Contents lists available at SciOpen

Food Science and Human Wellness

journal homepage: https://www.sciopen.com/journal/2097-0765

Health effects of fruit juices and beverages with varying degrees of processing

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A R T I C L E I N F O

Article history:
Received 1 December 2022
Received in revised form 5 January 2023
Accepted 20 February 2023

Keywords:
Fruit juices and beverages
Dietary guidelines
Degree of processing
Health effects
Mechanism

A B S T R A C T

The degree of processing is rarely considered an independent factor in the health effects of fruit juices and beverages (FJBs) consumption. In fact, the consumption of ultra-processed foods has been shown to pose health risks. In this study, we first integrated 4 systems used to classify the degree of food processing and then classified FJBs into three major categories, low (minimal), moderate and high. Second, we compared the differences in attitudes towards FJBs in dietary guidelines. Third, we integrated the results of existing epidemiological surveys, randomized controlled trials, and animal experiments to explore the health risks associated with consuming FJBs. Deepening the processing of FJBs has been found to lead to an increased risk of diseases. Dietary pattern, nutrients, addition agents and consumer preferences may be influential factors. Finally, we investigated whether there were any changes in the health benefits of 100% fruit juices produced by different processing methods. In conclusion, minimally/moderately processed 100% fruit juices provide more health benefits than highly processed fruit beverages. The results support the need to consider the extent of FJBs processing in future studies to adjust official nutritional recommendations for beverage consumption.

1. Introduction

The health benefits of fruits are undisputed. A moderate increase in daily fruit consumption can effectively reduce the risk of cardiovascular disease (CVD), stroke, coronary heart disease (CHD), oral cancer, and other diseases[1]. There is a consensus that the international dietary guidelines recommend 5 servings of fruits and vegetables per day[2]. However, the health benefits and risks of fruit juices and beverages (FJBs) as fruit-derived products are unclear and often misunderstood by consumers[3]. To classify the fruit-derived liquid products on the market, they are mainly divided into two categories: fruit juices and juice beverages. Juices can be divided into concentrated juice (FC juice) and non-concentrated juice (NFC juice), while beverages can be divided into fruit-flavored beverages and fruit juice beverages. FC juice is produced by adding water to the juice concentrate for blending and recovery. NFC juice is not subject to any concentration or recovery process. The fruit was washed and pressed to produce bottled juice immediately after sterilization. Depending on whether heat is required for sterilization, NFC juices can be divided into thermally processed and non-thermally processed juices.

Numerous epidemiological surveys have shown that FJBs are associated with noncommunicable chronic diseases (NCDs), including cardiovascular obesity[4-5], disease (hypertension (HTN), CHD, etc.)[6-7], diabetes[8-9], gout[10-11], cancer[12-13], dental caries[14], and mental illness[15]. These diseases are closely related to daily dietary habits. However, the definitions of "fruit juice" and "beverage" are not uniform in studies, especially "fruit-flavored beverage" "unsweetened fruit juice" "sweetened fruit juice" or "fruit juice". The inconsistency of the included ranges limits the comparison and interpretation of the results of different studies[16]. In addition, the current dietary guidelines of different countries classify FJBs differently[17]. It can be seen that the current evidence on the health effects of FJBs is inconsistent.

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Peer review under responsibility of Tsinghua University Press.

SciOpen Publishing services by Tsinghua University Press

http://doi.org/10.26599/FSHW.2022.9250202

As the concept of ultra-processed foods (UPFs) is gaining increasing attention, the degree of processing is found to have a major impact on the fruit[18]. However, the health effects of fruit drinks have rarely been studied regarding their degree of processing[19]. At the macro level, processing changes the size and status of the food[20]. At the micro level, processing has an impact on the amount and form of macro- and micronutrients in food[21-22], which affect the digestion and absorption of food in the human body. Food is consumed as a whole. The degree of processing is a good starting point for assessing the nutritional value and health benefits of foods.

This study examines the association between the consumption of FJBs at different processing levels and disease and explores the underlying mechanisms. This paper lays the foundation for future nutritional epidemiology studies and provides evidence to support the formulation of future national dietary guidelines and the proposal of related health policies.

2. Classification of FJBs according to the degree of processing

The processing of fruits changes their nutritional matrix fundamentally and usually harmfully[23]. The degree of processing appears essential for defining the health potential of the food. Different systems have been applied to characterize foods according to their degree of processing to evaluate their nutritional value. The commonly used systems are the NOVA system[24] and those developed by the International Agency for Research on Cancer (IARC)[25-26], the International Food Information Council (IFIC)[27-28], and the University of North Carolina (UNC)[29] (Table 1).

Among these, the NOVA system is the most widely used. As a novel categorization, the international NOVA classifies foods and beverages "according to the extent and purpose of industrial processing"[30]. It was first proposed in 2009[31] and was based on the effects of processing on the food matrix and its sensory properties rather than nutritional ingredients included[32]. This system divides food into 4 categories: 1) UPFs, 2) processed foods (PFs), 3) processed culinary ingredients (PCIs), and 4) unprocessed or minimally processed foods (MPFs)[30]. UPFs are defined as industrial formulations and include all kinds of beverages with multiple ingredients at the high end of the beverage industry[33]. On the contrary, MPFs are minimally modified foods, with no new substances added or introduced. According to NOVA, minimum allowable steps in processing food include cleaning, scrubbing, washing, winnowing, hulling, peeling, grinding, grating, squeezing, flaking, skinning, portioning, filleting, drying, pasteurization (PT), sterilizing, chilling, refrigeration, freezing, sealing, bottling (as such), simple wrapping, vacuuming, and gas packing[34]. Fruit-flavored beverages and fruit juice beverages were among the UPFs,while the classification of juices is different. Since the production of FC juices requires concentration and recovery processes, FC juices are not minimally processed. The category of FC juices depends on their beverage additives. Those containing only sugar are PFs, while those with flavors and sweeteners are UPFs. The classification of NFC juices is determined by whether they are thermally treated or not. Of the thermally sterilized NFC juices, only pasteurized juices can be classified as MPFs and the rest as PFs. The newest type of fruit juices, non-thermal NFC juices, which are fresher, cleaner, and more sustainable than the others, belong to MPFs. Non-thermal processing techniques such as high-pressure processing (HPP), high-pressure

Table 1
Classification of different types of FJBs according to 4 different food processing classification systems.

Juice/ Beverage	Types of FJBs	Content of fruit (%)	Ingredients (except fruits and water)	Processing methods	NOVA system	UNC system	IFIC system	IARC system
Beverage	Fruity-flavored beverages	Generally ≤ 5	Sugar, additives (may also include carbonic acid, alcohol)	/	Ultra-processed foods (UPFs)	Highly processed	"Ready-to-eat" foods	Highly processed foods
	Fruit juice beverages	≥ 10 and < 100	Sugar, additives	/	UPFs	Highly processed	"Ready-to-eat" foods	Highly processed foods
Juice	FC juice	100	Sugar	/	Processed foods (PFs)	Moderately processed	Processed for preservation	Moderately processed foods
	FC juice	100	–	/	PFs	Basic processed–Processed for basic preservation or precooking	Processed for preservation	Moderately processed foods
	NFC juice	100	–	Thermal sterilization: UHT, HTST	PFs	Basic processed–Processed basic ingredients	Processed for preservation	Moderately processed foods
	NFC juice	100	–	Thermal sterilization: PT	Unprocessed and minimally processed foods (MPFs)	Basic processed–Processed basic ingredients	Processed for preservation	Moderately processed foods
	NFC juice	100	–	Non-thermal sterilization: HPP, HPCD, PEF, ionizing radiation, CP, LEDs, UV, US, MW, etc.	MPFs	Basic processed–Processed basic ingredients	Processed for preservation	Moderately processed foods
	Fresh juice	100	–	Mechanical methods	MPFs	Basic processed–Processed basic ingredients	Processed for preservation	Non-processed foods

Notes: /, Sterilization method is not the main indicator of NOVA classification; –, No other additives except fruit and water. UHT, ultra-high temperature instantaneous sterilization; HTST, high temperature short time; PT, pasteurization; HPP, high-pressure processing; HPCD, high-pressure carbon dioxide; PEF, pulsed electric fields; CP, cold plasma; LED, light emitting diodes; UV, ultraviolet; US, ultrasound; MW, microwave.

carbon dioxide (HPCD), pulsed electric fields (PEF), and ultrasound (US) allow minimal processing of foods at low temperatures and better preserve the nutrients, texture, color, and freshness of foods[35]. In general, FJBs can be broadly classified into three categories according to NOVA. Two indicators used in the classification of fruit juices to distinguish PFs from MPFs are the presence of added free sugars and whether the original fruit substrate was severely damaged during sterilization.

UNC system was created to provide a comprehensive list of foods that consumers can purchase in US supermarkets by processing category to reduce subjectivity[29]. For this purpose, foods are first classified by species, and then the degree of processing of each food item is graded. According to UNC system, FJBs are all classified as "beverages" rather than "fruits, vegetables, legumes," mainly to distinguish liquid foods from solid foods. This system provides the most detailed description of the four classification systems. It follows two classification criteria: a 4-category classification based on the degree of processing and a 3-category classification based on convenience[19]. Commercial 100% juices are classified according to whether they are concentrated and reduced, with FC juices classified as "processed for basic preservation or precooking" and NFC juices classified as "processed basic ingredients", just like freshly squeezed juices. All juices in this category are excluded from the "unprocessed/minimally processed" category.

IFIC classifies foods into 5 levels according to the degree of processing and subdivides the term "processing" into "which foods are processed" and "the purpose of the processing"[27]. In this system, sugar is not emphasized, and specific processing techniques are not clearly mentioned. Only homemade foods were marked, but this was of little importance for the classification of FJBs. Fruit juices are broadly classified and are all in the "processed for preservation" category, which is defined as "to preserve and enhance the nutrients and freshness of food in its prime condition"[28].

The IARC system is based on the degree of physical processing of foods and is derived from the method design of the European Prospective Investigation into Cancer and Nutrition (EPIC)[25], so some articles have also called it the EPIC system[19,26]. Food has been classified into three categories. In the IARC system, the "non-processed foods" category includes "fresh juices", while "canned in water/brine or in its own juice" belongs to the "moderately processed food"[25].

As highlighted in the classification by the level of processing, recent evidence confirms that higher levels of processing can have negative effects on human health[36-37]. However, studies based on different taxonomic approaches have found that many metabolites have variable associations and inconsistent concentrations of nutrients[38-39]. Although both classifications conclude that the degree of processing is positively associated with health risks, subtle differences in classification may influence the interpretation of biological mechanisms. If the degree of food processing is identified as a factor influencing health, the association should not be influenced by definition[19].

In this review, to avoid bias in conclusions caused by conceptual differences, any of these 4 classifications were not used. In order to achieve conceptual unity, we have integrated and unified 4 classifications (Fig. 1). Beverages are undoubtedly the most processed, while freshly squeezed juices are the least processed among FJBs. Although the claims of 100% fruit juices are inconsistent, they are generally considered moderately processed foods. In terms of processing technology, all systems noted that emerging non-thermal processing technologies produce NFC juices that tend to be minimally processed, while FC juices tend to be medium-processed foods. Moreover, the addition of sugar deepens the processing of FJBs. As consumers have become increasingly concerned about human health and food safety recently, the processing of FJBs is evolving in a healthier and more sustainable direction.

The classification system based on the degree of processing is completely different from other general classifications because it is not based on any nutritional parameter but on the overall variability of the food[40]. To be specific, as the proponents of the NOVA system explained, when considering food, nutrition, and public health, the most important factor is the nature, extent, and purpose of processing

Four different categorization systems of foods

Degree of processing	NOVA	IFIC	IARC	UNC
High	Ultra-processed foods	Prepared foods/meals "Ready-to-eat" foods	Highly processed foods	Highly processed • Highly processed ingredients • Highly processed stand-alone
Medium	Processed foods	Mixtures of combined ingredients	Moderately processed foods • No further cooking • Cooked foods, from raw or moderately processed foods	Moderately processed • Moderately processed for flavor • Moderately processed grain products
Low	Processed culinary ingredients Unprocessed or minimally processed foods	Processed for preservation Minimally processed	Non processed foods, consumed raw	Basic processed • Processed basic ingredients • Processed for basic preservation or precooking Less processed • Unprocessed/minimally processed

Fig. 1 Comparison of 4 processing classification systems.

and what happens to food and to us because of processing, but rather nutrients or foods[31]. We consume foods as a whole complex matrixes, not as a sum of nutrients, which agrees with holism in nutrition. Traditional nutritional evaluation methods are mainly based on reductionism, which is intended to conduct separate research on each part of a complex system[41]. However, the goal of processing is to obtain a new product[42]. Therefore, classifications based on the degree of processing should focus more on the damage to the original components by the techniques and explore the end food product as a whole.

3. Dietary guidelines for FJBs

There are various recommendations for the consumption of FJBs worldwide. A global review of food-based dietary guidelines found that 7% of countries specifically mention that fruit juices are harmful and/or grouped with sugar-sweetened beverages (SSBs)[17]. Table 2 uses typical 100% fruit juices and SSBs as examples to show attitudes toward FJBs in some representative countries. The following dietary guidelines originated from the Food and Agriculture Organization of the United Nations (FAO)[43]. Many national dietary guidelines do not distinguish between recommended intakes of FJBs. For example, the most recent *Canadian Dietary Guidelines*, published in 2019, do not equate 100% fruit juices with SSBs but classify fruit juice as a "sugary beverage" that is not recommended because of its high free sugar content. In 2015, the *Dutch Dietary Guidelines* directly classified fruit juices as SSBs[44]. There are also dietary guidelines in countries that distinguish between the recommended consumption of 100% fruit juice and that of fruit beverages. *British Dietary Guidelines* recommend 5 servings of fruits and vegetables per day, of which 100% fruit juice should not exceed one serving. The *South African Dietary Guidelines* state that fruit juice can be used as a substitute for fruits and vegetables[45]. Finland does not classify fruit juices in the fruit group but allows one cup of 100% fruit juice per day and recommends reducing consumption of FJBs. The *Chinese Dietary Guidelines*, while noting that fruit juice cannot fully replace fresh fruit, recommend increasing fruit and vegetable intake by consuming fruit juice (without removing the residue). The 2020–2025 edition of the *Dietary Guidelines for Americans* allows up to half of the recommended daily intake of fruit to be replaced with fruit juice. According to statistics, 23% of the dietary guidelines clearly indicate that fruit juice is part of the fruit group, but another 38% of the dietary guidelines are unclear about the classification of pure fruit juice[17]. Attitudes toward sugary drinks are consistent from country to country; although some countries classify them by beverage and others by sugar, all recommend reducing their consumption as much as possible. Additionally, emerging artificially sweetened beverages (ASBs) are not mentioned in the global dietary guidelines. The *German Dietary Guidelines for Drinking Water* clearly state that calorie-free or low-calorie light beverages are not recommended because they contain

Table 2
Description of 100% FJBs in dietary guidelines for countries around the world[47].

Region	Country	Year of publication	Group of 100% juice	Differentiate between 100% juice and SSBs	Specific claims about 100% fruit juice	Specific claims about SSBs
Africa	South African	2013	"Vegetables and fruit"	√	"Acceptable as an occasional substitute"	"Use sugar and foods and drinks high in sugar sparingly"
Africa	Kenya	2017	"Sugar and sweets"	√	"Should be used sparingly"	"Limit the consumption of sweetened foods and drinks"
Europe	Sweden	2015	"Beverages and alcohol"	×	"Juices are not something you drink for health" "It is best not to drink these drinks so often"	/
Europe	Dutch	2015	"Drinks"	×	"Minimize consumption of sugar-containing beverages"	/
Europe	Finland	2014	"Drinks"	√	"Can drink a glass of fruit juice daily"	"Drink only infrequently"
Europe	United Kingdom	2016	"Fruit and vegetables"	√	"Limit fruit juice and/or smoothies to 150 mL a day"	"Try cutting down free sugar intake"
North America	United States	2015–2020	"Fruits"	√	"One cup of 100% fruit juice counts as one cup of fruit" "At least half of the recommended number of fruits should come from whole fruits"	"When added sugars in foods and beverages exceed 10% calories, a healthy eating pattern may be difficult to achieve"
North America	Canada	2019	"Sugary drinks"	×	"Sugary drinks should not be consumed regularly"	/
Latin America	Mexico	2015	"Fruit"	√	"Use ripe fruits to make flavored water, you do not need to add sugar and whenever possible, you should use the peel" "Prefer fresh and whole fruits instead of juices"	"Drink plain agua frescas or flavored water without added sugar instead of sweetened drinks"
Asia	China	2016	"Fruit and vegetables"	√	"Juice does not represent fresh fruit" "Making your own fruit and vegetable juice (without removing the residue) is a good way to eat more fruits and vegetables"	"Avoid or limit sugar-sweetened beverages"
Asia	Japan	2016	–	–	–	–
Asia	India	2011	"Vegetables and fruits"	√	"Fresh fruits are nutritionally superior to fruit juices"	"Limit consumption of sugar and unhealthy processed foods"
The Pacific	Australia	2013	"Fruit"	√	"Only occasionally: 125 mL (½ cup) fruit juice (no added sugar)"	" Limit intake of foods and drinks containing added sugars such as sugar-sweetened soft drinks and cordials, fruit drinks"

Note: √: Right; ×: No; −: No mention; /: No separate mention.

other food additives such as sweeteners, colorings, and flavorings[43]. Additionally, only a few countries mention UPFs in their dietary guidelines. The *Canadian Dietary Guidelines* specify, "Limit highly processed foods. If you choose these foods, eat them less often and in smaller amounts"[43]. India states, "processed foods rich in fats, salt, sugar, and preservatives may pose a health risk if consumed regularly"[43]. These dietary guidelines have generally been published only recently, as the concepts of UPFs and MPFs have been widely publicized and gained traction only in recent years. The concept of FJBs is still incompletely understood in various countries. Also, the current perception of the health benefits of FJBs is not uniform.

4. Health effects of FJBs

Few studies on the health benefits of FJBs have been classified by the degree of processing. Epidemiological surveys only broadly classify beverages and only distinguish between juices and beverages. There is no further subdivision of 100% juice into freshly squeezed NFC and FC juices, let alone whether they are thermally processed. The problem with randomized controlled trials (RCTs) and animal studies is that only FJBs with high levels of a particular nutrient are studied and are therefore not sufficiently representative. Additionally, the range of juices and beverages was unclear in some studies. SSBs have the greatest variation in scope due to the concept of added sugar, while the classification of 100% fruit juice has the greatest consistency[16]. This leads to difficulties in compiling the literature. Due to the lack of evidence, the health benefits of FJBs are presented in this review as differences between 100% fruit juices and fruit drinks (especially SSBs). 100% fruit juices are moderately/MPFs, whereas fruit drinks are highly processed foods. This review analyzes the health effects of different degrees of processing of FJBs in broad categories.

Although the adverse effects of SSBs on NCDs are widely recognized, the association between fruit juices and metabolic disease risk remains controversial and contradictory (Tables 3 and 4). Some people believe that 100% fruit juice is nutritionally equivalent to fruit but not as nutritious as solid fruit[46]. Fruit juices are considered as harmful to health as SSBs, as classified in some dietary guidelines[47].

4.1 Clinical trials and epidemiological investigations

4.1.1 Weight gain, overweight, and obesity

Being overweight and obesity are serious human health problems worldwide[48]. The impact of FJBs on body weight is controversial. In addition to the common overweight and obesity based on body mass index (BMI), there is normal weight obesity (NWO), which is associated with the accumulation of adipose tissue[49]. Weight gain has negative effects on some bodily functions and carries an increased risk of CVD[49], HTN[50], type 2 diabetes mellitus (T2DM)[51], hyperlipidemia[52], stroke[53], female reproductive problems[54], asthma[55], oral health problems (e.g., dental caries)[56], certain cancers[57], etc. Multiple pathways may have harmful effects. The "hypothalamic-pituitary-ovarian axis" is disrupted, and bioactive molecule adipokines released from adipose tissue will interact with various molecular pathways, such as inflammation, coagulation, and insulin resistance[54].

4.1.1.1 Children and adolescents

Although the consumption of 100% fruit juices is thought to lead to weight gain when some confounding factors are excluded, a more consistent conclusion is that there is no direct relationship between the consumption of 100% fruit juices and obesity. The consumption of 100% fruit juices peaked in the late 1990s when daily intake by children and adolescents exceeded the recommendations of the American Academy of Pediatrics (AAP)[20]. Nevertheless, a systematic review in 2008 found no systematic association between obesity and consumption of 100% juice during this period[58].

A systematic review of children aged 1–18 years summarized the results of 22 studies that showed no association between the consumption of 100% juice and weight gain after excluding energy intake factors. Assessment of fiber, vitamin C, magnesium, and potassium intake in children found that 100% juice did not affect the adequacy of nutrient intake[59].

However, a meta-analysis of age-group studies showed that consumption of 100% juice was associated with a slight (although clinically insignificant) increase in body weight in children 1–6 years of age[5]. Regular consumption of 100% juice at age 2 may increase the likelihood of obesity at age 2−4 years[60]. This phenomenon was not observed in children aged 7–18 years. Another study found that consumption of 100% fruit juice can lead to central obesity in children younger than 5 years but did not affect children aged 6–12 years. However, fruit juice consumption was positively associated with obesity in children of all age[4].

Although controversial, most evidence shows that moderate consumption of 100% fruit juice provides beneficial nutrients for children's growth and does not lead to teenage weight gain, whereas beverages have no benefit for child development.

4.1.1.2 Adults

There is a consensus that SSBs are harmful to health. Qin et al.[61] found in a meta-analysis of 39 studies that a 250 mL increase in daily SSB consumption was associated with a 12% increased risk of obesity, with a corresponding increased risk of T2DM, HTN, and all-cause mortality.

However, there is no single answer for the relationship between fruit juice and weight change. Hebden et al.[62] investigated the possible relationship between fruit and juice consumption and weight gain in adults. The review included 11 RCTs and 6 prospective cohorts (PCs). Results of the RCTs found that whole fruit consumption helped reduce the risk of long-term weight gain in middle-aged adults by mediating a reduction in total energy intake. However, fruit juices have the opposite effect by promoting long-term weight gain. This was also the conclusion of a survey of 49 106 postmenopausal women. Weight monitoring over 3 years revealed that they gained approximately 0.13 lb (59 g) per year from one serving of juice per day[63]. A Harvard study found that fruit juice increases body weight by 0.05 lb (22 g) per year[64]. Although the above conclusions show the effect of fruit juice on weight gain, the Harvard study did not correct the effect of total energy intake, and the other two studies did not distinguish between sugar-sweetened fruit juice and 100% fruit juice.

Table 3
Association of consumption of different FJBs with metabolic or health outcomes (meta-analysis of investigative studies).

Type of component studies	Population (age (year))	Intervention	Health outcome	Reports included	Relative risk (95% CI)	Heterogeneity test I^2 (%) (P value)	Reference
Prospective cohort studies	Adults (≥ 18)	SSBs intake increased by 250 mL/day	Obesity	7	1.12 (1.05, 1.19)	67.7 (P = 0.005)	[61]
	Adults (≥ 18)	SSBs intake increased by 250 mL/day	T2DM	19	1.19 (1.13, 1.25)	82.4 (P < 0.001)	
	Adults (≥ 18)	SSBs intake increased by 250 mL/day	Hypertension	7	1.10 (1.06, 1.14)	58.4 (P = 0.034)	
	Adults (≥ 18)	SSBs intake increased by 250 mL/day	Allcause mortality	10	1.04 (1.01, 1.07)	58.0 (P = 0.020)	
Prospective cohort studies	Older children (7−18)	1 daily 6−8-oz serving increment of 100% fruit juice	BMI z-score	5	0.003 (0.001, 0.004)	0 (P = 0.90)	[5]
	Younger children (1−6)	1 daily 6−8-oz serving increment of 100% fruit juice	BMI z-score	2	0.087 (0.008, 0.167)	27 (P = 0.24)	
Prospective cohort studies	Adults (≥ 18)	Fruit juice	Gout and hyperuricaemia	3	1.77 (1.20, 2.61)	0 (P = 0.54)	[80]
	Adults (≥ 18)	SSBs	Gout and hyperuricaemia		2.08 (1.40, 3.08)	0 (P = 0.52)	
Prospective cohort studies	Adults (≥ 18)	Sugar-sweetened fruit juice	T2DM	4	1.28 (1.04, 1.59)	43.3 (P = 0.184)	[8]
	Adults (≥ 18)	100% fruit juice	T2DM	4	1.03 (0.91, 1.18)	6.2 (P = 0.362)	
Prospective cohort studies	Adults (≥ 18)	SSBs (before adjustment for adiposity)	T2DM	17	1.18 (1.09, 1.28)	89	[74]
	Adults (≥ 18)	SSBs (after adjustment for adiposity)	T2DM	17	1.13 (1.06, 1.21)	79	
	Adults (≥ 18)	Fruit juice (before adjustment for adiposity)	T2DM	13	1.05 (0.99, 1.11)	58	
	Adults (≥ 18)	Fruit juice (after adjustment for adiposity)	T2DM	13	1.07 (1.01, 1.14)	51	

Note: SSBs, sugar-sweetened beverages; BMI, body mass index; T2DM, type 2 diabetes mellitus; CI, confidence interval.

Table 4
Association of consumption of different FJBs with metabolic or health outcomes (meta-analysis of RCTs).

Health outcome	Duration (week)	Population (age (year))	Intervention	Comparison	Index	Subject (n)	Difference (95% CI)	Heterogeneity test	Reference
Cardiovascular disease	1−13	Adults (18−65)	A range of 250–750 mL/day orange juice	A placebo that was similar in its appearance to orange juice	Glucose	5 (n = 5)	−2.92 mg/dL (−5.327, −0.530)	P = 0.017	[103]
					Insulin	5 (n = 5)	−1.229 (−2.083, −0.374)	P = 0.005	
					HOMA-IR	5 (n = 5)	−0.464 (−0.747, −0.181)	P = 0.001	
					Total cholesterol	9 (n = 10)	−9.84 mg/dL (−15.43, −4.24)	P = 0.001	
					LDL-C	9 (n = 10)	−9.14 mg/dL (−15.79, −2.49)	P = 0.007	
					CRP	7 (n = 7)	−0.467 mg/L (−0.815, −0.120)	P = 0.008	
Cardiovascular disease	2−12	Adults (> 18)	Orange juice	No intervention or control FJBss	Total cholesterol	10	−6.84 mg/dL (−12.38, −1.29)	P = 0.01	[203]
					IR	4	−0.390 (−0.770, −0.006)	P = 0.04	
Diabetes	3−16	Adults (> 18)	100% fruit juice	A control beverage (e.g., sugar/carbohydrate or energy-matched beverage, water, or no beverage)	Fasting blood glucose	16	−0.13 mmol/L (−0.28, 0.01)	P = 0.07	[75]
					Fasting blood insulin	11	−0.24 pmol/L (−3.54, 3.05)	P = 0.89	
					HOMA-IR	7	−0.22 (−0.50, 0.06)	P = 0.13	
					HbA1c	3	−0.001 (−0.380, 0.380)	P = 0.28	
Diabetes	4−12	Adults (> 18)	Fruit juice	Placebo beverage, water, or controlled FJBs	Fasting glucose concentration	12	0.79 mg/dL (−1.44, 3.02)	P = 0.49	[9]
					Fasting insulin concentrations	5	−0.74 μIU/mL (−2.62, 1.14)	P = 0.44	
					HbA1c concentrations	3	−0.03 (−0.28, 0.23)	P = 0.84	
					HOMA-IR	3	0.59 (0.20, 0.97)	P < 0.01	

Note: IR, insulin resistance; HOMA-IR, homeostasis model assessment- insulin resistance; LDL-C, low density lipoprotein-cholesterol; CRP, C-reactive protein; HbA1c, hemoglobin A1C.

Most recent studies have concluded that 100% fruit juices, unlike SSBs, are not positively associated with weight gain. One meta-analysis showed no significant change in body weight after consumption of 100% fruit juice[7]. In another pooling of RCTs on 100% orange juice, there was no statistically significant change in body weight at 250–500 mL of orange juice per day (102–205 kcal energy) compared to those who did not consume orange juice[65].

The effect of fruit juice on body weight depends largely on the frequency and amount consumed. The main energy-providing substance in fruit juice is liquid sugar, which is the same as in SSBs. People generally consume much less fruit juice than SSBs. Additionally, fruit juice consumption generally does not affect the original daily diet, which is considered an additional food intake[66]. There are two reasons for not gaining weight after juice consumption. First, the juice intake is moderate and the total daily energy intake is not excessive. Because it is difficult for consumers to achieve the daily fruit intake recommended in the dietary guidelines, moderate consumption of 100% fruit juice does not lead to excessive energy intake, overweight, or obesity[67]. Second, the juice retains some of the biologically active substances that help slow down the absorption of energy.

4.1.2 CVDs

CVD has always been a major medical concern and a leading cause of death[68]. Fruits and vegetables are considered to be important dietary components for CVD prevention. All national dietary and disease guidelines recommend the consumption of fruits and vegetables to reduce the incidence of CVD[69].

The CVD risks of SSBs are clear. In a cross-sectional study of 8 492 nurses without diabetes and CVD, Yu et al.[70] examined the association between SSBs, fruit juices consumption and intermediate biomarkers of cardiometabolic risk. Results showed that high consumption of SSBs was associated with poor levels of cardiometabolic biomarkers such as fetuin-A, C-reactive protein (CRP), intracellular adhesion molecule 1 (ICAM-1), lipocalin, insulin concentrations, and total cholesterol. In contrast, increased hemoglobin A1C (HbA1c) concentrations and decreased adiponectin concentrations were observed with high fruit juice consumption. In conclusion, the metabolic risk of CVD was higher with habitual consumption of SSBs than with 100% fruit juice.

Whether fruit juice can replace fruit and play a role in CVD prevention is a matter of differing opinions. In a prospective study, Scheffers et al.[71] found that replacing SSBs with 100% fruit juice reduced cardiovascular risk, whereas replacing fruit with 100% fruit juice did not have the same effect.

Additionally, the consumption of free sugars has been questioned as a factor in increasing the risk of HTN. SSBs can cause HTN. Although 100% fruit juices and SSBs have comparable sugar content, the harmful association between sugary drinks and HTN has not been shown to extend to other foods with fructose sources[72]. Protection against HTN has been demonstrated for 100% fruit juice in moderate doses (100–250 mL)[72]. A meta-analysis of PC and RCT studies showed that consumption of 100% juice was not associated with increased cardiovascular risk. There was no evidence of heterogeneity between the studies, supporting the validity of this finding[7].

4.1.3 Diabetes

As one of the most challenging health problems in the world, diabetes, especially T2DM, has complications that can seriously affect the quality of life. Diabetes is caused by abnormal control of blood glucose levels in the body. Since it cannot be cured, it places a heavy burden on patients and society[73]. Therefore, it is essential to prevent and reduce the incidence of diabetes.

In a systematic analysis of cohort observational studies, SSBs consumption increased the incidence of T2DM independent of obesity. In contrast, although fruit juices were also positively associated with the incidence of T2DM, the quality of the evidence was limited by potential bias and heterogeneity, and the article did not specify whether sugar was added to the fruit juices[74]. In a meta-analysis comparing the association between sugary and 100% fruit juices and diabetes, high consumption of sugary fruit juices was found to be a significantly higher risk factor for T2DM (relative risk (RR) = 1.28 (95% confidence interval (CI) 1.04–1.59)), whereas the consumption of 100% fruit juices was not associated with T2DM (RR = 1.03 (95% CI 0.91–1.18))[8]. In a meta-analysis of 12 RCTs, diabetes risk was analyzed using 4 indicators: fasting glucose, fasting insulin, HbA1c, and homeostatic model assessment-insulin resistance (HOMA-IR). The study did not distinguish whether juice-only was consumed, and the conclusion was that juice consumption had no significant effect on fasting blood glucose and insulin concentrations[9]. Another meta-analysis with 18 RCTs reached similar conclusions[75]. In summary, there was no strong association between the consumption of 100% fruit juice and diabetes risk.

4.1.4 Gout and hyperuricemia

As an independent risk factor for metabolic syndrome and diabetes, hyperuricemia and gout are manifestations of elevated blood uric acid (UA) levels, which in severe cases can lead to gouty arthritis[76-77]. A consistent finding of studies is that consumption of SSBs is inevitably associated with gout, particularly in relation to fructose intake[11,78]. Fructose is a class of sweeteners commonly used in food processing and widely used in sweeteners such as sucrose (composed of fructose and glucose) and high fructose corn syrup (HFCS)[79]. FJBs contain large amounts of fructose. The metabolism of fructose leads to uncontrolled phosphorylation of adenosine triphosphate (ATP) to adenosine monophosphate (AMP), a precursor of UA. UA in serum is a determinant of metabolic syndrome, and accumulation of UA can lead to hyperuricemia and gout[10].

High fruit consumption is considered a protective factor against metabolic diseases, but the effect of fruit on gout is complex, as is the role of fruit juices[79]. A meta-analysis comparing the highest and lowest intakes of fruit juice showed a negative association between fruit juice consumption and gout attacks[80]. Interestingly, fruit juices derived from different varieties have inconsistent effects on the incidence of gout. In a study using nurses as subjects, it was found that orange juice was positively correlated with an increased incidence of gout, whereas apple juice, grapefruit juice, and tomato juice were not associated with the incidence of gout[81]. The different risk effects are mainly due to differences in fructose content and protective components for elevated UA (vitamin C, dietary fiber (DF), potassium, catechins, and flavonoids)[79]. Overall, fruit juice consumption was associated with mild gout events but not as severe as SSBs[11].

4.1.5 Mental health

Mental health is a popular health topic today, including depression, suicidal thoughts and behaviors, and other psychological stressors. However, the potential impact of FJBs on mental health remains largely unknown. A study published in 2021 found a 26% (95% CI 1.11–1.43) increase in the prevalence of poor mental health associated with higher daily consumption of SSBs compared with no consumption. No evidence of an association was found in the analysis of fruit juice[82]. In another study of the elderly, regular consumption of FJBs increased the risk of depression. Beverages with added low-energy synthetic sweeteners have a higher risk associated with the modulation of neurotransmitters in the brain, such as dopamine and serotonin[15]. However, the mechanism of this positive association is not entirely clear. Perhaps people suffering from depression or people with psychological problems have a craving for sweetened drinks.

4.1.6 Oral health

A strong synergistic relationship exists between food intake and oral health problems. Increased dietary intake of acids can lead to increased tooth wear and progressive loss of enamel and dentin[83]. Acidic foods can lower the pH of the oral environment, which can lead to more microorganisms attaching to the tooth surface. The pH of the fruit is usually acidic. The pH of fruit juice is similar to that of fruit juice, which leads to dental caries[84]. In a meta-analysis of children with dental caries, consumption of more than one serving of 100% fruit juice (240 mL) per day was associated with a 20% increased risk of tooth decay compared with the consumption of less than one serving per week (odds ratio (OR) = 1.20 (95% CI 1.02–1.42))[14]. In an RCT study comparing the effects of commercially processed and freshly squeezed juices on oral pH, it was found that more acidic saliva was produced after 15 min of consuming processed juices than fresh juices and fruits. The oral pH tended to be neutral 30 min after consuming the processed juices, while the oral pH returned to neutral 15 min after consuming freshly squeezed juices[85]. Processing is shown to affect the rate of oral pH recovery, and processed juices have a higher risk of causing tooth decay than freshly squeezed juices. In another study on the relationship between total beverage consumption and dental caries in childhood, it was found that higher juice consumption was associated with a low incidence of caries at age 17, whereas higher consumption of SSBs was associated with a high incidence of caries incidence[86].

In addition to pH, oral health risks for FJBs arise from free sugars. Children whose sugar consumption accounts for 2%−3% of their energy intake over a period of more than three years are more susceptible to dental caries, both in resistant and susceptible teeth. Because of the cumulative nature of dental caries throughout the life cycle, the incidence of caries is higher in adults than in children[87].

4.2 In vivo animal studies

In addition to the epidemiological surveys and RCTs described above, animal experiments are also a reliable source of experimental data. Animal experiments can exclude the interference of confounding factors and facilitate the elaboration of the underlying mechanism. As shown in Table 5, the animal experimental literature on FJBs in the last 5 years mainly had the following characteristics. First, there are two main directions in the selection of fruit species. One category includes species with little research data or infrequent consumption, such as red pitaya[88], *Passiflora edulis*[89], mandarin[90], and noni[91]. The other category, which is rich in specific bioactive substances, includes citrus[92], grape[93], and apple[94]. These varieties are often used in commercial juice. In a study of apple juice, the salient point was the comparison between different varieties[94]. In another study on blackberries, Fernandez et al.[95] formed high and low-dosage groups based on the content of polyphenols in the juice rather than the juice. Second, the selection of diseases studied was broad. The health effects of fruit juices or the interaction between juices and drugs/toxic substances have been studied by constructing animal models of specific diseases. The specific objective is to explore the mechanisms by which juice consumption promotes drug absorption and usage or inhibits toxic effects. Ruiz et al.[96] constructed a mouse model of cadmium poisoning and found that grape or apple juice can upregulate the expression of runt-related transcription factor 2 (RUNX2) and downregulates that of receptor activator of nuclear factor-κB ligand (RANK-L) in the immune system, thereby reducing irritation and protecting bone tissue. Third, a dose-dependent relationship between juice and beverage consumption and disease risk is evident. The benefits and harms of fruit juices tended to differ significantly in the high-dose group. The outcomes of animal research show that a modest diet of fruit juice helps to healthier outcomes by causing minor molecular modifications in the organism.

In conclusion, the results of animal experiments are scattered, extensive, and contradictory. However, the indicators examined in animal studies are more numerous and subtle, and the mechanisms studied are relatively more profound than those examined in epidemiological studies. For example, studies of pomegranate juice have found that the mechanism of its hypoglycemic effect is related to the inhibition of carbohydrate absorption mediated by enzymes in the intestine and interaction with glucose transporter proteins, which cannot be determined by correlation analysis based on surface area alone[97]. However, conclusions on dose ratios obtained from animal experiments cannot be extrapolated directly to the population. Different experimental conditions may affect the results. Overall, most experiments showed good results. They provide broader ideas for studying the effects of FJBs on human health and expand our understanding of diseases and their mechanisms.

5. Factors affecting the health outcomes of FJBs with different levels of processing

5.1 Total energy intake and dietary pattern

There is considerable controversy over the health effects and policy recommendations for FJBs intake. Compared to whole fresh fruit, 100% juice loses nutrients (less fiber, more free sugars, and higher risk of overconsumption) but retains most of the nutrient content of the fruit. Nutritionists were concerned about whether fruit juice would replace fruit consumption, affecting the quality of consumers' diets[98]. Few people consume the 5 servings of fruits and vegetables required using dietary guidelines every day[99-100]. Consuming juice as a beverage does not interfere with solid food intake but helps consumers reach their goal of 5 servings of fruit.

Fruit juice increases the total energy intake, with the same effect as other beverages such as cola or milk[101]. The effect is not all bad, however, because caloric beverages consumed before meals are associated with incomplete energy balance. Juice consumers tend to have a relatively low BMI. Additionally, a positive relationship has been demonstrated between the consumption of 100% juice and an increased intake of vitamin C, vitamin A, folic acid, magnesium, potassium, and fiber[66,102-104]. Consumers of 100% juice tend to have higher quality dietary patterns, as measured by overall dietary structure, rather than consumption of individual foods or nutrients[20]. In a study of the association of beverages and eating patterns, the consumption of juices was found to be strongly associated with prudent eating behaviors, while SSBs were strongly associated with relatively unhealthy Western eating behaviors.

Table 5
Characteristics of the *in vivo* animal studies and the effect of fruit juices.

Species	Total sample size	Number of groups	Fruit	Treatment	Duration	Results	Reference
Adult Wistar rats	20	4	Grape; apple	Cadmium chloride (1.2 mg/kg BW); 0.8 mL grape juice per day; 1.0 mL of apple juice per day	15 days	↑Runt-related transcription factor 2 (RUNX-2) ↓Receptor activator of nuclear factor-κB ligand (RANK-L) Increase bone formation	[96]
Adult Wistar rats	64	4	Grape (*Vitis labrusca*)	Organic and conventional grape juice with 5% lemon juice 7 μL/g BW	32 days	-Weight; -Biochemical parameters	[204]
Young (4 months) and old (24 months) male Wistar rats	24	4	Grape	10 μL/g of grape juice	28 days	↑Ferric ion reducing antioxidant power (FRAP) and glutathione (GSH); ↓Reactive oxygen species (ROS) and malondialdehyde (MDA)	[205]
Sprague-Dawley adult rats	24	4	Red pitaya (*Hylocereus polyrhizus*)	10 g/(kg·day)	8 weeks	↓Serum triglyceride, serum cholesterol and serum LDL; Improve anti-obesity	[88]
Female bilaterally ovariectomized Sprague-Dawley rats aged 4 months	24	4	Tomato (*Solanum lycopersicum*)	11, 15 g/(200 g·day)	28 days	↓Matrix metalloproteinase (MMP-2) on the vaginal wall; ↑Type-1 collagen on the vaginal wall	[206]
Male Wistar rats, 21 days old (fed with high-sucrose + cholesterol diet)	37	3	Blackberry (*Rubus americanus*)	4.2 mL/kg of juice	4 weeks	↓Glucose in the serum (17%); ↓Abdominal and pericardial adipose tissue; ↓Liver, heart and kidney weight	[207]
Male Wistar rats, weighing 200–250 g	45	5	Blackberry (*Rubus fruticosus* L.)	Low: 2.6 mg/kg anthocyanins, 14.57 mg/kg polyphenols Intermediate: 5.83 mg/kg anthocyanins, 27.10 mg/kg polyphenols High; 10.57 mg/kg anthocyanins, 38.40 mg/kg polyphenols	21 days	An anxiolytic-like effect: the intermediate dose of blackberry juice A protective effect of anti-acute stress: the high and intermediate doses of blackberry juice	[95]
Male Wistar rats (100–120 g)	20	4	*Saccharum officinarum*	1.0, 3.2 and 10.0 mL/kg of fresh *S. officinarum* juice once daily	8 weeks	↑Testosterone level and sperm count Impair the histological integrity of the testes and epididymis	[208]
Male Wistar rats (weight 200–250 g)	72	6	*Aronia melanocarpa*; *Rosa canina* (rosehip)	10 mL/(kg·day)	10 days	↓The severity of indomethacin-induced gastric lesions; Antagonize the effects of indomethacin on apoptosis and lipid peroxidation	[209]
Adult male Wistar rats (7 weeks old) (normal diet, high fat diet)	24	4	Pineapple (*Ananas comosus*)	Raw pineapple juice (15%, *V*/*V*); raw pineapple juice (100%, *V*/*V*)	8 weeks	↓The increment of *FAS* and *SERBP-1c* mRNA expression in liver ↑Hormone-sensitive lipase (HSL) and glucose transporter-2 (GLUT-2) expressions ↑The muscular lipolytic carnitine palmitoyltransferase-1 (CPT-1) expression	[210]
Matured female Wistar albino rats weighing between 120−130 g	40	5	Watermelon (*Citrullus lanatus*)	200, 500, 1 000 mg/kg	14 days	Anti-oxidant properties and inhibitory activities against *α*-glucosidase and *α*-amylase in a dose-dependent manner	[211]
Healthy, male, 4-month-old Wistar rats (weight approximately 200 g)	42	7	Moro orange (*Citrus sinensis* (L.) Osbeck)	200 mL of pure moro orange juice	70 days	Reverse most of the metabolic abnormalities exhibited by obese rats Unfeasible	[212]
Male Wistar rats (8-weeks old and weighing between 210–240 g)	6	-	Noni (*Morinda citrifolia*)	500 μL of noni juice	14 days	Enhance bioavailability of soy isoflavones and modify metabolism of oligosaccharides	[91]
Adult male Wistar rats with diabetes weighing about 110−130 g	21	3	*Citrus maxima*	300 and 600 mg/(kg·day) of *C. maxima* fruit juice	14 days	↓Blood glucose ↓Total cholesterol and triglyceride levels ↑Body weight	[92]
Male Sprague-Dawley rats, 8 weeks old	24	4	Tomato	NA (normal diet and water), NL (normal diet and tomato juice), HA (hypercholesterolemic diet and water) and HL (hypercholesterolemic diet and tomato juice)	5 weeks	Stimulate the biosynthesis of GSH and amino acids of the transulfurization pathway ↑The levels of metabolites related to the antioxidant response	[213]

Table 5 (*Continued*)

Species	Total sample size	Number of groups	Fruit	Treatment	Duration	Results	Reference
Male Wistar rats (weighing 200–250 g)	20	2	Pomegranate (*Punica granatum*)	Pomegranate juice 4 mL/(kg·day)	3 weeks	Strong protective effects against ischemia and reperfusion-induced arrhythmias in isolated rat hearts	[214]
Pregnant Wistar rats at 12 weeks of age	40	4	Purple grape	Control diet (CD), high-fat diet (HFD), grape juice and control diet (GJCD) and grape juice and high-fat diet (GJHFD)	42 days (21 days of gestation + 21 days of lactation)	Alter the acetylcholinesterase levels ↓Acetyl cholinesterase (AChE) activity in descendants ↓Protein oxidation in descendants	[93]
Albino Wistar rats (125–150 g) (isoprenaline induced cardiotoxicity)	36	6	Apple (Gala and Fuji)	3 mL/day p.o.	16 days	↑GSH, superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPx) level ↓Aspartate aminotransferase (AST), alanine transaminase (ALT), lactate dehydrogenase (LDH), creatine kinase (CK), Troponin-I level and MDA content ↓Cholesterol, triglyceride, phospholipids, LDL and very low-density lipoprotein (VLDL); Prophylactic and protective effects against isoprenaline-induced cardiotoxicity in rats Effective: Gala > Fuji	[94]
Male Wistar albino rats (weighing 150–180 g)	66	11	Lemon (*Citrus limon*); lime (*Citrus aurantifolia*)	0.5 and 1.0 mL/kg of lime and lemon juices	21 days	Improve nitric oxide (NO) production and inhibit the activities of phosphodiesterase (PDE-5), arginase, angiotensin converting enzyme (ACE), monoamine oxidase (MAO), ATP diphosphohydrolase (ATPDase), AMP diphosphohydrolase (AMPDase), and activated antioxidant enzymes ↑The therapeutic properties of sildenafil (lime) Improve erectile function	[215]
Albino male, Sprague-Dawley rats, strain weighing 170–200 g, with experimental isoproterenol (ISO) treated	36	6	*Passiflora edulis* (var. *Flavicarpa*)	0.5, 2 mL/kg BW	30 days	A protective effect on distorted biochemical and histopathologic parameters compared with reference drug metoprolol	[89]
Male Wistar rats with a body weight of (336 ± 8) g	18	3	Mandarin (*Citrus reticulata* Blanco)	24% (*V*/*V*) mandarin juice	21 days	Significantly change: percentage weight gain, reduced visceral adipose tissue and the inflammatory markers tumor necrosis factor (TNF) and interleukin-6 (IL-6) influence irisin pathway and increase its plasma levels Contribute to improve mitochondrial membrane potential	[90]

Note: −: No significant difference; ↓: Decrease; ↑: Increase.

5.2 Nutrients

Nutrition science is mainly concerned with the analysis of the nutrient content of foods. In the dietary guidelines of most countries, foods are classified according to their nutrient content. Fruits are rich in bioactive natural compounds that can be used as novel therapeutics and directly or indirectly affect human health[105]. Processing inevitably destroys the nutrients in the fruit. As shown in Table 6, the composition of fruit juice is similar to that of fresh fruit, while the nutritional value of the beverage is significantly different from that of fruit.

5.2.1 Sugar

Sugar is one of the three main nutrients and is central to providing energy to the body. However, excessive sugar consumption can lead to the development of NCDs. According to a US study, SSBs are an important source of added sugars, especially in young people[106]. Studies have shown that excessive consumption of added sugars is positively associated with a 10% increase in total energy intake. The discussion about sugar revolves around the concepts of free sugar and fructose.

5.2.1.1 Effect of processing

Compared with fruit, the production of fruit juice breaks cells and turns sugar from solid to liquid. Human body registers liquid and solid sugar calories differently, with liquid sugar calories leading to a higher energy intake than solid sugar calories[107-108]. Sugar in fruit juices and fruit beverages is both liquid sugar, which is no difference. Sugar is not easily destroyed during processing; therefore, the processing method has little effect on the free sugar content. In a French study, Chanson-Rolle et al.[109] found the same total sugar content in NFC and FC orange juices. However, the addition of sweeteners in the beverage will increase the total sugar content and the proportion of fructose. In addition, the intake of sugars is influenced by other nutrients, and the processing method may affect other nutrients' content.

5.2.1.2 Free sugar

Sugar is divided into endogenous sugar and free sugar. Endogenous sugar refers to the sugar in fruits and vegetables. By definition, free sugars in FJBs mainly include all added sugars in any form, all sugars naturally present in fruit and vegetable juices, purées, pastes, and similar products in which the structure has been broken down, and all sugars in beverages (except for dairy-based beverages)[110]. This means that there is no difference in the form of sugar in fruit juices and fruit beverages, both are free sugar. Unlike the slow release of endogenous sugar in cells, free sugar can be rapidly absorbed by the human body, causing large fluctuations in metabolism in the body, leading to many chronic diseases. The World Health Organization (WHO) limits free sugar intake and recommends reducing free sugar intake to less than 10% of the total energy intake for adults and children over a lifetime[111]. Public health and regulatory assessments on sugar increasingly focus on free sugars in food[112].

However, free sugar is a theoretical concept that cannot be applied in practice. Although free sugar can be estimated, it cannot be accurately calculated and analyzed separately from non-free sugar[113], and databases usually list only total sugars (all monosaccharides and disaccharides contained in foods)[98]. The concentration of free sugar in fruit juice is approximately 100–120 g/L, depending on the variety and quality of the fruit[111]. The release of free sugars depends on various factors, such as the shape of the fruit itself, the sugar content, and the processing method, which is a complex and dynamic process[112]. The sugar contents of the FJBs were almost identical. Since the main energy source of the beverages is sugar, fruit juices and fruit beverages have similar calories[114]. The main reason juices and beverages are not distinguished in some dietary guidelines is that both contain numerous free sugars. In Nutri-Score labeling, 100% of juices received worse scores than SSBs with protein added[103]. One study suggests that the biological response to free sugars, whether in beverage or juice, is essentially the same once metabolized[115]. But does the similarity in sugar content mean that they both lead to the same metabolic consequences? In fact, most consumers consume less juice than sugary drinks. A systematic survey shows that the average daily juice consumption of American adults over 20 years old is about

Table 6
Nutrient composition comparison of different kinds of fruits processed in different methods[216-219].

Parameters	Unit	Orange			Apple			Grape			Lemon			Pomegranate		
		Raw	100% juice	Beverage	Raw	100% juice	Beverage	Raw	100% juice	Beverage	Raw	100% juice	Beverage	Raw	100% juice	Beverage
Energy	kcal	47	45	21	52	46	22	69	60	21	29	22	46	83	–	–
Total protein	g/100 g	0.94	0.7	0.21	0.26	0.1	0	0.72	0.37	0.13	1.1	0.35	0	1.67	0.59	0.15
Carbohydrates	g/100 g	11.75	10.4	5.42	13.81	11.3	5.1	18.1	14.77	5.17	9.32	6.9	12.08	18.7	13.4	13.13
Total sugars	g/100 g	9.35	8.4	4.17	10.39	9.62	4.8	15.48	14.2	4.97	2.5	2.52	11.67	13.67	12.39	12.65
Fiber, total dietary	g/100 g	2.4	0.2	0	2.4	0.2	0	0.9	0.2	0.1	2.8	0.3	0	4	–	–
Sodium	mg/100 g	0	1	4	1	4	13	2	5	4	2	1	6	3	2.04	9
Magnesium	mg/100 g	10	11	10	5	5	5	7	10	4	8	6	2	12	9.31	7
Potassium	mg/100 g	181	200	188	107	101	51	191	104	36	138	103	10	236	229.9	214
Zinc	mg/100 g	0.07	0.05	0.02	0.04	0.02	0.04	0.07	0.07	0.03	0.06	0.05	0.01	0.35	–	0.09
Calcium	mg/100 g	40	11	0	6	8	3	10	11	6	26	6	2	10	2.04	11
Iron	mg/100 g	0.1	0.2	0	0.12	0.12	0.2	0.36	0.25	0.09	0.6	0.08	0	0.3	0.51	0.1
Phosphorous	mg/100 g	14	17	4	11	7	9	20	14	5	16	8	1	36	19.35	11
Vitamin C	mg/100 g	53.2	50	30	4.6	10.3	24	3.2	25	8.8	53	38.7	3.1	10.2	–	0.1

Note: Raw: fresh fruit; –: missing data.

80 mL, and the intake of sugary drinks is 237 mL[116]. Compared with fruit juice, the high intake of beverages increases the burden on the body.

5.2.1.3 Glycemic index (GI)

Sugar metabolism is a complex process that is determined not only by the free form and content of the sugar but also by the matrix in which it is found. The GI is a good indicator of the metabolic process of fructose in the human body. A low GI indicates that the blood sugar rises relatively slowly[117-118]. SSBs typically have a GI of approximately 68 (high GI), while 100% of fruit juices have a GI of ≤ 50 (low GI)[103]. It appears that potential factors influence the absorption of free sugars in fruit juice, which may be related to the abundance of polyphenols, vitamin C, and other bioactive compounds. In an experiment with orange juice, hesperidin was found to inhibit intestinal glucose transporter protein to delay the absorption of free sugars in 100% orange juice and regulate the postprandial glycemic response[119]. Additionally, the prebiotic effect of fruit juice on the intestinal flora could also be responsible for the delayed absorption of free sugars[120-122].

5.2.1.4 Metabolic processes

The natural sugar in fruit juice consists of fructose, glucose and sucrose. The ratio of fructose to glucose in most natural foods is 1:1. Unlike fruit juices, additional sweeteners are added to beverages, including corn syrup, sucrose and high-fructose corn syrup (HFCS), etc.[123]. Because fructose has a relatively low GI but is 2.3 and 1.7 times sweeter than glucose and sucrose, it is favoured by manufacturers and is now used in beverage processing. Sugars are eventually broken down in the body into dietary sugars (glucose and fructose), which are absorbed in the small intestine. Is there a clear link between sugar and health risks? Within the limits of rate-limiting enzymes, glucose provides the body with the appropriate amount of energy and tends to synthesise glycogen. However, unlike glucose, fructose cannot be used directly by cells to produce energy in organs[47]. Excessive amounts of fructose can spill over into the liver causing metabolic disorders.

Several hypotheses have been proposed to explain the mechanism underlying the association between fructose and NCDs (Fig. 2). Fructose is absorbed via the intestine and transported to the liver for metabolism, promoting hepatic gluconeogenesis (GNG) and *de novo* lipogenesis (DNL). This increases plasma glucose and triglyceride (TG) levels in the body, which increases the risk of insulin resistance and dyslipidemia[124-125]. Additionally, fructose consumes intracellular phosphate and ATP, converting it to AMP and generating the metabolite UA. The accumulation of UA can directly lead to hyperuricemia and gout. UA production decreases endothelial nitric oxide (NO), which can lead to endothelial dysfunction and vascular damage[126]. Malabsorption of fructose produces numerous advanced glycation end-products (AGEs) in situ in the intestine. AGEs can bind to the pro-inflammatory receptors for AGEs and dissociate with other tissues, causing inflammation such as atherosclerosis, CHD, pancreatitis, autoimmune arthritis, and asthma[127]. AGE is also a pathway that promotes impaired β-cell function. Mass fructose metabolism is significantly associated with elevated levels of CRP, interleukin-6 (IL-6), and tumor necrosis factor (TNF)[127]. Taylor et al.[128] found that dietary fructose increased intestinal cell survival and increased the length of intestinal villi. The increased length of the intestinal villi increases the intestinal surface area and thereby improves nutrient absorption, increasing the incidence of obesity and gastrointestinal cancer. Fructose can create a vicious cycle that further increases the delivery of lipids to the liver[129]. The most common visual indicator used to assess changes in adipose tissue is the changes in body weight.

5.2.2 DF

Daily consumption of DF is considered beneficial for health. DFs are polysaccharides that are difficult to digest, usually derived from plant-based foods[130]. The EU/UK Dietary Guidelines recommend a daily amount of 30 g DF.

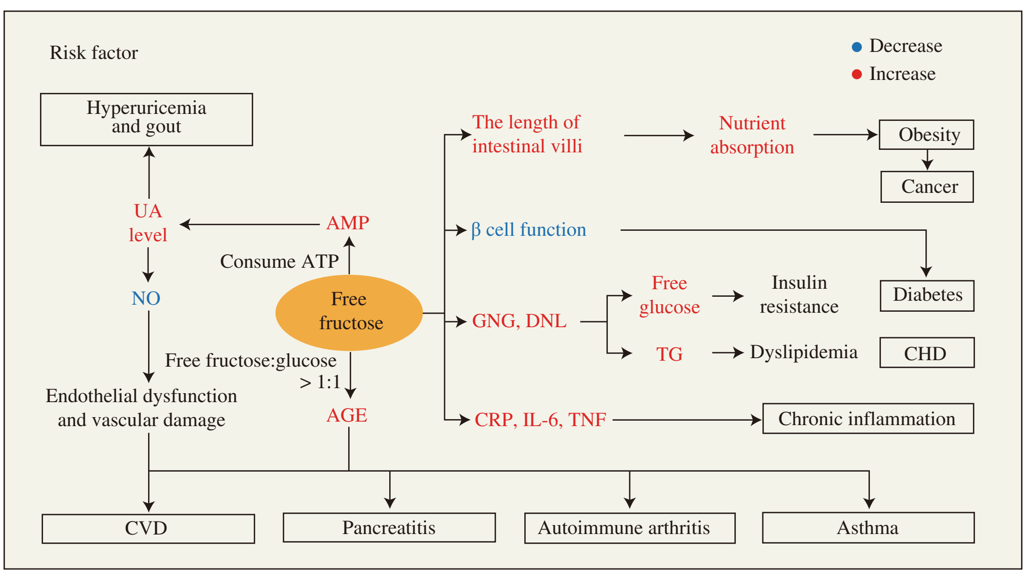

Fig. 2 Potential disease risk during free fructose metabolism. UA, uric acid; AGE, advanced glycation end-product; NO, nitric oxide; ATP, adenosine triphosphate; AMP, adenosine monophosphate; GNG, gluconeogenesis; DNL, *de novo* lipogenesis; CRP, C-reactive protein; IL-6, interleukin-6; TNF, tumor necrosis factor; TG, triglyceride; CHD, coronary heart disease; CVD, cardiovascular disease.

5.2.2.1 *Effect of processing*

The degree and method of processing greatly affect the content of DF in the product. In the beverages, the DF content was negligible, except for the additional additives. Processed juices contain less DF than whole fruit, due to the discarding of the pulp (mechanical separation). The difference between the DF in the whole orange (80 g) and the edible portion of 150 mL of orange juice is 2 g[131]. In addition, high temperature can degrade DF. Pectin is the most representative of soluble DF and is found in many fruits. During the processing of juices, most methods involve high temperature heating, and heating will affect the physicochemical and functional properties of pectin[21]. At high temperature, pectin mainly undergoes a depolymerization reaction, breaking down into some small molecules that are more easily absorbed by the stomach and intestines[132]. The pectin molecules in carrots have been demonstrated to be dissolved, depolymerized, and demethoxylated by heat treatment[133]. Therefore, non-thermally processed juices tend to contain more DF than thermally processed juices.

5.2.2.2 *Metabolic processes*

DF is closely associated with the feeling of satiety. Juices with a large proportion of retained pulp have a high DF content and are viscous. However, because of the liquid texture, even juice with a high percentage of pulp is not as satiating as the whole fruit[134]. In an RCT, it was confirmed that the consumption of 1.4 g/100 mL DF is significantly more satiating than regular orange juice[135]. The products associated with fruit are ranked in the order of satiety, from the strongest to weakest: Whole fruits, purées, 100% fruit juices, and beverages. As shown in Fig. 3, several pathways through which DF affects energy intake and chronic disease have been suggested, primarily by delaying the absorption of free sugars and free fatty acids[136], increasing satiety, and accelerating gastrointestinal motility[137]. The feeling of satiety has an influence on the total energy intake of humans. DF intake increases the feeling of satiety in 2 ways. Firstly, DF reduces the speed of transport in the intestine, slowing down the absorption of nutrients and prolonging the process of satiety[137]. However, DF is neither digested nor absorbed in the small intestine but is fermented in the large intestine to short-chain fatty acids (SCFAs). The increased concentration of SCFAs may also indirectly increase the body's feeling of satiety[138]. Additionally, the DF contained in fruit juice is mainly viscous fibers, which reduce subjective appetite more effectively than non-viscous fibers[139]. Viscous fibers fuse into a gel in the stomach, increasing gastric distension and thereby triggering satiety signals in the vagus nervous system[140].

5.2.3 *Polyphenols*

Polyphenols are a class of phytochemicals with diverse biological activities. Polyphenols regulate oxidative and inflammatory stress, alter the digestion of macronutrients and act as prebiotics for the gut microbiota[141]. There are many fruits rich in these micronutrients, such as oranges, cherries, pomegranates, apples, apricots, grapefruits, grapes, and strawberries[142]. 100% fruit juice is an excellent source of dietary polyphenols[143].

5.2.3.1 *Effect of processing*

Fruit beverages contain almost no polyphenols because of the extremely low fruit content. The polyphenol content of fruit juices is strongly influenced by the fruit variety and processing. Different processing methods affect the concentration and solubility of polyphenols, resulting in differences in their bioavailability and health benefits[144]. First, extrusion processes increase the bioavailability of phenols, possibly due to the release and depolymerization of free and bound phenolics[22]. However, the ultrafiltration (UF) process filters the pomace and reduces the content of antioxidant substances in the juice. The total phenol and vitamin C content of NFC apple juice treated with UF (0.05 μm) decreased by 33.50% and 26.52%, respectively[145]. Second, fermentation and enzyme treatment can enhance the antioxidant and anti-inflammatory effects of polyphenols[22]. HPP and high temperature short time (HTST)

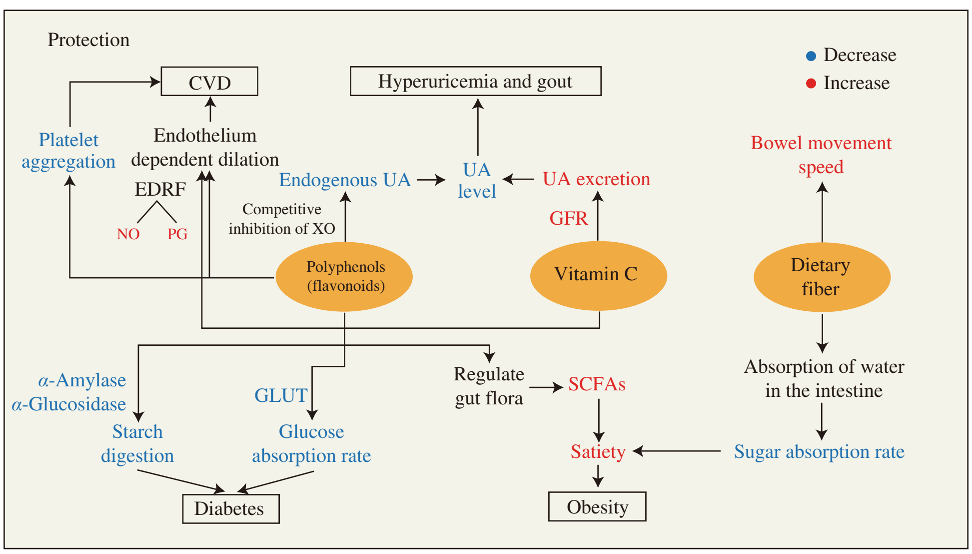

Fig. 3 Potential protective effects of nutrients in fruit juice on disease incidence. CVD, cardiovascular disease; UA, uric acid; EDRF, endothelium derived relaxing factor; NO, nitric oxide; PG, prostaglandin; XO, xanthine oxidase; GFR, glomerular filtration rate; GLUT, glucose transporters; SCFAs, short-chain fatty acids.

treatment can improve the activity of superoxide dismutase (SOD) in sea buckthorn juice, which could better exert the antioxidant effect of polyphenols[146]. In addition to the above processing steps, heat treatment also has an important impact[132]. The phenolic content may be affected by complicated physical and chemical processes brought on by heat treatment, including the release of phenolic compounds from their bound states as well as the decomposition and transformation of phenolic compound[147]. It has been reported that pasteurization significantly reduces the antioxidant and anti-inflammatory activity of blackberry, strawberry, and orange juice, resulting in a decrease in 2,2-diphenyl-1-picrylhydrazyl (DPPH) and NO-capture capacity[148-150]. Non-thermal NFC juices significantly improve the preservation of polyphenols and their biological activity compared to traditional heat treatment, as demonstrated in many studies[149-152]. For example, 240 mL serving of FC orange juice and pasteurized NFC orange juice contained approximately 43–132 mg hesperidin and 7–19 mg narirutin, and the content of didymin in NFC orange juice was higher than that in FC orange juice[153]. In addition, the residue of the peel can increase the polyphenol content of the juice. The peel, pulp and seeds of fruits are separated before juice extraction. However, due to the inaccuracy of the process, the peel and seeds are not completely removed[131]. Fruit juice contains more fruit components than the whole edible part of the fruit. For example, 77.3% of the phytonutrients in grapes are found in the seeds, 21.6% in the skin, and only 1.1% in the pulp[154]. Most of the phenolic and flavonoid compounds in oranges are stored in the peel. Apples have a higher polyphenol content in the peel than in the flesh[22]. This results in commercial juices retaining more antioxidants than hand-pressed juices. For example, commercial juicing extracts 22% more phenolics and 25% more vitamin C than hand-pressed juices. In addition, the pharmacokinetics of polyphenol metabolism in the body is key to its health benefits. Silveira et al.[144] found that there is no significant difference in the kinetics of polyphenols in flavonoids from fresh and processed commercial juices. But because there are so many kinds of polyphenols (more than 1 000), it's hard to generalize. The most well-absorbed polyphenols are isoflavones and gallic acid, followed by catechins, flavanones and quercetin glycosides[140]. Although the half-life varies from type to type, it is generally maintained at about 8 h in plasma. Maintaining a high level of polyphenols in the body requires regular consumption and supplementation.

5.2.3.2 Representative polyphenols

Two categories can be used to categorize the significant polyphenolic components of juices: flavonoids such anthocyanins (ACN), flavonols, flavan-3-ols, and flavanones, and phenolic acids like chlorogenic acid.

Hesperidin is the most abundant flavanone in citrus juices with high bioavailability[155]. In a 4-week study, it was found that postprandial acetylcholine-mediated dilation was improved after consumption of orange juice or pure hesperidin[156]. And orange juice was more effective than pure hesperidin, suggesting that there are other components of orange juice that produce similar effects[157]. Hesperidin may improve endothelial function by activating endothelial NO synthase and increasing the ability to produce prostacyclin[156,158-159].

ACN, a type of flavonoid, give bright colors to plants, especially those rich in dark fruits, such as blueberries, cherries, etc.[142,160]. Destruction of ACNs during processing may cause the color of the juice to differ from the true color of the fruit, affecting consumer choice. ACNs are unstable. The pigments can be degraded and discolored by a variety of processing factors such as pH, temperature and enzymes. Ensuring relevant enzyme activity is important in the design of the extraction procedure. Studies have shown that HHP can effectively protect the color of ACN-rich juice, mainly by inactivating enzymes such as polyphenol oxidase (PPO) and peroxidase (POD)[161].

5.2.3.3 Metabolic processes

Polyphenols play vital roles in human body as antioxidants and/or cellular messengers. The health effects of polyphenols are extensive (Fig. 3). Polyphenol polymorphs are digested and absorbed in the small intestine immediately after consumption, whereas individual polyphenols (e.g., flavonoid glycosides) must be deglycosylated before absorption[162]. Flavonoids are mostly absorbed in the colon, but some are also broken down in the distal part of the small intestine[163]. Polyphenols are closely associated with the intestinal flora[164]. This was a two-way process. Gut microbes can metabolize polyphenols. Polyphenols can exert a prebiotic effect by inducing the microbiota to change into a more health-friendly combination and promoting the production of SCFAs[165]. As fuel for intestinal cells, SCFAs have the function of improving the barrier function and inhibiting inflammation[166]. Duque et al.[67] studied the changes in the intestinal flora of subjects after treatment with fresh orange juice and PT orange juice. They found that the richness of the total bacterial population decreased, whereas the number of *Lactobacillus* and *Bifidobacterium* increased. Simultaneously, they observed an increase in SCFAs and antioxidant activity and a decrease in the ammonium level[67]. In another study, RCT also found that habitual orange juice consumption selectively modulated the gut microbiota. This change was negatively correlated with blood glucose, insulin, HOMA-IR, TG, total cholesterol, and low-density lipoprotein cholesterol (LDL-C), allowing positive regulation of blood glucose and lipids[121]. Additionally, flavonoids reduce platelet aggregation, which has a positive effect on the incidence of CVD[167]. At the cellular level, flavonoids can influence cellular functions by selectively inhibiting or stimulating intracellular signaling pathways such as phosphatidylinositol 3-kinase (PI 3-kinase), Akt/protein kinase B (PKB), tyrosine kinase, protein kinase C (PKC), and MAP kinase (MAPK)[168]. In addition，hesperidin may improve endothelial function by activating endothelial NO synthase and increasing the ability to produce prostacyclin[156,158-159].

Polyphenols are natural antioxidants with excellent biological activity. The antioxidant mechanisms of polyphenols are divided into 4 categories. 1) As hydrogen donors, they form intramolecular hydrogen bonds directly by reacting with free radicals. For example, proanthocyanidins release H, which binds competitively with free radicals to block free radical chain reactions[169]. 2) Polyphenols react with enzymes involved in free radicals. For example, the hydroxyl structure of ACN can increase SOD activity to inhibit oxidative stress[170]. 3) Polyphenolic compounds chelate metal ions, thus reducing the production of free radicals. Chlorogenic acid was found to prevent NH_2Cl-induced fragmentation of neutrophil plasmid

DNA, suggesting that it could inhibit DNA damage induced by redox reactions[171]. 4) Polyphenolic compounds produce synergistic antioxidant effects with other substances. A variety of natural extracts have been found to synergize with polyphenolic compounds, such as sweet potato extracts of polysaccharides, vitamin C, and carotenoids[172].

5.2.4 Vitamin C

Vitamin C is a micronutrient with antioxidant activity and is often found in fruit juices, especially orange juice[173]. Due to its natural antioxidant properties, it is used in the food industry for fruit and vegetable preservation and anti-browning. In addition, vitamin C has a sour taste and is used to adjust the flavor of the juice.

5.2.4.1 Effect of processing

The content of vitamin C in FJBs is highly uncertain. Vitamin C is often added to beverages for its flavor and antioxidant effects. Therefore, despite processing might destroy vitamin C, the extra addition makes the vitamin C content of juices and beverages unreliable. Additionally, the vitamin C content in fruit juice is generally lower than that in fresh fruit. But because vitamin C is a water-soluble vitamin, the substantial vitamin C content can be preserved in juice[109,174].

Vitamin C contained in fruit juice is easily degraded. Many processing steps of fruit juice, especially heating, can damage it. Even the mildest heating step, PT, can cause the vitamin C content in the pulp of orange juice to drop by about 60%, reducing the antioxidant capacity of orange juice by nearly half[175]. Compared to PT, the contents of total vitamin C and total ACN were significantly reduced in juices after a HTST[161]. In addition to heating, US can lead to the degradation of ascorbic acid due to oxidation reactions. However, the use of US technology can improve the preservation of ascorbic acid during storage[176]. In a study of blueberry-grape-pineapple-cantaloupe juice blends, the US-treated blend showed a 22.33% reduction in ascorbic acid compared to the US-untreated blend[177]. Other non-thermal processing was relatively better at preserving the vitamin C content of the juice. de Ancos et al.[178] treated orange juice under HPP conditions (200 MPa/(25 °C·min)) and found that compared to freshly squeezed orange juice, the flavonoid and vitamin C content was well preserved. Additionally, storage at room temperature may cause vitamin C depletion in commercial 100% juices compared to freshly squeezed juices, but they are within the expected range of acceptability[109].

5.2.4.2 Metabolic processes

The antioxidant and anti-inflammatory effects of vitamin C are similar to polyphenols, which can promote the increase of endothelial factor NO and prostaglandin (PG) (Fig. 3)[179]. In an RCT, ingestion of one serving of blood orange juice (300 mL, containing 150 mg of vitamin C) was found to provide early protection for mononuclear blood cells (MNBC) and prevent oxidative DNA damage[180].

5.2.5 Carotenoids

Carotenoids are lipophilic pigments that naturally exist in plants[181]. As secondary metabolites of plants and as precursors to vitamin A, they have the effects of antioxidation, immune regulation, anti-cancer and anti-aging. According to chemical composition, they can be divided into carotenes (α-carotene, β-carotene, lycopene) and xanthophylls (lutein, zeaxanthin). Carotenoids are often found in red and yellowish fruits[182]. Since the human body cannot synthesize such chemicals, diet, especially fruit, is an important source of carotenoids.

5.2.5.1 Effect of processing

There is little retention of carotenoids in the fruit beverages. While during juice processing, different processing methods can lead to different results. Most of the time, hot processing increases the amount of carotenoid content, but excessively high temperatures or prolonged heating may cause carotenoid content to drop[183]. The increase in carotenoid content is mainly due to the release of carotenoids from fruit matrix through proper processing. Carrot juice's content of β-carotene and lutein rise by 260.48% and 98.61%, respectively, after 90 °C, 1 min of pasteurization[184]. But Esteve et al.[185] found that the total carotenoid content in orange juice was significantly lower after treatment with PT compared with freshly squeezed juice. Non-thermal processing can retain or increase the content of carotenoids in most cases, showing an advantage over thermal processing. The total carotenoid content in carrot juice increased by 5%−7% at 300−600 MPa HPP for 5 min[186]. US (200−400 W, 25 kHz, 20 min) treatment of tomato juice increased the total lycopene content by 13.45%−35.09%[187]. The *in vitro* bioavailability of carotenoids after US treatment is significantly higher than that after heat treatment. But there are also special cases. Etzbach et al.[188] found no difference in the carotenoid content of orange juice after processing with conventional PT and new non-thermal methods such as PEF and HPP.

5.2.5.2 Metabolic processes

Carotenoids move through various dynamic processes in the body, including gastrointestinal digestion and absorption, lymphatic transport or hepatic biotransformation and circulation in blood and tissues[183]. About 60% of carotenoids are biotransformed in intestinal and hepatic cells[189]. The best-known carotenoids biotransformation process is conversion to vitamin A. The synthetic family of vitamin A can play a crucial role in human health in a variety of ways, including skin and eye health, reproduction, immune regulation and cancer prevention. Other carotenoids biotransformation mechanisms include breakage of polyene structures and oxidation of functional groups, which can occur alone or simultaneously[190]. The oxidation of carotenoids *in vivo* is complex and has not been fully elucidated. This high level of antioxidant activity is due to the ease of oxidation of carotenoids, including bursting of singlet oxygen and scavenging of reactive oxygen and nitrogen species[183]. These antioxidant pathways have been shown to be effective in the prevention and treatment of a variety of diseases.

In addition, similar to polyphenols, carotenoids must maintain a certain serum concentration to exert their antioxidant effects. Studies have shown that serum carotenoid concentrations in subjects increased by 10%−15% after 25 days of continuous orange juice consumption. However, serum concentrations returned to baseline levels after three days of discontinued consumption[191]. Additionally, the consumption of orange juice selectively increased serum carotenoid concentrations. In one experiment, 500 mL of orange juice per day over 2 weeks in healthy adults resulted in a significant increase in serum lutein concentrations and an increase in α- and β-cryptoxanthin concentration[192].

5.3 Addition agents

Ingredients added to FJBs fall broadly into three categories. One is added sugars, the same as the free sugars mentioned above. However, the form of the sugar is not uniform; it may be saccharin, sucrose, fructose, sweeteners, or honey. The final effect is to match the taste of the FJBs and increase their sweetness, enticing consumers, especially children, to consume them. When these sugars are added to juice, it inevitably leads to more juice processing. Sugar is often used in beverages as a primary flavoring agent and energy source. Because beverages contain little to no real fruit pulp, the digestion and absorption of sugar are not buffered, which can easily lead to obesity and other metabolic disorders. This is also the main reason why the consumption of SSBs is not recommended. Additionally, the recent popularity of artificial sweeteners has attracted much attention. Artificial sweeteners include aspartame, acesulfame potassium, and cyclamate. This category of sweeteners was chosen primarily because, unlike free sugars, they are hardly digested and absorbed by the human body and therefore are not converted into calories that cause consumers to gain weight. Artificial sweeteners are showing up in ASBs, one of the up-and-coming beverages considered healthy and theoretically help with weight loss. However, existing studies have consistently shown that artificial sweeteners can have harmful effects on the neurohormonal regulation of satiety, body weight, and energy regulation[193]. For example, aspartame can trigger systemic oxidative stress by generating excess free radicals and cortisol, and it can also alter gut microbial activity and affect *N*-methyl-*D*-aspartate receptors, leading to insulin deficiency or resistance[194]. Existing national dietary guidelines exclude references to the inclusion of ASBs[6].

Second, additives. Food additives are defined as substances added to foods to preserve their flavor or improve their taste, appearance, or other qualities[195]. The advent of additives is the key to the development of the food industry and brings convenience to consumers[196]. The use of additives requires strict compliance with food quality and safety standards, and the amount added should be well below the range that endangers health. Therefore, additives are often considered safe. However, safety and health are two different concepts, and it is still controversial whether the accumulation and combination of additives can cause harm to health. Additionally, it is difficult to assess the content of food additives. Beverage packaging only describes the type of additive and ranks them according to their content, but the exact amount added is unmarked[197]. Additives can be divided into two categories based on their origin: synthetic and natural. Many additives used in processing are naturally present in the daily diet. The amount of natural food was much greater than the added amount added[19]. The widely used antioxidant vitamin C is abundant in plants. Many common food colorants, such as carotene, caramel, beet, and chlorophyll, are also derived from natural foods. These compounds are useful bioactive components. However, the doses of these additives are far below what the body needs and do not provide significant health benefits. However, the addition of additives does not significantly affect the composition of the juice.

The third category includes fortified ingredients. In some fruit juices or SSBs, manufacturers intentionally add extra nutrients, such as vitamin C, fiber, and zinc, to increase their nutritional value. These nutrient-enriched ingredients can compensate for nutrient losses during food processing or enhance the effectiveness of certain nutrients, effectively preventing malnutrition and promoting a balanced diet.

5.4 Consumer preferences

Personal preferences have a great influence on the choice of beverages. Packaged beverages have a greater advantage than freshly squeezed juices. Packaged juices and beverages are more likely to get consumers "addicted" to highly processed SSBs. Evidence suggests that two systems in the body determine food choices[198]. One is an unconscious system that relies on metabolic neural afferent (MNA) metabolic signals. MNA signals reach the brain and directly reflect the nutritional value of the food. The nutritional content of PFs does not match that of natural foods, particularly when sweeteners are added. Non-nutritive artificial sweeteners (calorie-free) can disrupt the natural synergy between sweetness and energy, resulting in a controlled amplification of energy signals. This can increase the "addictive potential" of PFs[198]. The second system relies on self-conscious, subjective choices. Consumers assess the taste, calorie content, value for money, and health value of different foods, which influence consumption[198]. SSBs have a strong flavor and are a source of water[199]. Since their creation, they have become very popular due to their portability and low cost. However, with the call for healthy greens, SSBs consumption has declined recently.

Although 100% fruit juice is not a complete substitute for fruit, it is relatively healthy. For consumers with low fruit consumption, barriers to consumption include high price, inability to maintain freshness over a long period, the time required for preparation before consumption, and inability to satisfy appetite[99]. Juice offers solutions to these problems. Commercial 100% juice is convenient, inexpensive, and has a long shelf life. It takes about 15 oranges to make a liter of orange juice, but the juice costs only about a quarter of the price of the whole fruit[142].

Intrinsic motivations are more likely to have a positive impact on guiding the public's beverage choices than extrinsic interventions. Therefore it is important to guide the public to consciously identify with healthier beverages[142].

6. Does fruit juice produced by different processing methods result in different health benefits?

The influence of the processing method is clearly mentioned in the classification criteria for the degree of processing of FJBs. However, direct clinical studies and epidemiological evidence to support the health effects of the various fruit juices are lacking. Among the above mentioned influencing factors, the nutrient content and bioactivity of fruit juice are clearly influenced by the processing method. Overall, the processes that most damage nutritional quality of juices by reducing the nutritional density and attenuating the "matrix" impact are those that destroy the fruit's fibrous matrix through heat,

Table 7
Effects of thermal and non-thermal processing on polyphenols, vitamin C and carotenoids in fruit juices.

Juice	Non-thermal treatment	Thermal treatment	Index	Results			Reference
				Control	Non−thermal treatment	Thermal treatment	
Apple juice	HPP: 500 MPa, 6 min	HTST: 110 °C, 8.6 s	Total phenols	57.44 mg GAE/100 mL	57.56 mg GAE/100 mL	55.64 mg GAE/100 mL	[145]
			Vitamin C	138.07 mg/100 mL	110.45 mg/100 mL	107.65 mg/100 mL	
Carrot juices	HPP: 550 MPa, 6 min	HTST: 110 °C, 8.6 s	Lutein	0.039 mg/100 g	0.036 mg/100 g	0.037 mg/100 g	[220]
			α-Carotene	0.818 mg/100 g	0.618 mg/100 g	0.358 mg/100 g	
			β-Carotene	1.718 mg/100 g	1.386 mg/100 g	0.979 mg/100 g	
			Total phenols	47.82 mg/100 g	47.92 mg/100 g	42.32 mg/100 g	
Red grapefruit juice	HPP: 550 MPa, 10 min	HTST: 110 °C, 8.6 s	Total phenols	−	/	Decrease 7.7%	[221]
			Vitamin C	−	Decrease 8.82%	Decrease 27.9%	
Cape gooseberry juice (*Physalis peruviana* L.)	US: 42 kHz, 30 °C, 10 min	HP: 80 °C, 10 min	Total phenols	801.45 μg/g	835.62 μg/g	770.20 μg/g	[222]
			Vitamin C	17.17 mg/100 mL	12.80 mg/100 mL	12.98 mg/100 mL	
			α-Carotene	2.13 mg/L	2.98 mg/L	2.17 mg/L	
			β-Carotene	3.26 mg/L	4.07 mg/L	3.16 mg/L	
			Zeaxanthin	3.36 mg/L	4.20 mg/L	3.34 mg/L	
Sugarcane juice (*Saccharum officinarum*)	HPP: 523 MPa, 50 °C, 11 min	90 °C, 5 min	Total phenols	33.81 mg/100 mL	35.38 mg/100 mL	33.15 mg/100 mL	[223]
			Vitamin C	1.76 mg/100 mL	Decrease 11%	Decrease 25%	
Persimmon juice (*Diospyros kaki* L.)	Pre-HPP (300 MPa, 8 min) + HPP (550 MPa, 5 min)	Pre-HPP (300 MPa, 8 min) + HPP (95 °C, 5 min)	Total phenols	17.15 mg/100 g	16.07 mg/100 g	11.78 mg/100 g	[224]
			Vitamin C	37.83 mg/100 mL	37.92 mg/100 mL	27.83 mg/100 mL	
Korla pear juice (*Pyrus bretschneideri rehd*)	HPP: 500 MPa, 10 min	HTST: 110 °C, 8.6 s	Total phenols	26.89 mg/100 mL	26.05 mg/100 mL	24.76 mg/100 mL	[225]
			Vitamin C	318.33 μg/mL	299.20 μg/mL	263.57 μg/mL	
Asparagus juice (*Asparagus officinalis* L.)	HPP: 200 MPa, 10 min	HP: 121 °C, 3 min	Total phenols	301.25 mg/L	298.02 mg/L	271.64 mg/L	[226]
			Vitamin C	108.35 mg/L	106.21 mg/L	83.43 mg/L	
Lemonade juice: water, lemon and maple syrup	HPP: 600 MPa, 3 min; UV-C light: 125.7 mJ/cm^2	HTST: 75 °C, 90 s	Total phenols	33.16 mg/100 mL	HPP: 32.92 mg/100 mL UV−C: 30.26 mg/100 mL	31.97 mg/100 mL	[227]
			Vitamin C	1.28 mg/100 mL	HPP: 1.21 mg/100 mL UV−C: 0.10 mg/100 mL	0.11 mg/100 mL	
Citrus juice: grapefruit, orange and lemon	HPP: 600 MPa, 3 min; UV-C light: 186.5 mJ/cm^2	HTST: 75 °C, 90 s	Total phenols	537.93 mg/100 mL	HPP: 551.30 mg/100 mL UV−C: 481.11 mg/100 mL	497.27 mg/100 mL	
			Vitamin C	25.21 mg/100 mL	HPP: 24.66 mg/100 mL UV−C: 19.48 mg/100 mL	22.16 mg/100 mL	
Green juice: apple, cucumber, spinach, kale, ginger and lemon	HPP: 600 MPa, 3 min; UV-C light: 344.3 mJ/cm^2	HTST: 75 °C, 90 s	Total phenols	242.29 mg/100 mL	HPP: 243.06 mg/100 mL UV−C: 221.03 mg/100 mL	243.67 mg/100 mL	
Mandarin juice (*Citrus unshiu*)	HPP: 600 MPa, 1.5 min; US: 19 kHz, 36 min; MW: 800 W, 90 °C, 70 s	HP: 90 °C, 30 s	Total phenols	43.78 mg/100 mL	HPP: 31.21 mg/100 mL US: 32.07 mg/100 mL MW: 29.17 mg/100 mL	22.50 mg/100 mL	[200]
			Vitamin C	26.82 mg/100 mL	HPP: 25.16 mg/100 mL US: 24.49 mg/100 mL MW: 24.80 mg/100 mL	23.68 mg/100 mL	
			Total carotenoids	1.22 mg/100 mL	HPP: 0.98 mg/100 mL US: 1.25 mg/100 mL MW: 1.09 mg/100 mL	0.73 mg/100 mL	
Peach juice (Freestone peaches)	HPP: 8 000 psig, 3 min; US: 19 kHz, 5 min	HP: 72 °C, 15 s	Total phenols	876.03 μmol TE/L	HPP: 2 480.98 μmol TE/L US: 3 111.78 μmol TE/L	1 554.64 μmol TE/L	[228]
			Vitamin C	34.33 mg/100 mL	HPP: 30.03 mg/100 mL US: 31.26 mg/100 mL	26.78 mg/100 mL	
Strawberry-apple-lemon juice	HHP: 500 MPa, 15 min, 20 °C; US: 376 W, 10 min, 35 °C	HTST: 86 °C, 1 min	Total phenols	877.69 mg/L	HPP: increase 18% US: increase 7%	Slightly decreased ($P > 0.05$)	[229]
			Vitamin C	2.78 mg/100 mL	HPP: Decrease 9% US: Decrease 11%	Decrease 23%	
Cherry juice	HHP: 500 MPa, 2 min	HTST: 95 °C, 15 s	Total phenols	101.87 μg/mL	101.06 μg/mL	85.42 μg/mL	[230]
			Vitamin C	199.12 mg/100 mL	191.01 mg/100 mL	90.11 mg/100 mL	
Strawberry juice (*Fragaria* × *ananassa*)	HPP: 300 MPa, 1 min; US: 25 kHz, 55 °C, 3 min; PEF: 35 kV/cm, 27 μs, 155 Hz	HP: 72 °C, 15 s	Total phenols	137.81 mg/100 mL	HPP: 143.53 mg/100 mL US: 137.59 mg/100 mL PEF: 144.97 mg/100 mL	132.21 mg/100 mL	[231]
Korla pear juice (Pyrus bretschneideri rehd)	HPP: 500 MPa, 10 min	HTST: 110 °C, 8.6 s	Total phenols	25.99 mg GAE/100 mL	26.05 mg GAE/100 mL	24.76 mg GAE/100 mL	[232]
			Vitamin C	304.45 μg/g	299.20 μg/g	263.57 μg/g	

Note: −: missing data; /: no significant difference. Lutein, α-carotene, β-carotene, zeaxanthin and lycopene are carotenoids. HPP, high pressure processing; UV-C light, ultraviolet-C light; US, ultrasound; MW, microwave; PEF, pulsed electric fields; HTST, high temperature short time; HP, heat processing.

mechanical, and sugar addition processes. Firstly, mechanical damage is a necessary part of all juice production, and there is no difference between juices. Secondly, thermal treatment can degrade the nutrients and make them biologically inactive. As shown in Table 7, the effects of thermal and non-thermal processing methods on the content of vitamin C, polyphenols, and carotenoids in juices were compared. Non-thermal processing techniques have an advantage over thermal processing techniques in retaining the phytochemical composition. Citrus juice treated by HPP was taken as an example. The contents of total phenols, vitamin C and total carotenoids were 22.5, 23.68 and 0.73 mg/100 mL, respectively, when treated with 90 °C HP conditions for 30 s, while the contents of the three substances were 31.21, 251.6 and 0.98 mg/100 mL, respectively, when treated with 600 MPa HPP for 1.5 min[200]. The fruit components are less damaged by shorter, lower temperature processing conditions in thermally processed juices. Thirdly, the difference between NFC juice and FC juice is whether it has been concentrated and reduced. The concentration reduction step destroys the natural bioactive substances in the fruit. Although NFC juice and FC juice are both 100% fruit juice, the amount of bioactive substances contained varies greatly. Compared to NFC juice, FC juice is less similar to fruit and it is difficult to retard the absorption of sugar. Finally, fruit juices with added sugar are evaluated to be more processed than those without added sugar. This is consistent with the negative health effects of sugar. To summarize, we conclude that different levels of processing of 100% fruit juices (FC juices, thermally processed NFC juices and non-thermally processed NFC juices) lead to different health risks.

7. Prospect

Different health effects of FIBs with varying degrees of processing has been summaried in the Fig. 4. As can be seen from the 4 classifications, processing methods and sugars are important factors influencing the health benefits of FJBs. SSBs are reconstituted beverages that contain little or no fruit. Its juices are derived from fruit. By the level of processing, 100% of fruit juices fell into the "less processed" category. Of all juice types, non-thermally processed NFC juices are the closest to freshly squeezed juices as they contain the greatest number of nutrients. However, fruit juice has many disadvantages compared with fresh fruit. First, the digestion and absorption processes occur more rapidly in fruit juice than in fresh fruit. Second, during the decomposition of the cell walls, large amounts of sugar are released in liquid form. Free sugar is more harmful than solid sugar. Third, most commercial juices discard large amounts of pomace. Many bioactive compounds (antioxidants and fiber) are in the solids (pomace), so they do not pass into the finished juice, reducing its health benefits. Additionally, juices have many unique benefits. First, juice consumption does not interfere with daily fruit consumption and helps consumers achieve the recommended daily intake of 5 servings of fruits and vegetables. Although fruit juice is not a substitute for fruit, its moderate consumption helps improve diet quality. Second, with the improvements in juice processing technology, the nutrients in juices are less destroyed. This concentration process also increases the concentration of some nutrients. Third, the consumption of fruit juices reduces the intake of SSBs. Fourth, the advantages of 100% fruit juice over fruit are convenience, uniform product form, longer shelf life, and lower prices, which offer consumers a new way to consume fruit.

There have also been some biases in the perception of fruit juices. First, some scientists and clinicians indiscriminately claim that the consumption of beverages with natural or added sugars is harmful. Second, some consumers cannot distinguish between FJBs. In a study of pregnant women, 100% fruit juice was found to be the only relevant factor in beverage consumption, primarily because they thought the two were identical[201]. Therefore, it is important to make the public aware of the differences between beverages. Classification by the degree of processing can best address these issues and may be applied to human health practices in the future.

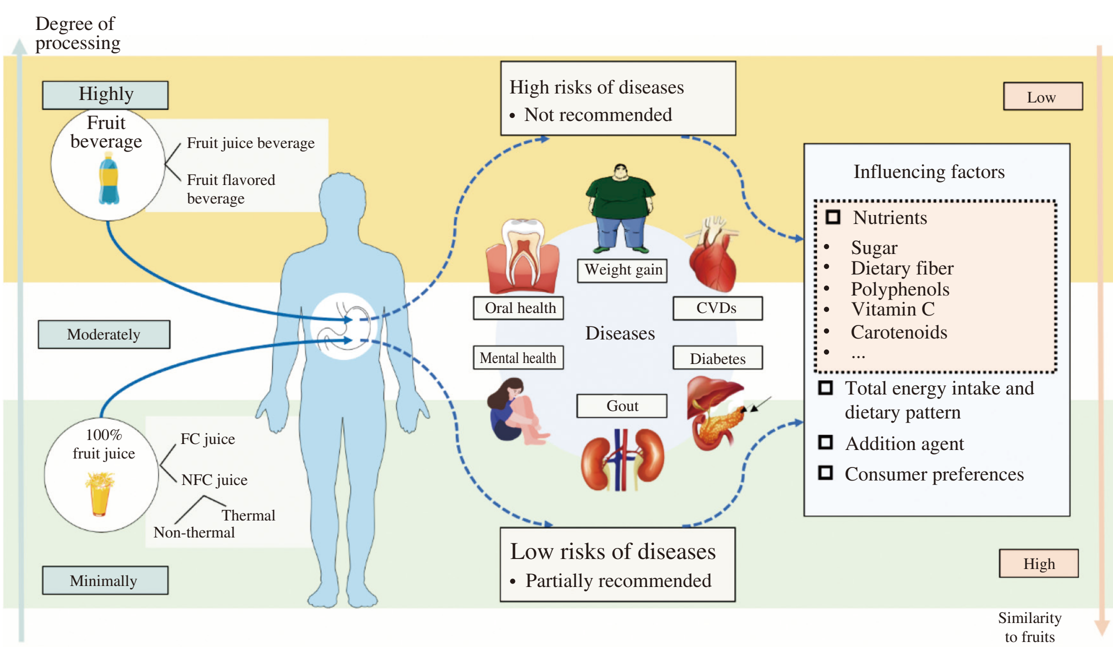

Fig. 4 Different pathogenic effects of FJBs and their influencing factors. CVDs, cardiovascular diseases; FC juice, concentrated juice; NFC juice, non-concentrated juice.

Although specific antioxidant bioactive compounds in fruits have long been identified as major contributors to chronic disease prevention, current knowledge does not make it particularly clear which single nutrient alone has a major effect[202]. When assessing the potential antioxidant activity of food, it is important to consider it as a whole, as antioxidants can act synergistically[46]. It becomes clear that it is necessary to analyze the food as a whole and not the individual nutrients.

If the degree of processing is considered an independent risk factor for food health risks, the classification criteria must be clear and consistent. The definitional differences among the 4 existing classifications hinder the analysis of the relationship between disease and beverages. Additionally, the classification criteria for the degree of processing should not focus on the number of steps. Since the purpose of the systems is to assess health risks, the key to classification should be based on the similarity of the original natural fruit.

Declaration of competing interest

The authors declare no competing financial interest.

Acknowledgment

This research was funded by the National Natural Science Foundation Program of China (31901707) and the 2115 Talent Development Program of China Agricultural University.

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