV intake. However, the effects of many strategies, particularly those targeting agricultural production practices, the supply chain and the broader food system, have not yet been reported, even in primary research papers but particularly in systematic reviews. Thus primary studies assessing the effects of these under-explored strategies, with the subsequent inclusion of the findings in systematic reviews, are needed to better inform global efforts to increase FV intake in a sustained way and, ultimately, improve public health nutrition.

Context: food costs and economic crisis

These discussions have to be set against, firstly the recent global pandemic, where FV was shown to be reduced by 0·7 portions/d[64], likely due to reductions in income and changes in shopping behaviour potentially resulting in reduced fresh produce purchase. The current economic crisis, with rising food costs will also have a potential impact on FV intake, with 35 % of adults surveyed between March and June 2022 reporting trying to spend less on food shopping in response to increases in living costs[65]. Meanwhile a recent report from the Food

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Fig. 3. NOURISHING policy framework identifying policy actions within three domains: food environment, food system and behaviour change communication that influence how and what we eat[62].

Foundation suggests that the poorest fifth of UK households is now estimated to spend 47 % of their disposable income on food to meet the cost of the government-recommended healthy diet[66].

What also has to be borne in mind is the complexity of the link between FV intake and deprivation, which is not simply about resource available to buy food, but also about the local food environment and accessibility. The link between FV intake and area income deprivation was the subject of an analysis conducted by Hawkesworth *et al.*[67], who investigated the local food environment and how this was associated with FV intake in older men and women living in twenty different UK towns. There was strong evidence of an association between area income deprivation and FV consumption in this cross-sectional analysis; those in the most deprived areas had a 27 % (95 % CI 7, 42) lower probability of being in a higher FV consumption category relative to those in least deprived areas. However, there was no consistent evidence for an association between FV consumption and other food environment factors explored by the research team, including density of shops selling FV, density of premises selling fast food, the diversity of food retail in the local area, the walkability of the local area, transport accessibility or the local food marketing environment. This suggests that, unless the effect is

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small and could not be picked up by this analysis, older people were less influenced by the physical characteristics of neighbourhood food environments than might have been hypothesised or previously suggested, and that other aspects, perhaps social, might be more important.

Given recent price rises in food, and the need for higher level interventions that are structural rather than requiring individual level behaviour change, a number of studies have examined the impact of food taxes and subsidies on economic and health outcomes and these have been systematically reviewed[68–70]. Most recently Andreyeva *et al*. (*n* 54 studies; meta-analysis *n* 15 studies) showed that FV subsidies increased FV sales but had no significant effect on consumption, which might be considered surprising[70]. However, studies on consumption were only based on a small number of studies which tended to be low quality. It was also highlighted that the outcomes of FV subsidies were heterogeneous, especially for sales and the authors suggested that this could be due, at least in part, to large variation in study design and quality and the differences in how the subsidies were delivered, which would not have been captured in this synthesis, for example variation in type and rate. The authors state that future evaluations of subsidies should focus specifically on measuring consumption changes in both children and adults using adequately powered studies with more comprehensive dietary assessment. As more research becomes available, the effectiveness of specific food taxes and subsidies across designs, food products covered and subsidy jurisdictions can be examined using further meta-analyses. For now, the authors concluded that the implications for population-level consumption, diet and health outcomes are uncertain.

Context: food supply and impact of climate change

Amongst the strategies to increase FV intake that have been relatively understudied[63] are food production, the supply chain and the broader food system. The food system is a rapidly changing system, with increasing concerns about climate change and resulting impacts on food supply[71]. Production is growing and sufficient and efficient food systems need to be in place to ensure food security. Almost half of FV supplies are lost or wasted[72] and currently production of FV is less than the global requirements for healthy, sustainable diets worldwide[73]. Falling crop yields and field losses can be attributed to climate change. A European Environment Agency report predicted that climate change could reduce the European agriculture value by 16 % by 2050 due to an increase in droughts and higher rainfall[74].

The lack of a stable food chain poses concerns for achieving adequate FV intake and is an area which needs to be addressed by governments globally. Such environmental concerns may, at the same time, offer some opportunities in terms of the FV group. Driven by sustainability concerns, there has been a large increase in the availability of plant-based meat alternatives[75,76]. These plant-based meat alternative products often include FV, particularly vegetables, thus representing an opportunity to use these products as an indirect avenue to increase FV intake[76,77].

There may be an impact of climate change on FV production and its resulting nutritional content. A systematic review that focused on environmental changes and impacts on yield and nutritional quality of fruits, nuts and seeds[78] suggested that environmental changes are likely to reduce yields and, against a background of global FV intakes which are already below recommendations, may adversely affect population health. The authors evaluated the impact of water availability and salinity, temperature, carbon dioxide and ozone. Focusing on the findings for fruit, a total of eighty-one papers were identified. Reduced water availability and increase in salinity were associated with reductions in fruit yield, while increases in carbon dioxide concentrations had positive yield impacts. Evidence for increased ozone concentrations and increasing temperatures (>25°C) was relatively scarce, but consistently negative in terms of yield impacts. The impacts on nutritional quality were difficult because of a lack of data and what data existed was mixed. The authors suggest that adaptation strategies and careful agricultural and food system planning will be essential to optimise crop productivity in the context of future environmental changes that are likely because of climate change. Such strategies will be essential to support and safeguard sustainable and resilient food systems.

The bioactive content of FV, variability in this content and how this relates to health outcomes is also relatively understudied[79]. It is well known that successful crop production depends on factors that come into play before and after harvest. Pre-harvest factors include genetic background, geographic location, climate, and, most importantly, growing conditions (soil nutrition, irrigation, fertilisation, attack of insects or microorganisms)[79]. After harvest, vegetables are stored under a range of conditions and are then stored and prepared differently by consumers prior to consumption. The authors of a systematic review[79] aiming to determine the reporting of the conditions and varieties of FV used in intervention trials looking at health outcomes found that there was very little published data regarding the effects of cultural practices and growing conditions, the genotype or the post-harvest factors that influence bioactive compound content. The authors concluded that there is a real issue in terms of how to compare the many studies exploring the health benefits of vegetables, because of the lack of information within the publications on the variety used, growing conditions and post-harvest factors. Each of these could influence bioactive compound content and any heterogeneity in study outcomes might be related to this variation in content. It was suggested that such data should be reported in future human intervention studies; and to do this will require analysis of the FV being given within these trials, as food tables will not reflect the full range of bioactive compounds, or be comprehensive or current in terms of locally available FV.

Conversely, specific breeding approaches may increase the content of certain phenolic compounds that could

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enhance the impact on health outcomes[80]. Given that significant diversity in phenolic acid content has been found amongst cultivars and associated wild relatives of many vegetable crops, it has been suggested that initial identification of these sources of variation, followed by use of modern genomics and biotechnological strategies, could be used to potentially enhance phenolic content of vegetables. The generation of new vegetable varieties in this way may also affect other traits important for variety success and so a combination of conventional and modern methods may be required.

FV supply is also changing. Scheelbeek *et al.*[81] have analysed UK FV imports and how these have changed, including the countries they come from and their particular vulnerabilities to projected climate change. The effects of these changing imports on the resilience of the UK food system were also explored. The UN FAO bilateral trade database was used as the data source to estimate the changes in UK FV supply over 27 years, and the Notre Dame Global Adaptation Initiative climate vulnerability categories used to assess climate vulnerability of countries supplying FV to the UK. The authors found that the domestic contribution to UK FV supply decreased from 42 % in 1987 to 22 % in 2013. Over the same period the diversity of FV supply increased from twenty-one crops (which comprised of 80 % of all FV supplied to the UK) to thirty-four crops by 2013. It wasn't only number of crops which changed, as, between 1987 and 2013 the contribution of tropical fruit rapidly increased while that of more traditional vegetables (e.g. cabbages and carrots) declined. The proportion of FV supplied to the UK from climate vulnerable countries increased from 20 % in 1987 to 32 % in 2013. The authors concluded that this demonstrated increased reliance on supply from climate-vulnerable countries could negatively affect the availability, price and consumption of FV, with potential downstream impacts on overall dietary intake and health. Certain sub-populations, such as older people and low-income households, may be particularly affected. The authors point to a need for inter-sectoral actions across agriculture, health, environment and trade, both in the UK and in countries that export to the UK to increase the resilience of the food system, and, ultimately, support population health.

The same research group has modelled the hypothetical adoption of the 5-a-day message[82] and impact on health but also environmental outcomes. Dietary data were examined that had been collected in the National Diet and Nutrition Survey (18 006 food diaries collected from 4528 individuals). Four different scenarios were modelled, which differed in terms of their prioritisation of fruit *v.* vegetables and whether UK-produced or imported varieties were being consumed. Greenhouse gas emissions, blue water footprint and total diet cost were quantified for each 5-a-day scenario, as were changes in life expectancy. It was suggested that achieving the 5-a-day target in the UK could increase average life expectancy at birth by 7–8 months, reduce diet-related greenhouse gas emissions by 6·1–12·2 Mt carbon dioxide equivalents/year and change water footprint by −0·14 to +0·07 km^3/year. When the different scenarios were explored, greater reductions in greenhouse gas emissions could be achieved by increasing vegetable consumption over fruit. In terms of water footprint, a greater reduction was obtained by prioritising vegetable varieties which were UK-produced. Of note, all consumption pathways increased diet cost (by £0·34–0·46/d). These analyses suggest that meeting dietary recommendations for FV could benefit both population and environmental health, particularly alongside consideration of FV supply chains.

Recently, concerns over pesticides and pesticide residues have increased in public discussion and in media coverage[83]. Dietary risk index system results show primarily FV consumption accounts for the majority of pesticide dietary risks[84]. The use of pesticides on crops raises the question of whether, if the public were to increase their FV intake would their exposure to pesticides also increase. Due to pesticide health concerns, some consumers opt for an organic diet to consume FV with lower levels of pesticide levels. The Soil Association has seen between 2020 and 2021, an increase (1·8 %) in organic produce sales[85]. However, due to higher production costs, the price of organic produce tends to be approximately 10–40 % higher than produce which has been grown conventionally. The United States Department of Agriculture has concerns that people may end up eating fewer FV rather than paying more for organic produce if they have concerns about pesticide exposure[86].

Recent analyses have explored whether exposure to pesticide residues associated with FV modifies the association with disease outcomes[87,88]. Using data from the nurses' health study (1998–2012), the nurses' health study-II (1999–2013), and the health professionals follow-up study (1998–2012) and FV data from FFQ, FV were categorised as having high- or low-pesticide residues using a validated method based on pesticide surveillance data obtained from the US Department of Agriculture. In models which had been adjusted for potential confounders, a greater intake of low-pesticide residue FV was associated with a lower risk of CHD whereas high-pesticide residue FV intake was unrelated to CHD risk. Compared with those consuming <1 serving/d of low-pesticide residue FV, those consuming ≥4 servings/d had a 20 % (95 % CI 4, 33) lower risk of CHD. The corresponding hazard ratio for high-pesticide residue FV and CHD was 0·97 (95 % CI 0·72, 1·30)[87]. In a separate analysis focusing on all-cause and disease-specific mortality, but with the same comparisons (comparing consumption of ≥4 servings/d to <1 serving/d), for low-pesticide residue FV the high intake group had 36 % (95 % CI 32, 41) lower mortality risk compared to those consuming <1 serving/d. The corresponding estimate for high-pesticide residue FV intake was 0·93 (95 % CI 0·81, 1·07), and patterns were similar across the three most common causes of death (CVD, cancer and respiratory diseases)[88]. These analyses suggest that exposure to pesticide residues through diet may offset the beneficial effect of FV intake on mortality and effects on specific conditions, including CVD. This is clearly of some

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concern but further confirmation of these findings, especially using biomarkers for assessment of pesticide exposure, is needed. The development of such biomarkers would help offset many of the current challenges surrounding intake estimates of pesticide residues where often assumptions have to be made regarding washing, peeling, processing (all influencing factors) and the possible combinations of pesticide residues that may be present.

Advances in science will also help keep abreast of the evolving nature of pesticide use, whereby differences can exist between jurisdictions (e.g. EU/UK and USA) regarding pesticides permitted for use and levels of application to crops as underpinned by safety assessments from regulatory bodies using traditional health benchmarks[89–92]. Whilst regulatory bodies conduct annual assessments to ensure the safety of our food supply regarding pesticides[90,91], beyond these assessments, a holistic approach is needed whereby the balance between health-promoting aspects of FV (fibre, bioactive compounds) and detrimental aspects (pesticide exposure) and how these mirror or cancel each other out in these analyses and, ultimately, in terms of impact on risk remains to be fully explored. An additional separate concern related to pesticides is that extensive use of fungistatic agents (i.e. azoles) in agriculture have the potential to also cause emergence of antimicrobial resistance in non-environmental fungi[93].

Conclusions

FV are a key food group. They are low in energy density and micronutrient dense. Intake of FV is encouraged across all dietary guidelines. Increased FV intake has been consistently associated with improved health outcomes, although the evidence is largely based on observational studies. Population FV intake has remained below what is recommended and this has been consistent over the past decade. Opportunities for increasing FV intake are complex, with consideration of the current context of economic uncertainty and climate change/food supply issues required. Ultimately, it is likely that we will need multi-level, coherent and sustained structural interventions and policies across the full food system/supply chain to increase intake. If this is achieved, benefits to both population and environmental health could be expected from meeting the FV 5-a-day target.

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Authorship

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