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The drivers, trends and dietary impacts of non-nutritive sweeteners in the food supply: a narrative review

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Abstract

Poor diets, including excess added sugar consumption, contribute to the global burden of disease. Subsequently, many nutrition policies have been implemented to reduce added sugar intake and improve population health, including taxes, education, labelling and environmental interventions. A potential consequence of these policy actions is the substitution of added sugars with non-nutritive sweeteners (NNS) in a variety of foods and beverages. NNS are used to reduce the energy and sugar content of foods and beverages while maintaining their palatability. Evidence of the toxicological risks of NNS is inconsistent, though concerns have been raised over the potential substitution effects of ultra-processed foods containing NNS for whole foods. This review aimed to provide an overview of current NNS food supply and consumption patterns, assess added sugar-reduction policies and their impact on NNS, and determine the impact of NNS on food choice, energy intake and diet quality. NNS are widely available in a variety of products, though most commonly in carbonated beverages, dairy products, confectionery, table-top sweeteners and fruit drinks. However, the longitudinal trends of different product categories, and differences between geographies and economy-income levels, require further study. Few studies have examined NNS consumption trends globally, though an increase in NNS consumption in beverages has been observed in some regions. Research examining how the increased availability of low-sugar, NNS-containing products affects global dietary patterns is limited, particularly in terms of their potential substitution effects.

Introduction

Unhealthy diets and poor nutrition are leading risk factors for the rising rates of non-communicable diseases globally[1]. Dietary guidelines are developed as a reference standard to inform policy actions and regulation to attenuate these dietary risk factors[2]. At the time of writing, ninety countries have developed food-based dietary guidelines, eighty-two of which recommend limiting or reducing the consumption of free or added sugar[3,4]. Added sugars, generally defined as all monosaccharides and disaccharides added to foods by the manufacturer, cook or consumer[5], have increased in the food supply over the last 30 years, and are often a component of ultra-processed foods[6,7]. The WHO recommends 'free sugar' consumption (consisting of both added sugar and sugars that are naturally present in honey, syrups and fruit juices) of no more than 10 % of total energy intake[8]. Similarly, the Scientific Advisory Committee on Nutrition (SACN) in the UK and the USA dietary guidelines recommend limiting the intake of free sugar to 5 % and added sugar to 10 % of energy intake, respectively[9]. Despite these recommendations, added sugar consumption contributes on average 11–17 % and 7–11 % of energy intake in European children and adults[10], and 7·5–19·5 % across the American population[11]. Frequent overconsumption of added sugar has been linked with obesity, non-communicable diseases including type 2 diabetes, and dental caries, particularly from sugar-sweetened beverages (SSB)[12–15].

A variety of policy actions have been implemented globally to reduce added sugar intakes[16]. Examples include: education based on the recommendations of food-based dietary guidelines[17]; food reformulation[18]; taxation of added sugar[19]; restricting sugar-enriched food and drink availability[20]; marketing restrictions[21]; public awareness campaigns[22]; and front-of-pack nutrient labelling[6,23,24]. Contesting paradigms exist regarding which types of policy actions should be implemented to reduce the consumption of added sugar. Broadly, these competing paradigms can be described as either 'holistic' or 'reductionist' in their approach to public health[25]. Policy actions that align with the holistic paradigm target broader economic and food system changes, including improving dietary patterns, food security, the preservation of biodiversity and sustainability[26]. Conversely, a reductionist worldview promotes policy actions that target individual food products and their nutrient and ingredient composition[26]. The reductionist worldview has also been described as 'nutritionism' – an ideology in which the nutrients that comprise foods determine their value in the diet, as opposed to the whole food or dietary pattern[27].

A case study of saturated fat provides an example of the unintended consequences of reductionist policy. After research

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Abbreviations: ADI, acceptable daily intake; HEI, Healthy Eating Index; NNS, non-nutritive sweetener; SSB, sugar-sweetened beverage.

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linked saturated fat to heart disease, consumers were encouraged to decrease its consumption[28]. Consequently, *trans*-fats (partially hydrogenated plant oils) were often used to replace saturated fats in processed foods[28]. Though *trans*-fats were initially regarded as a healthier, cheaper and often plant-based (i.e. 'natural') alternative, evidence now demonstrates that they contribute to heart disease to a greater extent than some saturated fats[29], and potentially increase the risk of type 2 diabetes and abdominal adiposity[30,31]. In turn, *trans*-fats have now been reduced or removed from many food supply chains globally, though in many cases have been replaced with interesterified fats[32,33]. The health effects of interesterified fats, particularly in terms of cardiovascular health, are debated[32,33]. Parallels may be drawn between the reductionist approach to decrease saturated fat consumption by *trans*-fats substitution and current nutrient-specific policy actions to decrease added sugar consumption.

Substituting non-nutritive sweeteners (NNS) for added sugar in ultra-processed food is one action that may reduce added sugar in the food supply. NNS are non-energy food additives that impart sweetness when added to a product[34]. They are used as substitutes for nutritive sweeteners (including sugar, honey and high-fructose maize syrup, among others) to reduce the energy and sugar content of processed foods while maintaining their palatability[35]. The phrase 'NNS' has been chosen for this review based on terminology used by organisations including the Codex Alimentarius Commission (Codex), the United States Department of Agriculture and the FAO, as well as being commonly used throughout the literature. NNS are also commonly referred to as artificial sweeteners (although this term ignores 'natural' sweeteners including stevia and monk fruit extract), non-caloric sweeteners, low-calorie sweeteners, intense sweeteners and high-intensity sweeteners. There are currently thirteen NNS approved for use globally (though specific types of sweeteners permitted for use differ between countries). The amounts of NNS that can be used in a product, and the products to which they can be added, is determined by each country's food standards regulating body. Online Supplementary Table S1 details all NNS currently in the global food supply, including their sweetener class, acceptable daily intake (ADI), relative sweetness to sucrose, energy per g, uses and properties. In this instance, NNS does not include polyols, as these additives have a small energy content[36].

Given the novelty of many NNS, questions have been posed about their risk to public health[37]. Systematic reviews have found that the benefits and harms of NNS are inconsistently reported[38,39]. Experimental animal studies and observational studies in human subjects have reported associations between NNS consumption and weight gain[38,40–42], changes to the gut microbiome (by saccharin, sucralose and stevia)[43] and an increased risk of type 2 diabetes[44,45]. Relationships from observational studies can only be classified as correlational and may suffer from bias, as participants with existing morbidities may be more likely to consume NNS than those without. Comparatively, clinical trials and experimental studies in human subjects have generally shown that NNS consumption is associated with a reduction in BMI[46–48] and fasting blood glucose[49,50]. Additionally, some experimental studies have found no effects of NNS consumption on BMI[51,52]. As public health impacts typically rely on dietary patterns, more studies are needed that detail the impacts of diets high in NNS

on dental health, type 2 diabetes and other health outcomes. The overall consensus throughout the literature is that NNS are not carcinogenic[53,54]. In addition to these toxicological concerns, particular NNS (including acesulfame-K) are 'micro-pollutants'; they are not effectively removed from wastewater after treatment, and hence may contaminate water supplies[55,56].

In public health, the nature and scope of risk are broader than the toxicological outcomes outlined above. Concerns have also been raised over the potential substitution effects of low-energy, NNS-containing discretionary foods for nutritious whole foods, and the long-term impact this may have on population health[37]. Nutrient-level policies to reduce added sugar consumption may encourage the reformulation of existing high-sugar products with NNS. This can create a 'health halo effect', allowing industry to make discretionary products appear 'healthy'[57]. This perception of healthiness may be used to promote the consumption of low-sugar, low-energy discretionary foods while displacing more nutritious foods from the diet.

Despite the increasing attention on added sugar intake, and subsequent policy actions to reduce it, there is a lack of understanding of the politics influencing the promotion of such actions, the impact of these policy actions on the added sugar and NNS composition of foods and beverages, and the subsequent impact on NNS consumption and overall dietary balance. Thus, the aim of the present review is to evaluate how policy actions to reduce added sugar consumption may influence NNS-related food supply trends, the consumption of NNS and dietary patterns more broadly. This review will be divided into three sections: (i) an overview of current NNS food supply and consumption patterns; (ii) added sugar-reduction policies and their impact on NNS; and (iii) the impact of NNS on food choice, energy intake and diet quality.

Methods

A narrative review method was adopted, given the complexity of the topic, and the diverse aims, study designs and methods of the included literature[58,59]. To improve the rigour of the review, a systematic search of the literature was performed. This involved restricting the focus to well-defined areas of interest, and the application of strict inclusion and exclusion criteria[60]. The search followed four steps: (i) a scoping review; (ii) systematic search for relevant literature; (iii) appraisal of studies selected for review; and (iv) data extraction, analysis and synthesis of the results.

Scoping review and systematic search for relevant literature

After consultation with a research liaison librarian, databases used included EBSCOhost (advanced search database – Academic Search Complete; Business Source Complete; CINAHL Complete; Global Health, GreenFILE; Health Policy Reference Center, MEDLINE Complete, PsycINFO, SocINDEX), Web of Science and Scopus. These databases were chosen for their comprehensiveness and conventional use in the public health nutrition discipline. Given the broad nature of the review, three searches with different search strings were used to capture all relevant literature.

Table 1. Search strings used for the present review

Search no.	Guiding question for each search	Search string
1	What are the policy actions to reduce added sugar intake that may impact the levels of non-nutritive sweeteners in the food supply?	(sugar OR sweetener*) *AND* (policy OR policies OR legislat* OR regulat* OR government* OR environ* OR "consumer demand" OR "novel technology" OR "new technology" OR manufact* OR consump* OR corporat* OR price OR cost) *NOT* (ethanol or alcohol or fuel or energy or salt)
2	What are the consumption and food supply trends of non-nutritive sweeteners?	("artificial sweeteners" OR "artificial sweetener" OR "non-nutritive sweetener" OR "non-nutritive sweeteners" OR "non nutritive sweetener" OR "non nutritive sweeteners" OR "high-intensity sweetener" OR "high-intensity sweeteners" OR "high intensity sweetener" OR "high intensity sweeteners" OR "non-caloric sweetener" OR "non-caloric sweeteners" OR "non caloric sweetener" OR "non caloric sweeteners" OR "low calorie sweetener" OR "low calorie sweeteners" OR "low-calorie sweetener" OR "low-calorie sweeteners" OR "sugar substitute" OR "sugar substitutes") AND ("food environment" OR landscape OR "food supply" OR consumption OR eating)
3	How does non-nutritive sweetener consumption impact dietary intakes (diet quality, energy intake and overall dietary balance)?	(artificial sweeteners" OR "artificial sweetener" OR "non-nutritive sweetener" OR "non-nutritive sweeteners" OR "non nutritive sweetener" OR "non nutritive sweeteners" OR "high-intensity sweetener" OR "high-intensity sweeteners" OR "high intensity sweetener" OR "high intensity sweeteners" OR "non-caloric sweetener" OR "non-caloric sweeteners" OR "non caloric sweetener" OR "non caloric sweeteners" OR "low calorie sweetener" OR "low calorie sweeteners" OR "low-calorie sweetener" OR "low-calorie sweeteners" OR "sugar substitute" OR "sugar substitutes" OR "intense sweetener" OR "intense sweeteners") AND ("dietary pattern" or "diet" or "consumption" or "energy intake" or "food intake" or "energy balance")

Table 2. Inclusion and exclusion criteria for the present review

Inclusion	Exclusion
(1) Published in English	(1) Dates before 1878 or after January 2020
(2) Peer-reviewed academic journal articles	(2) Opinion pieces, perspectives, study protocols, viewpoints, editorials and commentaries
(3) 1878*–January 2020	(3) Studies that occurred where people were not free living and healthy
(4) Healthy, free-living populations	(4) Animal studies
(5) Studies of adults or children	(5) Modelling studies
(6) All geographies	

* The year 1878 was chosen as this was when the first non-nutritive sweetener (saccharin) was discovered.

Search terms were identified from an initial scoping review. The search was conducted in March and April of 2019 and updated in January of 2020. Search strings are shown in Table 1. A citation snowballing technique was also used, which involved hand searching key papers' reference lists.

The inclusion and exclusion criteria are shown in Table 2. The year 1878 was chosen as the starting date for literature as this marked the discovery of the first NNS (saccharin).

Appraisal of selected studies for review

Duplicates were removed. Remaining records were then screened against the inclusion and exclusion criteria listed in Table 2. This involved the following steps: (i) screening of studies by title; (ii) screening of remaining studies by abstract; (iii) screening of remaining studies by full text. A second reviewer independently screened 10 % of articles by title and abstract, and all full-text articles, to minimise bias. Disagreements were resolved through discussion; where no agreement was reached, a third party acted as an arbiter. As this research aimed to assess the effects of

existing, implemented policy initiatives, modelling studies were intentionally excluded. This decision was made to clearly address the research question and aims, for which policy actions needed to have been implemented such that their influence on the food supply and consumption could be determined. For search 1, only studies that explored how a policy action directly affected NNS consumption or levels in the food supply were critically analysed. Despite the potential for the same policy actions discussed in other studies to have an impact on NNS, it was not possible to infer this outcome if the authors had not specifically analysed the change in NNS consumption, sales or levels in the food supply. Fig. 1 shows a PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow chart of the search.

Data extraction, analysis, and synthesis

Included studies were uploaded to the qualitative analysis software NVivo (QSR International, version 12) for data extraction and analysis. First, all studies were coded using a coding schema derived from the scoping review. Constant comparative analysis
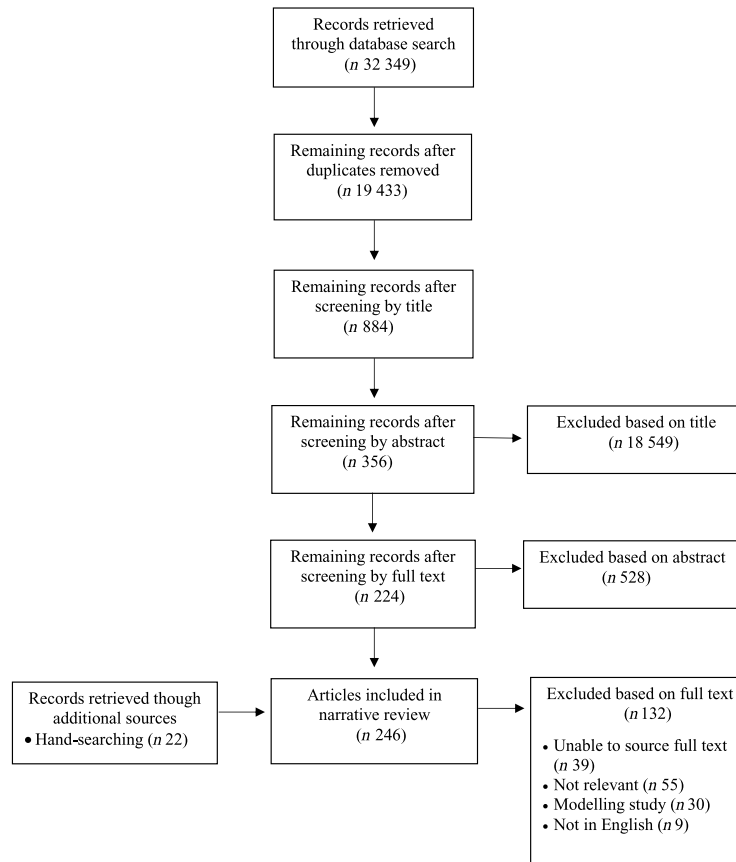
Fig. 1. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flowchart of the search.

was used to compare, integrate, modify and/or generate new codes through ongoing rounds of data analysis[61,62]. The coded data were used to identify major themes that were then synthesised into the results. Results were discussed comprehensively with the research team as the analysis progressed to limit researcher subjectivity.

Results

Overview of studies

A total of 246 peer-reviewed journal articles were included in the review. As shown in Fig. 2, the frequency of studies assessing NNS increased over time. This suggests an increased research interest in this topic area, consistent with a growing number of policy actions targeting added sugar internationally and the rise in variety and regulation of NNS.

Current non-nutritive sweetener food supply and consumption patterns

Fifty-four studies included in the review explored NNS consumption trends and levels in the food supply. A description of these studies is included as online Supplementary Table S2.

Food supply patterns. Studies found NNS in a wide variety of products across the global food supply, often in food that consumers may not expect, were not labelled as 'diet' or 'lite' and were not

traditionally sweet. These products included yoghurt[63–77], dairy desserts (including mousse and ice-cream)[64,66–69,71,72,74,77–79], milk[80,81], carbonated beverages[63–65,67–70,72–92], energy drinks[73,78], bakery products[68,76,77,81,93], other drinks (fruit drinks, ice tea, vegetable juice, nectar, cordial and flavoured mineral water)[63–65,68–70,72,73,77,84,86,88,94], pre-made coffee/tea[80,83–85,88], table-top sweeteners[64,65,67,69,70,72,76,84], confectionery (including chewing gum)[64–67,69–72,76,77,79–81,83,85], pickled food[83,85], processed fruits and vegetables[93], jam[64,70–72,75], salad dressing[67,73,85], cream substitutes[67], alcoholic drinks[66,80,83,85,95], condiments[66,71,72,76,79,85,87], syrup[72,80], cereal[81,93], miscellaneous snack foods[85], protein bars[73], baby food[73], flavoured ice[85,96], fish products[75,85] and pan masala[96]. While most of these sweetened products were found in several countries, pan masala was specific to India, whilst the alcoholic drinks Soju, Takju and Yakju were specific to South Korea. It is important to note that all products found to contain NNS were ultra-processed foods.

The products contributing the most to NNS consumption were carbonated beverages[63,65,67,69,70,72–75,77,78,80,82–84,86,87,89–91], dairy products (especially yoghurts)[63,65–68,70,72–74,77,78], confectionery (including chewing gum)[64–66,72,77,81,97], table-top sweeteners[64,67,69,70,72,84] and juices[63,69,77,84]. Some studies found that NNS did not always entirely replace sugar in sweetened products; rather, they were used in addition to nutritive sweeteners[73,89,98].

Non-nutritive sweetener consumption. Few studies (*n* 10) explored the trends of NNS consumption over time. Those that

Table 3. Trends of non-nutritive sweetener (NNS) consumption by country

Country	Trend	Magnitude of change	Reference
Norway	↑	Frequency of NNS beverage intake increased from 1·2/week in 2001 to 1·6/week in 2016	Bolt-Evensen et al. (2018)[100]
USA	↑	Proportion of adults consuming 'diet' drinks increased from 3 % in 1965 to 20 % in 2018	Bleich et al. (2014)[99]
USA	↑	Proportion of adults consuming NNS beverages increased from 14·9 % in 1999 to 18·3 % in 2008 Average weight of NNS beverages consumed increased from 148 g/d in 1999 to 183 g/d in 2008	Drewnowski & Rehm (2015)[101]
USA	↑	Percentage of females consuming NNS beverages increased from 17·8 % to 21·2 % and males increased 13·9 % to 19 % from 1999 to 2010	Fakhouri et al. (2012)[103]
USA	↑	Proportion of individuals consuming NNS increased from 3 % in 1965 to 15 % in 2004	Mattes & Popkin (2008)[102]
USA	↑	Low-/no-energy beverage consumption tripled from 2001 to 2010 Intake rose from 34 to 90 g Prevalence of consumption increased from 8·2 % to 22·6 %	Mesirow & Welsh (2015)[88]
USA	↑	Increase in NNS products purchased from 13·3 % in 2005 to 15·2 % in 2009	Ng et al. (2012)[73]
USA	↑	Purchase of beverages containing NNS increased significantly from 2000 to 2010 (amount not specified)	Piernas et al. (2013)[89]
USA	↑	Proportion of children consuming NNS increased from 8·7 % in 1999 to 14·9 % in 2008 and in adults from 26·9 % in 1999 to 32 % in 2008	Sylvetsky et al. (2012)[98]
USA	↑	Proportion of children consuming NNS increased from 8·7 % in 1999 to 25·7 % in 2012 and in adults from 26·9 % in 1999 to 41·5 % in 2012	Sylvetsky et al. (2017)[74]

↑, Increase.
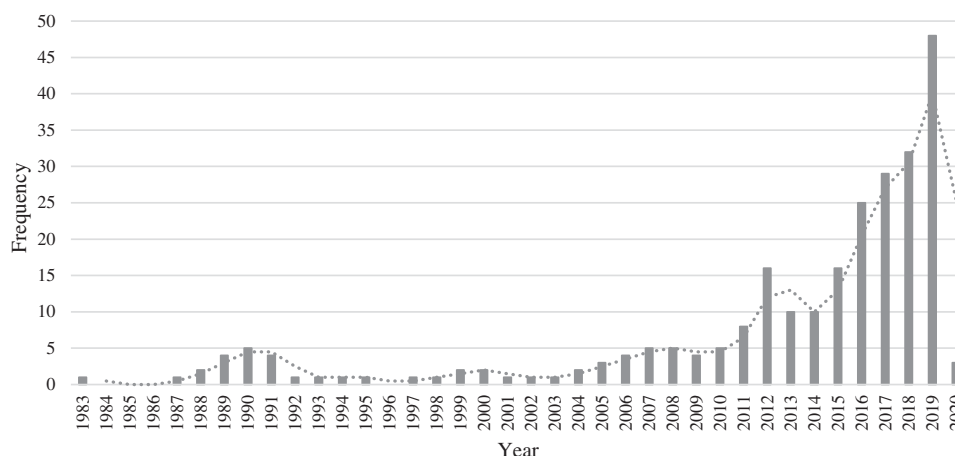
Fig. 2. Frequency of studies included in the review by year.

did demonstrated an increase[73,74,82,88,89,98–103] (Table 3). Consumer purchasing data are included together with data on consumption, as the trends in NNS purchasing were often used as a proxy by studies to estimate consumption trends. The major contributors to the increase in NNS consumption were beverages[88,89,98–101,103], though changes in beverage consumption were also often the only variable studied.

Though longitudinal studies suggested that the proportion of the population consuming NNS is increasing, almost all cross-sectional studies demonstrated that amounts consumed did not exceed the ADI (the amount of the sweetener that can be consumed on a daily basis over a lifetime without appreciable risk to health)[63–66,70,72,79,82,83,85–87,93,95,97,104–106]. Generally, this was determined through either food records[64,65,82,104] or a combination of diet recalls (to determine consumption) and food label surveys/HPLC (to determine the amount of NNS in food and beverage items)[66,72,80,85,86,95,105,106]. There were exceptions to this finding, although these were generally found in particular

sub-groups of consumers[63,104,107]. Consumption of NNS was closer to the ADI for toddlers and children, probably due to their lower body mass but not proportionately decreased consumption of sweeteners[69,79,83,90,93,104,107]. Illustratively, Garavaglia et al.[69] found that 1·1 % of pre-schoolers and 0·9 % of school children in Argentina exceeded the ADI of cyclamate. Additionally, Meenakshi et al.[96] found that an Indian sub-population could be exceeding the ADI for saccharin due to high consumption of pan masala and crushed ice. Of the sweeteners studied, cyclamate was almost always the sweetener closest to or exceeding the ADI[63,64,69,97,104,108]. Contributing factors may include the relative affordability of cyclamate when compared with other sweeteners, the higher amounts by weight included in food (as cyclamate is only 30 × sweeter than sugar, compared with advantame, which is 20 000 × sweeter) and its prevalence as a commonly used sweetener in many countries' food supplies[109].

The characteristics of NNS consumers were consistent across most studies. Frequently, in comparison with non-consumers,

NNS consumers had a higher BMI[70,74,84,90,98,99,110–114] (though one study found this association only in women, not men[63]), higher education level/socio-economic status[63,70,74,76,84,89,99,100,111–113,115], were more likely to be women[64,70,74,84,89,90,98–100,111,112,115], had increased consumption with age[70,74,84,100,111,112,115] (though two studies found the opposite[99,110]), were more likely to be non-Hispanic whites[70,74,84,89,99,111,115], more likely to be on a diet[70,84,90,100] or have type 2 diabetes[70,74,110] and were more likely to live in an English-speaking country[70,115,116].

Added sugar-reduction policies and their impact on non-nutritive sweeteners in the food supply

A total of 134 studies included in the review assessed policy actions to reduce added sugar consumption. Five main policy categories emerged: taxation (*n* 38), education (*n* 41), food environment interventions (*n* 49), labelling (*n* 22) and reformulation (*n* 6). Here, *n* is larger than the total number of studies as some described more than one policy action.

A summary of studies that have assessed the impact of these policy actions on added sugar consumption, and how this has affected either NNS consumption or levels in the food supply, is shown in Table 4. Studies that assessed policy actions promoting the consumption of whole foods or improved dietary patterns, including subsidies on fruits and vegetables or the promotion of dietary guidelines, were infrequent. Instead, the majority of the policy actions studied were reductionist, focusing only on nutrients (added sugar) rather than the foods or dietary patterns.

Taxation. Of the studies included in the review, thirty-eight focused on taxation[6,19,117–152]. This includes those that both did and did not directly assess the impact of sugar taxes on NNS consumption and levels in the food supply. In this instance, studies referred to an excise tax – an indirect tax imposed on the manufacture of certain types of goods and products[153]. Taxes on added sugar are used to increase the price of a product relative to its low-sugar counterparts, following the economic principle of 'price elasticity' (the percentage change in demand caused by a percentage change in price)[154]. In this model, less expensive alternatives are thought to be more desirable to consumers, thus reducing the demand for high-sugar products[154,155]. At the time of writing, forty-one countries have enacted a SSB tax (excluding the USA, where taxes are state-specific)[156]. Generally, SSB taxes (as the name suggests) only apply to SSB, though select countries (including France, Philippines, India and the state of Philadelphia in the USA) also tax beverages containing NNS. Chile is currently the only country to subsidise 'diet' beverages, further enhancing the price elasticity between SSB and beverages containing NNS[157].

Few of the studies assessing taxes explored how this intervention may affect NNS consumption or levels in the food supply (*n* 13; Table 4). Despite not directly reporting so, it is likely that the SSB taxes discussed in other studies also had an effect on these outcomes, as encouraging industry to reformulate is one of the key aims of nutrient-specific taxes[156,158]. SSB sales decreased in all studies that explored this outcome in response to a tax (Table 4)[19,119,121,125–127,130,140,142,144,145,152]. While some

studies (*n* 6) suggested that a tax on SSB increased the purchase of NNS beverages[19,119,121,126,130,145], others (*n* 3) found the opposite[125,142,152], and yet others (*n* 3) found no change in consumption or purchasing behaviour[127,140,144]. In four studies, NNS beverages were grouped with all non-SSBS[19,119,130,144]. This may confound the results, as the change in non-SSB sales could be attributable to water, milk or juice. In South Africa, Stacey *et al.*[148] found that prices for artificially sweetened and low-sugar drinks increased, despite not being affected by the SSB tax, which may have impacted the effect of the tax on beverage purchases overall. Zhong *et al.*[152], Cawley *et al.*[127] and Roberto *et al.*[142] found decreases in NNS beverage consumption post-tax; however, the tax in Philadelphia (which the studies analysed) also targeted NNS beverages. This reduced the likelihood of consumers substituting SSB with NNS beverages, as there would be no relative change in price elasticity.

The main data source for these studies was scanned labels of products, either by participants in the home or at the point of sale. Though the sample size generated by these methods is extensive, there is an absence of information on food consumed outside the home or grocery store purchases. This is problematic, as a large proportion of 'soft' drinks (both NNS and SSB) are likely to be purchased and consumed outside the home[159,160]. Additionally, in data sources including Nielsen Homescan Panel Data, participants must scan all groceries at home. The process of recording all purchases can be time consuming, which could result in under-reporting[161].

Education interventions. Education-based interventions included media campaigns[6,137,162–170], community education[171–178] and education in schools and childcare centres[179–196] on the harms of excess added sugar consumption. Of the studies exploring this policy action (*n* 39), only eight (Table 4) addressed the impact that education interventions to reduce added sugar intake may have on NNS consumption and levels in the food supply. While most studies (*n* 5) found that NNS beverage consumption and sales decreased in response to education addressing added sugar consumption[164,172,185,191,197], one study found the opposite[162], and yet two others found no association[166,198].

When analysing responses to the 'Beverage checklist' (a guide for beverage selection based on the nutritional value of a drink) in 2012, Luger *et al.*[172] found that while the percentage of beverages containing NNS increased initially, by 2017 there was a net decrease of 7 %. During this period, added sugar content in beverages decreased significantly, suggesting a lack of substitution of sugar with NNS. In school settings, both Veitch *et al.*[191] and Rauba *et al.*[185] found that an SSB education campaign directed at children greatly reduced both SSB and NNS beverage consumption. In studies from Farley *et al.*[164] and Schwartz *et al.*[197] NNS beverage sales decreased in both groups that received anti-SSB messaging and their controls.

Contrastingly, when using text messages and newsletters to promote positive beverage purchases, Zahid & Reicks[198] found that while SSB intake decreased, NNS beverage consumption was not affected. Similarly, Morley *et al.*[166] found that despite a decrease in SSB intake, there was no change in reported NNS beverage consumption after exposure to the *LiveLighter* campaign (a programme to encourage healthier dietary choices

Table 4. Summary of studies assessing the impact of policy actions targeting added sugar consumption on non-nutritive sweetener (NNS) consumption or levels in the food supply

Intervention	Country	Study methods	Sample	n	Time frame	Effect on SSB	Effect on NNS	Degree of NNS change	Reference
SSB tax	Barbados	Interrupted time-series design	Electronic point-of-sale data from one major grocery chain	1161 beverage products	2013–2016 (tax implemented 2015)	↓ Sales	↑ Sales (includes all non-SSB)	5·2 %	Alvarado et al. (2019)[119]
SSB tax	UK	Annual cross-sectional study	Nutrient composition data; volume sales data	7377 products	2015–2018 (tax implemented 2018)	↓ Sales	↑ Sales	40 %	Bandy et al. (2020)[121]
SSB tax	USA	Meta-analysis	Studies that assessed change in diet drinks after a SSB tax	Three studies	N/A	↓ Sales	↓ Sales	Not provided	Cabrera Escobar et al. (2013)[125]
SSB tax	Chile	Correlational research design	Household food purchases obtained from Kantar Worldpanel Chile	2000 households	2013–2015 (tax implemented 2014)	↓ Sales	↑ Sales	10·7 %	Caro et al. (2018)[126]
SSB tax	USA (Philadelphia)	Interviews; longitudinal surveys	Exit interviews; household surveys	1305 interviews; 440 surveys	2016–2017 (tax implemented 2017)	↓ Intake	↔ Intake	N/A	Cawley et al. (2019)[127]
SSB tax	Mexico	Longitudinal observation study	Nielsen Mexico's Consumer Panel Services (home-scan data)	6253 households	2012–2014 (tax implemented 2014)	↓ Sales	↑ Sales (includes all untaxed beverages)	4 %	Colchero et al. (2016)[130]
SSB tax	Mexico	Longitudinal observation study	Nielsen Mexico's Consumer Panel Services (home-scan data)	6645 households	2012–2015 (tax implemented 2014)	↓ Sales	↑ Sales (includes all untaxed beverages)	2·1 %	Colchero et al. (2017)[19]
SSB tax	Chile	Quasi-experimental study design	Household food purchases obtained from Kantar Worldpanel Chile	2863 households	2011–2015 (tax implemented 2014)	↓ Sales	↔ Sales	N/A	Nakamura et al. (2018)[140]
SSB tax	USA (Philadelphia)	Longitudinal difference-in-differences approach	Commercial retailer sales data	291 stores	2016–2017 (tax implemented 2017)	↓ Sales	↓ Sales	60·2 %	Roberto et al. (2019)[142]
SSB tax	Spain (Catalonia)	Longitudinal observation study	Males and females, 12–40 years residing in low-income neighbourhoods of Barcelona (intervention) and Madrid (control)	1929 participants	2017–2018 (tax implemented 2018)	↓ Consumers	↔ Consumers	N/A	Royo-Bordonada et al. (2019)[144]
SSB tax	USA (Berkeley)	Correlational research design	Electronic point-of-sale data at 26 stores	16·2 million barcode scans	2013–2016 (tax implemented 2015)	↓ Sales	↑ Sales (includes all non-untaxed beverages)	3·5 %	Silver et al. (2017)[145]
SSB tax	South Africa	Longitudinal observation study	Price observations	71 677 observations	2013–2019 (tax implemented 2018)	↑ Prices	↑ Prices	Not provided	Stacey et al. (2019)[148]

Table 4. (*Continued*)

Intervention	Country	Study methods	Sample	*n*	Time frame	Effect on SSB	Effect on NNS	Degree of NNS change	Reference
SSB tax	USA (Philadelphia)	Repeat cross-sectional study	Males and females, 18–64 years	1777 participants	2016–2017 (tax implemented 2017)	↓ Sales	↓ Sales	Not provided	Zhong *et al.* (2018)[152]
Education (media campaign)	USA	Intervention study and rolling cross-sectional survey	Philadelphia parents/ primary caregivers with a child between 3 and 16 years	1367 participants	15 months	↓ Intention to consume	↑ Intention to consume	Not provided	Bleakley *et al.* (2018)[162]
Education (media campaign)	USA	Intervention study Telephone surveys	Males and females, 18–45 years	Pre-intervention: 1031 Post-intervention: 1000	15 weeks	↓ Sales	↓ Sales	5·7 %	Farley *et al.* (2017)[164]
Education (beverage checklist)	Austria	Intervention study	Beverages available 2010–2017, using one large outlet in at least three out of nine federal states per each of the four main supermarket chains	2010 – 387 beverages 2017 – 584 beverages	7 years	↓ Sugar content	↓ NNS content	7·0 %	Luger *et al.* (2018)[172]
Education (*LiveLighter* media campaign)	Australia	Cohort study	Males and females 25–49 years	Intervention: *n* 673; comparison: *n* 730	6 weeks	↓ Intake	↔ Intake	N/A	Morley *et al.* (2018)[166]
Education (school intervention)	USA	Cohort study	Grade 3–5 students	Pre-intervention: 213 Post-intervention: 211	6 months	↓ Intake	↓ Intake	4·6 %	Rauba *et al.* (2017)[185]
Education (media campaign)	USA	Observational experiment	Weekly beverage sales data from supermarkets	Intervention 15; comparison 17	3 years	↓ Sales	↓ Sales	−0·3 litres/d	Schwartz *et al.* (2017)[197]
Education (school intervention)	Netherlands	Clustered RCT	Secondary schools located within 150 km of Amsterdam	18 schools	20 months	↓ Intake	↓ Intake	35·1 %	Veitch *et al.* (2011)[191]
Education (school intervention)	USA	Pre-post-surveys	Primary caregivers with a child 6–12 years	100 parents/ caregivers	4 weeks	↓ Intake	↔ Intake	N/A	Zahid & Reicks (2019)[198]
Labelling (multiple front-of pack labels)	Australia	Online RCT	18–35 years	1000 participants	2 weeks	↓ Intake	↔ Intake	N/A	Billich *et al.* (2018)[199]
Labelling (posters)	USA	Case-cross-over design and interviews	Purchases made by Black adolescents 12–18 years from six stores located in low-income Black neighbourhoods in Baltimore	4516 purchases	10 months	↓ Sales	↔ Sales	N/A	Bleich *et al.* (2012)[200]
Labelling (posters)	USA	Intervention study	Purchases made by Black adolescents 12–18 years from four corner stores near middle and high schools in Baltimore City	1600 purchases	3 months	↓ Intake	↑ Intake	0·09 %	Bleich *et al.* (2014)[203]

Table 4. (*Continued*)

Intervention	Country	Study methods	Sample	*n*	Time frame	Effect on SSB	Effect on NNS	Degree of NNS change	Reference
Labelling (traffic light system)	USA	Interrupted time series	Food outlets in RCHSD in San Diego, CA	Not specified	3 months baseline, 12 months intervention, and 4 months post-intervention	↓ Sales	↓ Sales	Not provided	Hartigan *et al.* (2017)[204]
Labelling (traffic light system)	Belgium	Intervention study	High schools in a radius of 30 km around Brussels	Three schools; 2959 students	7 weeks	↓ Sales	↑ Sales	Not provided	Stamos *et al.* (2019)[207]
Labelling (warning and energy labels)	USA	Cohort intervention study	Males and females 12–18 years	2202 participants	N/A	↓ Intention to purchase	↔ Intention to purchase	N/A	VanEpps & Roberto (2016)[216]
Environment (increased unsweetened milk availability in homes)	Chile	RCT	Males and females 8–10 years, SSB drinkers, BMI greater than the 85th percentile for sex and age	93 participants	16 weeks	↓ Intake	↑ Intake	275 ml/d	Albala *et al.* (2008)[244]
Environment (reduced price of NNS beverages in stores)	Australia	RCT	Female primary household shoppers	642 participants	19 months	↑ Sales	↔ Sales	N/A	Ball *et al.* (2015)[254]
Environment (increased SSB price in hospitals)	Australia	Interrupted time series	Males and females, all ages	Participant no. not reported; 1538 beverage sales	17 weeks	↓ Sales	↓ Sales (includes 100 % fruit juice)	27 %	Blake *et al.* (2018)[242]
Environment (reduced SSB availability in leisure centres)	UK	Interrupted time series	Attenders of public leisure centres, all ages	Ranged between 11 916 and 108 393 per month (no total given)	12 months	↓ Sales	↑ Sales	27 %	Breeze *et al.* (2018)[246]
Environment (reduced price of NNS beverages in stores)	Australia	RCT	Customers at remote Northern Territory stores	8515 participants	24 weeks	↑ Intake	↓ Intake	8 %	Brimblecombe *et al.* (2017)[250]
Environment (increased price of SSB)	UK	Interrupted time series	Jamie's Italian Restaurant chain	37 Restaurants	12 weeks	↓ Sales	↓ Sales	7·32 %	Cornelsen *et al.* (2017)[131]
Environment (SSB ban in hospitals)	USA	Intervention study	Food establishments in Nationwide Children's Hospital in Columbus, OH	Seven food outlets, unspecified number of vending machines	12 months	↓ Sales	↓ Sales	17 %	Eneli *et al.* (2014)[243]
Environment (increased low-energy beverage availability in homes)	USA	RCT	9th–10th graders, BMI ≥ 85th percentile for sex and age	217 participants	12 months	↓ Intake	↑ Intake	207 ml/d	Ebbeling *et al.* (2012)[245]
Environment (promotion of low-energy beverages)	USA	RCT	Supermarket sales	Eight supermarkets	6 months	↓ Sales	↓ In-aisle sales ↑ Check-out sales	2 litres/d 0·2 units/d	Foster *et al.* (2014)[251]

community centres[246], workplaces[247,248] and stores[131,209,249–254]. Of the studies exploring this policy action (n 49), only twelve (Table 4) addressed the impact that environmental interventions aiming to reduce added sugar intake had on NNS consumption and levels in the food supply. In some regions (including New York City), beverages containing NNS are not permitted for sale in schools, which may limit the number of studies able to assess changes in NNS consumption/sales in response to sugar policy. Similarly, some studies included NNS beverages as a type of SSB. Consequently, assessing responses of NNS products to a policy to reduce added sugar consumption was not feasible[232]. While some studies (n 4) found that NNS beverage consumption and sales increased in response to policy targeting added sugar[239,244–246], the majority (n 6) found the opposite[131,226,242,243,250,251], and two saw no association[241,254].

When free fruit was provided to children's homes, Øverby et al.[239] found that SSB and NNS beverage consumption decreased and increased, respectively, despite neither beverage being directly targeted by the intervention. Comparatively, Hovdenak et al.[241] found that supplying fruit to children in schools had no effect on either SSB or NNS beverage intake. Albala et al.[244] and Ebbeling et al.[245] found that when access to low-energy beverages in the home was improved, SSB intake decreased, while NNS beverage consumption increased. In a study of beverage availability and consumption in schools, Whatley Blum et al.[226] observed that reduced availability of SSB was often paired with a reduction in NNS beverage availability. This resulted in decreased consumption of both beverages in the intervention cohort[226]. In a hospital setting, Eneli et al.[243] found that a ban on SSB decreased NNS beverage sales significantly, despite these products being available after the intervention.

Influencing the prices of SSB and NNS beverages produced differing outcomes depending on the study. Blake et al.[242] and Cornelsen et al.[131] found that increasing the price of SSB in a supermarket and restaurant, respectively, resulted in decreased sales of both SSB and NNS beverage sales, despite the price increase not extending to the NNS beverages. Comparatively, Breeze et al.[246] found that when the price for SSB was increased in community leisure centres, though SSB sales decreased by 27 %, sales of NNS beverages increased by the same magnitude. When implementing in-store promotions of NNS and water, Foster et al.[251] found a decrease in NNS beverage purchases from supermarket aisles, but an increase in those purchased at the checkout. Interestingly, Brimblecombe et al.[250] found that when subsidising bottled water and NNS beverages, sales of SSB increased, yet sales of subsidised NNS beverages decreased. In a study subsidising the price of fruits, vegetables, water and low-energy beverages, Ball et al.[254] found no bearing of the intervention on NNS beverage sales.

Though most studies found that food environment interventions to reduce added sugar intake increased the sale and consumption of NNS beverages, the paucity and discordance of study results limit the dependability of this finding. Additionally, as the bulk of studies assessed interventions in the context of schools, results of these studies may not be generalisable to other settings or populations, particularly adults.

Reformulation. Reformulation can be used to reduce added sugar by modifying the ingredients in processed food[255]. Often, this involves replacing added sugar with other sweeteners (including NNS) to maintain the level of sweetness and palatability. Reformulation activities aim to improve the energy and nutrient intakes of the population without consumers making major changes to their dietary patterns[255]. At writing, no country has legislated a mandatory reformulation target for sugar, though voluntary reformulation policies and charters have been seen in countries including France, Switzerland and the UK[256,257]. Instead, reformulation targets are often a response to (or in pre-emption of) government policy to reduce added sugar in the food supply[63,68–70,74,78,80,83,100]. Six studies discussed reformulation of added-sugar products and the effect on the food supply, including NNS use[6,141,150,258–260]. Popkin & Hawkes[6] discussed NNS as a potential replacement for sugar in processed food, and commented on the ambiguity of how to include these additives within future policy. Vandevijvere & Vanderlee[150] suggested that labelling policies effectively stimulated reformulation by the food industry, and that despite a paucity of evidence, similar incentives are produced by taxes. Ortún et al.[141] speculated that policy actions to reduce added sugar, including taxes, encourage innovation by the food industry, including reformulation. Welsh et al.[259] and Borges et al.[260] reported an increased effort of beverage industries to market 'alternative beverages' (including NNS beverages) as healthier alternatives for consumers. Though Hashem et al.[258] conducted a meta-analysis which found that reformulation may decrease added sugar intake, how this may affect levels of NNS in the food supply was not examined.

The impact of non-nutritive sweeteners on diet quality, food choice and energy intake

Sixty-four articles focused on the effect of NNS consumption on dietary intakes. Compared with the other sections of this review, industry involvement was prevalent. Of the studies included in this section, approximately 50 % list either industry funding or a conflict of interest relating to the food industry. Of the studies explicitly funded by industry, four stated that their funders had no role in the design, analysis or presentation of the study, twenty-three stated only that the study was 'supported' by industry, and three stated direct involvement of industry in the study.

Dietary patterns, food, and nutrient consumption. A summary of articles (n 25) related to diet quality is shown as online Supplementary Table S3. Of these studies, fifteen were diet recalls, three were randomised controlled trials (RCT), three were food records, three were observational studies and one was a parallel study. The included articles assessed all three dietary exposure levels: dietary patterns, food groups, and nutrients.

(1) Dietary patterns
The effect of NNS consumption on overall dietary patterns was mixed. Some studies found that consumption of NNS was associated with a healthier dietary pattern, characterised as a higher Healthy Eating Index (HEI)-2005 score[115], an increased likelihood to have a 'restrained'[261] or 'prudent'[115,262,263] eating pattern, or

a higher Nutritional Quality Index (NQI) score (though this was only found in overweight and obese consumers)[264]. Moreover, Binkley & Golub[265] found that consumers who purchased NNS beverages made healthier food choices generally. Other studies found that NNS consumption was associated with a poorer dietary pattern than non-consumption, including emotional eating (eating in response to negative emotions such as anxiety or loneliness)[261], a lower HEI-2010 score (though only among high-socio-economic status consumers)[113] and a decreased likelihood of adhering to a prudent purchasing pattern[262]. Piernas *et al.*[262] found that NNS consumers were more likely to follow a fast-food/ready-to-eat meal pattern.

(2) Food groups

Comparably, there was no clear consensus in the literature on the impact of NNS consumption and intake of specific food and nutrient groups. While some studies found that, when compared with non-consumers of NNS, consumers ate more fruit[115,262,266,267], vegetables[115,262,266,267], nuts[262] and legumes[115], the opposite was found in other studies[266,268]. Moreover, Duffey & Popkin[269] found that consumers from the 'vegetable cluster' (a dietary pattern characterised by vegetable consumption) were less likely to drink diet drinks. Drewnowski & Rehm[115] found that NNS consumers had a higher intake of whole grains than non-consumers. An intervention by Piernas *et al.*[268] found that when compared with a cohort encouraged to drink water, those encouraged to drink NNS beverages did not decrease carbohydrate-rich grains. Yet another study by Piernas *et al.*[262] found that consumers of NNS had a higher percentage of energy intake from ready-to-eat cereals.

While Binkley & Golub[265] found that dairy product consumption in all product categories declined with increased NNS beverage consumption, others found that NNS consumers had a higher intake of low-fat dairy products[115,265,270] and dairy products overall[70] than non-consumers. Fowler *et al.*[40] found that specifically milk consumption was lower among NNS consumers, though Ca intake was similar. Comparatively, Gibson *et al.*[266] found no difference in milk consumption based on beverage consumption patterns. They also observed that consumers of NNS ate more fish than SSB consumers[266], though less than those who consumed no sweetened beverages at all[266]. Compared with non-consumers of NNS, consumers were found to have a higher oil intake[115]. Additionally, An[113] found that, overall, those consuming NNS had a higher energy intake from discretionary foods.

NNS beverage consumers were found to eat more snacks[99,262,265] and desserts than other beverage consumer clusters[262], with Binkley & Golub[265] suggesting that snacks offset the lower energy of diet beverages. Their study found that NNS consumers were more willing and likely to buy reduced-fat, -sugar and -energy versions of foods than other consumer groups, including milk, ice cream, frozen dinners and salad dressing[265,270]. A study by Bleich *et al.*[99] in obese adults found that this was particularly true for salty snacks. However, Piernas *et al.*[268] found that NNS consumers actually decreased dessert intake. Sigman-Grant *et al.*[267] reported that those that consumed NNS yoghurt, jelly and desserts consumed more of these products than those who consumed the full-sugar versions.

(3) Nutrients

NNS consumers were found to consume less carbohydrate generally[70,114,271–275] and less added sugar[70,114,115,266,267,271–273,275] than non-consumers, though Gibson *et al.*[266] suggested that this decrease in sugar is owing to the decreased contribution from beverages rather than from the diet overall. Comparatively, Sylvetsky *et al.*[276] found that children who consumed NNS beverages had higher intakes of added sugar, total sugar and carbohydrates (when compared with those who drank water). In habitual consumers of NNS, consumption of protein was lower from vegetable sources[114] yet higher from animal products[114,115]. Other studies found an increase in protein consumption overall compared with non-consumers[40,49,70,114,266,273,277]. Compared with non-consumers of NNS, consumers were found to have a higher intake of saturated fats[40,115,272,277] and a higher total fat consumption as a percentage of energy intake[40,273]. However, some studies found that NNS consumers consumed less energy from discretionary fats[115,267,270] and alcohols[49]. Generally, studies found that consumers of NNS had higher intakes of Na[70,115,278]. Additionally, Bellisle *et al.*[114] found that NNS consumers ingested higher amounts of cholesterol than non-consumers. Most studies found no difference in micronutrients between NNS consumers and non-consumers[114,266,267,271], though Winther *et al.*[278] found that intake of NNS was associated with a reduced intake of some vitamins.

Energy intake: (1) long-term studies

Long-term studies (those that assessed intake across more than 1 d) that investigated NNS consumption and energy intake (*n* 23) are shown as online Supplementary Table S4. Generally, NNS beverage consumption was associated with lower overall energy intake, ranging from a reduction of 76 kcal to 781 kcal (318 kJ to 3268 kJ) in average daily energy intake[40,49,113,114,263,265–267,270,274,279–281]. In some studies, SSB were included as dietary supplements, and their energy was included in daily totals, which may exaggerate these differences[274]. Bleich *et al.*[99] found that energy intake from solid food was higher in NNS consumers than those that drank SSB, though only in overweight and obese adults. Healthy-weight populations consuming NNS had a lower energy intake than non-consumers[99]. Gibson *et al.*[266] found that NNS consumers had a lower intake of energy from food, a difference of approximately 40–50 % when compared with SSB consumers. However, Winther *et al.*[278] and Piernas *et al.*[262,277] found the opposite, with higher energy intake associated with NNS consumption. Similarly, a study by An[113] found that NNS beverages were associated with the second largest increase in energy intake from discretionary foods (second to coffee) among beverage categories. This association was strongest among obese adults[113]. Yet other

studies found no clear association between NNS and long-term energy intake[70,266,273,282,283].

Compensatory effects of NNS were found in multiple studies[70,113,273]. This compensatory effect was most evident in high-income and -educated groups, which (as highlighted in the previous section) are higher consumers of NNS beverages than their low-socio-economic-status counterparts[113]. Leahy et al.[272] found that consumers of NNS beverages had a comparative energy intake to water consumers, while Stookey et al.[284] found that water consumption greatly reduced dietary energy intake over time.

The majority of these studies employed a dietary recall method. Whilst the most pragmatic method for this type of research, recalls are associated with desirability bias (in which participants may be dishonest in their responses to impress researchers), unreliability errors and measurement errors, which may affect results[285]. Despite these limitations, dietary recalls are often used in nutrition research as they can be culturally sensitive, do not require high levels of literacy, and provide quantitative data[285,286]. Additionally, evidence suggests that participants tend to overestimate how healthy their diet is, subsequently underestimating energy, Na, sugar and fat[286].

Energy intake: (2) short-term studies. Thirty-four primary studies assessed the effect of a pre-load of NNS on subsequent food intake in a post-intervention meal (online Supplementary Table S5). Six studies found an increase in food intake[287–292], twenty-four saw no significant difference[271,293–315] and four studies found a decrease in food intake[316–319]. Most participants were either 'healthy' or of a 'normal weight' (generally referring to a BMI of 18–25 kg/m^2) despite overweight and obese individuals being the primary consumers of NNS (as described previously). It is interesting to note that of the six studies that found an increase in food intake after a NNS preload, three were funded by the sugar industry[288,290,291], and a fourth was funded by a now fragmented multinational corporation[287]. Comparatively, three of the four studies that found a decrease in food intake were published by the same author, who has received direct and indirect funding from organisations including Coca-Cola, Sugar Nutrition and The International Sweeteners Association[316–318]. Additionally, these studies administered the NNS in tablet form, mitigating the potentially important effects of sweet taste or satiety of the preload. Overall, of the thirty-four studies that assessed NNS preloads and subsequent food intake, nineteen (or over 50 %) were either directly funded by, received products from, or had authors who had connections with industry[271,287,288,290,291,293,295–297,301,304–306,308–310,316–318].

Fluids were used as the pre-load almost exclusively throughout the studies. NNS beverages may be easier to manipulate in experimental studies, as NNS only need to impart sweetness in a beverage, as opposed to texture and other sensory variables that may be affected by the removal of sugar in other products. For most short-term studies assessing energy intake, consumption behaviour was measured under experimental conditions rather than in free-living populations. This may limit the applicability of the findings in real-world dietary patterns and behaviours[320]. Often, food intake was only measured over the course of a single meal, preventing the evaluation of compensatory effects in the long term. In addition, participants were often blinded to the use of NNS in their samples. In a real-world context, awareness of added sugar and energy content of a food or drink may contribute to compensation.

Discussion

The aim of the present review was to provide an overview of current NNS food supply and consumption patterns and to evaluate added sugar-reduction policies and their impact on NNS and the impact of NNS on food choice, energy intake and diet quality.

Assessment of the different types of sweeteners in the global food supply, and quantified amounts of sweeteners in products, was limited. It is difficult to measure direct quantities of NNS in the food supply, as many countries do not require the volume of NNS in a product to be declared on the label, only that they are an ingredient[321]. Despite comprehensive cross-sectional analysis of which products contain NNS, the trends of NNS use in the food supply are under-researched. There is a general consensus that the number of products containing NNS are increasing[69,70,72,85,100], which may contribute to an overall increased level in the food supply. However, no studies have measured the volume change of NNS in the food supply over time. This is a significant gap in the literature.

Most studies used cross-sectional study designs, thus demonstrating NNS consumption in a snapshot of time only. Due to the numerous different populations and study parameters, comparing these studies to derive consumption trends is not possible. Outside the USA, exploration of the consumption trends of NNS is limited. In many countries, national diet surveys are sporadic, and do not have up-to-date information on current rates of consumption. This is especially important for NNS, as there is the potential for a rapid increase in consumption given the accumulative legislative actions (particularly SSB taxes) to reduce added sugar in the food supply. Further research is needed to assess contemporary trends and patterns of NNS consumption globally.

High education/socio-economic status may be associated with NNS consumption as these consumers are typically more health-focused, and may desire low-energy alternatives[322]. Additionally, women may be more likely to consume NNS than men, as a larger proportion of 'diet' or 'lite' products are marketed to this group[63]. Women are also typically more likely to be on a 'diet' than men, thus may be more likely to choose lower-energy products[323]. One contradiction throughout the studies is that those who are overweight/obese are more likely to consume NNS than those with a healthy BMI. This could be for many reasons. First, these populations may be more likely to be the target of diet campaigns (NNS are prevalent in diet foods)[324]. Second, the results may be affected by reverse causality; those who are overweight aim to reduce their energy intake by consuming diet/low-energy food, rather than this food contributing to obesity[278,325,326]. Third, individuals may use the consumption of NNS as a rationale to make unhealthy food choices or to consume larger portion sizes as these products have less energy than their full-sugar counterparts[99,326,327].

While a broad range of policy actions targeting added sugar consumption was discussed, the underlying political factors that shape these policies, particularly in terms of the lack of holistic policy actions implemented globally, were not explored. Though some policy actions focused on 'discretionary' food, most policy actions targeted sugar as a nutrient, as opposed to suggesting a reduction in ultra-processed foods generally or promoting whole food consumption. Though broader national food policies may comprise policy actions that target different parts of the food supply, the results of this study demonstrate that the majority are nutrient-focused. As public health policy has an impact on the food supply and consequently consumption patterns, understanding why particular types of policy actions are promoted and implemented over others is imperative.

In general, the potential impact of these policy actions on NNS was not widely considered. The studies that did assess this outcome had mixed results. Though taxation seemingly increased NNS in the food supply in most studies, the opposite was true in others. Comparatively, education campaigns to reduce added sugar consumption were associated with a decrease in NNS purchases and intakes; yet others find the opposite, or no effect. Inconsistent associations were found for education labelling and food environment interventions. However, given the paucity of studies that explored these impacts, the conclusions that can be drawn are limited. While most studies were experimental in nature, the types of methods used, sample sizes and time periods analysed varied greatly. Furthermore, the impact of each policy action on NNS consumption can only be described as an association, not causative, as other factors may have made an impact on consumption rates. It is important to note that based on the available evidence it is not possible to suggest that one single policy action is the sole trigger for a change in added sugar or NNS consumption. Rather, an interaction between policy actions is likely to be the cause. Further research is needed to demonstrate how policy actions may have an impact on levels of NNS in the food supply, and to what magnitude.

Compared with the other sections of this review, industry involvement was prevalent in studies assessing the impact of NNS consumption on dietary intakes. Of the studies included in this section, approximately 50 % list either industry funding or a conflict of interest relating to the food industry. This involvement is a cause for concern, as previous studies suggest that when research is sponsored by the sweetener industry, both results and conclusions are more likely to be favourable towards NNS[328]. Comparatively, when studies were funded or supported by the sugar industry, the reverse was found[328]. The bias found in industry-sponsored studies is a well-documented issue in nutrition research, and may potentially undermine the results of the present review[328–331]. Greater research funding from governments and other funding agencies is needed to avoid a reliance on industry-funded analyses in the case of NNS.

The reviewed cross-sectional studies of the impact of NNS intake on diet quality were only able to show a correlative effect, not causative outcomes. How products containing NNS may create substitution effects in the diet, i.e. displacing one food for another, was not explored. This may be due to the limitations of the data sources used; large epidemiological studies, while useful for exploring the associations and potential impacts of NNS on overall dietary balance, do not explore consumer behaviour in

terms of food choice and direct substitution. Sample data were often limited, encompassing only a few days of intake, which may not be representative of usual consumption patterns. In addition, most studies used a self-administered diet questionnaire to obtain data. Participant bias, recall bias and social-desirability bias may make an impact on the validity of these results[285,332]. An additional limitation of food composition databases is their inability to accurately capture all NNS in the food supply; thus consumers may be assigned to clusters incorrectly. The metric used to determine the healthiness of a diet varied between studies, including HEI scores (including multiple iterations), Nutritional Quality Index (NQI) scores and the defining of food pattern clusters (for example, vegetable cluster, breakfast cluster). Additionally, the clustering of participants varied throughout the literature – while some participants were clustered as binary 'users' or 'non-users', others were further classified by dietary pattern ('prudent' or 'Western'). Given these limitations, developing and evaluating biomarkers for NNS intake would be a useful tool to monitor NNS consumption in the future.

In studies that assessed dietary patterns, there was no differentiation between types of NNS. Most studies assessed dietary patterns in relation to the consumption of NNS beverages, as opposed to all products containing NNS. This could be for many reasons. Beverages are the primary source of NNS in most diets[74]. Additionally, they are a well-known source of NNS to consumers, who may be more likely to recall them during FFQ or dietary interviews as opposed to other NNS-containing items, including sauces and dairy products. This is a considerable limitation of the literature, as NNS are becoming prevalent in food sources including yoghurts and desserts and are found across a wide variety of products in the food supply.

Overall, while food regulators and epidemiologists often focus predominantly on the immediate safety and toxicological aspects of NNS as opposed to the impact on dietary patterns, the progression of these additives in the food supply may be a powerful marker of the reductionist approach to public health that currently prevails in policy making. Consumer behaviour and food choice are greatly influenced by the food environment and food supply, which have been shaped by the current reductionist approach to public health. From the findings of the present review, questions can be raised regarding the fundamental effectiveness of current policy approaches at tackling the underlying causes of chronic disease. While they may reduce added sugar intake, whether these policies reduce the consumption of ultra-processed food, improve diet quality and improve population health is unclear. Fundamentally, reductionist policy actions can be seen as a marker for the 'business-as-usual approach' to public health and safety, and therefore do not target the underlying issues with our current global foods system.

Limitations and future directions

The present review was limited by the exclusion of studies published in languages other than English, particularly as countries in South and Latin America have been leaders in policy actions aiming to reduce added sugar reduction. Additionally, there is the potential for demonstrations of the relationship between

policy to reduce added sugar consumption and increases in NNS in the food supply from non-academic sources including industry documents or government reports that have not been included in the present review.

The present review highlighted many areas for future research. While a range of policy actions has been implemented to reduce added sugar intake, the potential impact of the policies on levels of NNS in the food supply is unclear and warrants further exploration. This includes a lack of research on the different effects of reductionist or holistic policies, as well as those that target either nutrients, food, dietary pattern of food systems, and on combinations of different policy actions on NNS in the food supply. The vast majority of studies included in this review explored high-income countries, despite the potential for changes in the consumption of ultra-processed food in middle-low income countries (particularly in response to the nutrition transition)[333,334]. Overall, there is some evidence to indicate that consumption of NNS is increasing in some contexts, though a global analysis of consumption trends is proposed. NNS are widely available in the food supply, especially in beverages, dairy products and confectionery. However, trends in the reformulation of different product categories, and differences between geographical locations and economy-income levels require further study. Research examining how the increased availability of low-sugar discretionary products affects global diets is limited, particularly potential substitution effects of low-sugar beverages for water and/or milk from the diet.

Conclusion

A range of policy actions has been implemented to reduce added sugar intake globally. The potential impact of these policy actions on NNS-related food supply changes and consumption has not been satisfactorily determined. Most of these policy actions were downstream in nature, potentially encouraging reformulation of individual food products as opposed to improving food systems or dietary patterns. The underlying political factors that shape these policies, and the implementation of reductionist policy actions, have not been explored. NNS were found in an extensive range of products across the food supply, and consumption of NNS has increased over the last two decades in some countries. The literature exploring how NNS consumption has an impact on overall dietary balance was mixed and potentially influenced by industry-funded research. The potential substitution effect of reformulated, ultra-processed food containing NNS for nutritious whole foods was unclear. It is therefore important for future research to determine why nutrient-focused policy actions are championed over others, what their impact is on the food supply and subsequently, how consumption and dietary intakes are affected.

Supplementary material

To view supplementary material for this article, please visit https://doi.org/10.1017/S0954422420000268

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