2 Carbohydrates for Energy

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Abstract

Carbohydrates are the most common source of energy for humans. Among this class of macronutrients, starch and sugar are the main representatives. Starches of different types can be obtained from tubers and grain-based foods such as cereals, legumes, pasta and noodles. Sugars can be extracted from plants or eaten as part of a wholesome food, typically fruits and milk. Nutritionally, low glycemic index offers the best long term health effects. That means choosing less refined food products (wholegrains vs refined; fruits vs. sugar). Processing can have a positive impact, as in the case of pasta vs. bread. Environmentally, grains require more resources than produce, while attracting consumers for their taste and competitive price. Innovations such as malt flour can provide an interesting alternative to other starches. Sugar wise, Stevia can be a sustainable sweetener, yet not providing energy. Upcycled sweeteners from spent grains are low in both glycemic index and carbon footprint, while fruits, sweet vegetables and fibre-rich syrups can be both energizing and environmentally friendly.

Keywords

Carbon footprint · Fruits · Glycemic index · Starch · Sugar · Wholegrains

2.1 Starch and Sugar as Source of Energy

Humans need energy to live. Food offers multiple sources of energy, in the form of lipids, protein and carbohydrates. While lipids deliver the highest caloric intake (9 kcal/g vs. 4 kcal/g of carbohydrates and protein), carbohydrates represent the most abundant source of energy in most diets (NIH, 2021; USDA, 2021). This is due to the higher carbohydrate content of most foods, particularly grains and starchy roots, followed by dairy. Dietary carbohydrates are a diverse group of nutrients, ranging from very simple structures (simple sugars like glucose and fructose), to disaccharides (sucrose, also known as table sugar), to starch. Starches have various degree of resistance to human digestion, resulting in different times of glucose release. It is important to observe that not only quantity and quality of carbohydrates affect how quickly they are digested, but also food composition. Factors like protein, lipid and fibre content, as well as physical

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Fig. 2.1 Representative sources of starch: traditional (rice) and innovative (potato starch)

structure, affect glucose release (Scazzina et al., 2016; Smith et al., 2017). A common way to analyse carbohydrate quality is by measuring the glycemic index: the speed at which glucose is release from a food product and it will be discussed as one of the key parameters. Multiple tests have been proposed to measure glucose release after a meal, with glycemic index considered as useful by numerous health agencies (Scazzina et al., 2016). The unit of measurement that is used to measure the quality of carbohydrate is Glycemic Index (GI). Glycemic Index refers to a scale that measures how quickly a food product causes a person's blood sugar to rise. Foods can be classified into three categories based on their GI values: high-GI foods (>70), intermediate-GI foods (>55−70), and low-GI foods (<55) (Eleazu, 2016). A high GI indicates that the carbohydrate in a food product is absorbed more quickly into the blood sugar. It's hard to measure the accurate GI of a food product as GI varies a lot depending on several factors such as the physical form of the food product (a mashed cube of potato can have 25% higher GI than an unmashed cube of potato), the type of the food product, the way the food product is processed and prepared, and the content of other macronutrients in the food product (protein, fat, fiber) (Pi-Sunyer, 2002). A slow glucose release is desirable since it provides satiety and prevents diabetes (Willett et al., 2002). An exception to this is represented by athletes who might look for fast release during their performance. Each food source has a different impact on the environment, requiring water and emitting carbon as a result of growing raw materials, processing into foods and distribution. Finally, nutrition and sustainability are not achieved without pleasant taste and affordable prices.

Therefore, this chapter will focus on starch and sugar as source of energy. Authors would like to emphasize that carbohydrates are not the only source of energy, but are presented separately in this chapter since it's the goal of this book to treat one nutrient at a time. Representative food sources of these nutrients will be presented for their nutritional value, environmental impact, and consumer acceptance. Traditional and innovative foods will be discussed, to offer the reader with a comprehensive toolset to make informed decisions when choosing a carbohydrate-based source of energy. An example of the modern trajectory of lipid-rich food products is depicted in Fig. 2.1.

Table 2.1 Representative food sources of starch: products, nutritional value (quantity, quality), sustainability (water and carbon footprint) and consumer acceptability (price, sensory)

	Nutrition		Sustainability		Acceptability	
Food products	Starch quantity (g/100 g)	Starch quality (GI)	Water footprint (L water/kg product)	Carbon footprint (kg CO_2/kg product)	Price (NZD/100 g)	Sensory profile
Corn Flakes	84	93	1,222 (corn)	1.26 (corn flour)	0.66	Crispy, sweet
	USDA (2020)	USDA (2020)	Mekonnen and Hoekstra (2012)	Xu et al. (2017)	Countdown (2021)	Chaunier et al. (2005)
Rice Noodles	80	53	2,500 (rice)	1.20 (rice)	0.84	White translucent colour, rice fragrance, sticky, chewy, delicate taste
	USDA (2013a, b)	Atkinson et al. (2008)	Mekonnen and Hoekstra (2012)	Xu et al. (2020)	Countdown (2021)	
Buckwheat Noodles (Soba)	75	56	3,463	1.91 (buckwheat flour)	1.18	Dark colour, hard, chewy, slightly bitter aftertaste
	USDA (1989)	Wee and Henry (2020)	Mekonnen and Hoekstra (2010)	Xu et al. (2017)	Countdown (2021)	
Pasta	72	48	1,336–2,847	0.18–0.49	0.50	Yellow, Slight nutty smell, firm
	Vernaza et al. (2012)	Atkinson et al. (2008)	Ruini et al. (2013)	Cimini et al. (2019)	Countdown (2021)	
Rolled Oats	68	55	2,416	0.55	0.28	Dry, soft, light taste
	USDA (2020)	Atkinson et al. (2008)	Mekonnen and Hoekstra (2010)	Heusala et al. (2020a, b)	Countdown (2021)	
Wholemeal Bread	38	74	1,300	1.18	0.28–0.49	Dark brown, wheat aroma, nutty flavour
		Food Composition Data (2019)	Mekonnen and Hoekstra (2010)	Chiriacò et al. (2017)	Countdown (2021),	

2.2 Traditional Food Sources of Carbohydrates

2.2.1 Starch

Six representative food products were chosen as sources of starch: breakfast items like corn flakes and rolled oats, as well as staple foods like rice noodles, buckwheat (Soba) noodles, pasta and wholemeal bread (Table 2.1).

The quantity of starch found in these products varied from 38 g/100 g of wholemeal bread to 84 g/100 g of corn flakes (USDA, 2020). However, after the noodle products are cooked, the carbohydrate content in each product is found to have decreased significantly with rice noodles having only 24 g/100 g, buckwheat noodle 27 g/100 g, and durum wheat pasta with the highest carbohydrate content among the three with 30 g/100 g (Sugiyama et al., 2003; USDA, 2013a, b, 2015). This is the case because when these food products are cooked (boiled in water) most of the starch in them leaches out into the water and especially for rice noodles the amount of starch that leaches out into the water is higher due to the small granule size of the carbohydrates in the noodle; the smaller the size of the molecule, the lower the weight of the molecule resulting in less intermolecular interaction of polysaccharide which will make it more soluble in water and this explains why so much starch is lost during the cooking of rice noodles (Guo et al., 2017; Low et al., 2020).

Pasta has the lowest GI among the three. There have been several studies aiming to determine the reason why pasta has a low GI despite being a starchy, carbohydrate packed food. One study said that pasta's low GI is due to its compact texture, the low degree of mastication before being swallowed and the large solid particles pasta becomes when it reaches the stomach (Kim et al., 2008). Its compact texture and large particle size limit the surface area of available starch that digestive enzymes are able to absorb hence limiting digestion rates. The large particle size also lowers the rate of gastric emptying. Another hypothesis is the presence of a continuous protein matrix that limit the accessibility of starch to α-amylase by trapping the starch granules. This result was in agreement with high GI for bread. Despite a fibre-rich recipe, wholemeal bread still presented a GI of 74 due to its light structure, result of yeast fermentation and baking. Overall, corn flakes represented the richest source of easily digestible starch (GI 93 vs. 48–74 of others), while noodles, pasta and rolled oats delivered similar quantity of starch at a lower speed.

As shown in the table above, the amount of water needed to make 1 kg of durum wheat pasta ranges from 1,336 to 2,847 L of water which is dependent on several factors such as the production site, conditions of the local environment, and the adoption of agricultural techniques used during the cultivation of the durum wheat (Ruini et al., 2013). Although this may seem like a high amount of water consumption, the durum wheat pasta is actually the most sustainable in terms of water consumption compared to the buckwheat noodle which requires 3,463 L of water just to produce 1 kg of buckwheat which means it will use up even more water to make 1 kg of the buckwheat noodle (Mekonnen & Hoekstra, 2010). Rice noodle is in between the durum wheat pasta and the buckwheat noodle in terms of water consumption with 2,500 L of water needed to grow 1 kg of rice but this also means more water will be needed to use the rice and turn them into rice noodle. The lowest water footprint was recorded for bread, although this might be due to its lower solid content.

In order to obtain a big picture, carbon footprint was examined, as an indicator of polluting emissions derived from food manufacturing. Interestingly, pasta production resulted in significantly lower carbon emissions than the other food examine: 0.18–0.49 kg CO_2/kg product vs. 0.55–1.91 kg CO_2/kg product (Table 2.1). Carbon emissions are the result of processing, distribution and transportation. From an environmental standpoint, pasta seems a more sustainable source of carbohydrates when compared to rice, corn and oat products. Results vary based on location and supply chain. High carbon footprint can be the result of low yield of raw material and/or more intensive processing needed to achieve the desired sensory quality.

Speaking of consumer acceptability, price and sensory were investigated. The cheapest product (according to New Zealand stores) is rolled oats, while the most expensive is rice noodles, at about three times the price (Table 2.1). The sensory profile of each food product is quite different from each other. Corn flakes are well known as crunchy and sweet. Noodles, on the other hand, are not crunchy. Buckwheat noodles have dark, brownish/greyish colour due to the presence of hull fragments found in the buckwheat flour used to make the buckwheat noodle (Wronkowska & Haros, 2014). Aside from its hard and chewy texture, buckwheat noodle is also known to possess a relatively high tensile strength and low extensibility which means it is stretchy (Ikeda et al., 2001). A research comparing buckwheat noodles made from common buckwheat and Tartary buckwheat found that buckwheat noodles made from Tartary buckwheat tasted more bitter than the ones made from common buckwheat; the noodles made from Tartary buckwheat also have a slightly bitter aftertaste (Starowicz et al., 2018). Rice noodles have a white, translucent colour and a clear fragrance of rice due to the rice flour used to make them. The cooking process and time affect the final texture of rice noodles; surface moisture gives the rice noodle its sticky texture (Li et al., 2021). To the best of my knowledge, rice noodle does not have a prominent taste nor aftertaste that can be uniquely identified and described. The durum wheat pasta has a yellowish colour which is caused by the natural carotenoid pigment content of the durum wheat and the oxidation of the durum wheat by a group of enzymes called Lipoxygenase (LOX) (Sissons, 2008). The durum wheat also has a nutty taste which gives the pasta a very slight nutty taste but to the best of my knowledge, it does not have any prominent taste nor aftertaste. The texture of durum wheat pasta is also harder and firmer than buckwheat noodle and rice noodle because of the slightly higher protein content in the durum wheat used to make the pasta but this firmness and hardness will vary according to the protein content in the durum wheat used to make the pasta (Sissons, 2008). Rolled oats are quite neutral in taste, while wholemeal bread is dark brown in colour, soft, with wheat aroma and nutty flavour.

2.2.2 Sugar

Sugar can be consumed either as is (extracted from beet or cane) or obtained from foods such as milk and produce. A representative selection includes refined cane sugar, raw cane sugar, milk powder, milk, apple juice and apples (Table 2.2). As expected, the GI of cane sugar is very high, but it is interesting to observe how this value increases when the raw sugar is refined, rising from 69 to 91 (Scazzina et al., 2016). Refined sugar is mostly sucrose, whereas raw sugar contains a mixture of about 95% sucrose and 5% molasses, thus being absorbed more slowly. Dairy is a popular food category, known for protein and lipids, among other nutrients. Some consumer may not realise that the most abundant nutrient in milk is sugar, specifically lactose, representing 40% of the solid fraction and at least 5% of fresh milk (USDA, 2019). The glycemic index is moderate (45 and 41 for powder and fresh, respectively) (Atkinson et al., 2008; Foster-Powell et al. 2002). These values were attributed to the presence of protein and fat, while the slightly higher GI for milk powder can be attributed to the spray-drying process, which reduces particle size, thus enhancing digestibility (Elversson & Millqvist-Fureby, 2005). A good source of sugar is fruit. Taking the example of apples, they contain about 12–13 g/100 g of sugars (USDA, 2019; USDA, 2020), whether it is in the raw form or processed into a juice. What is noteworthy, is the fact that the juice has a significantly higher GI: 41 vs. 36 (Atkinson et al., 2008). This is due to the fact that the juicing process eliminates fibre and other nutrients that allow slow sugar release from the fruit, in addition to represent a nutritional loss. Therefore, despite equal quantity of sugar, raw apples are a better choice than apple juice.

The water footprint of most sugar sources is limited, at around 1,000 L/kg product (Table 2.2). It is interesting to notice that, often, the more processing is required, the more water is consumed, such as in the case of sugar refinement (1,782 vs. 1,666 L water/kg product) and apple juicing (1,141 vs. 822 L water/kg product) (Mekonnen and Hoekstra 2010). The effect of processing becomes more relevant when looking at carbon emissions, with increases in the order of ten-fold. Juicing apples increased the carbon footprint from 0.1 to 1.0 kg CO_2/kg product (Cambridge Carbon Footprint, 2013; Figueiredo et al., 2014) while drying milk lifted this value from 1.0 to 9.0 CO_2/kg product (Flysjö et al., 2014). Juicing and spray-drying both have major environmental impacts, greater than sugar refining (Fig. 2.2).

When looking at consumer acceptability, it is well known how addicting sugar can be, and its low price lures consumers in. Less addicting sources of sugar are milk and produce like apples, other fruits and sweet vegetables. Key sensory differences are represented by dark colour and lower sweetness (raw vs. refined sugar) (Orlandi et al., 2017; Pinto et al., 2021). Milk is well known for its creamy texture and

Table 2.2 Representative food sources of sugar: products, nutritional value (quantity, quality), sustainability (water and carbon footprint) and consumer acceptability (price, sensory)

	Nutrition		Sustainability		Acceptability	
FOOD products	Sugar quantity (g/100 g)	Sugar quality (GI)	Water footprint (L water/kg product)	Carbon footprint (kg CO_2/kg product)	Price (NZD/100 g)	Sensory profile
Sugar, refined (100% sucrose)	100	91	1,782	0.2–0.5	0.19	Light color, sweet aroma and flavour
	USDA (2019)	Scazzina et al. (2016)	Mekonnen and Hoekstra (2010)	Rein (2011)	Countdown (2021)	Pinto et al. (2021)
Sugar, cane (95suc 5mol)	100	69	1,666	0.4	0.25	Dark, small granules, less sweet than refined sugar
	USDA (2019)	Scazzina et al. (2016)	Mekonnen and Hoekstra (2010)	Rein (2011)	Countdown (2021)	Orlandi et al. (2017)
Milk Powder	40	45	1,000	9.0	0.95	Sweet, granular
	USDA (2019)	Foster-Powell et al. (2002)	Ridoutt et al. (2010)	Flysjö et al. (2014)	Countdown (2021)	Cooper (1981)
Milk, whole fat	4.8	39	1,000	1.0–1.2 energy corrected)	0.18	Creamy, sweet
	USDA (2019)	Atkinson et al. (2008)	Ridoutt et al. (2010)	Flysjö et al. (2014)	Countdown (2021)	Chojnicka-Paszun et al. (2012)
Apple Juice	13	41	1,141	1.0	0.19	Sour, sweet, clear
	USDA (2019)	Atkinson et al. (2008)	Mekonnen and Hoekstra (2010)	Cambridge Carbon Footprint (2013)	New World (2021)	Okayasuand and Naito (2001)
Apples, Gala	12	36	822	0.1	0.50	Yellow flesh, crispy and juicy texture, sweet
	USDA (2020)	Atkinson et al. (2008)	Mekonnen and Hoekstra (2010)	Figueiredo et al. (2014)	New World (2021)	Corollaro et al. (2013)

sweet taste (Chojnicka-Paszun et al., 2012; Cooper, 1981). Apples vary in flavour based on the cultivar. For example, Gala apples have a yellow flesh, crispy and juicy texture and sweet flavour (Corollaro et al., 2013) while their juice is sour, sweet and clear in appearance (Okayasuand and Naito, 2001). Unfortunately, fresh fruit is expensive. In fact, it is more expensive than juice: 0.50 vs. 0.19 NZD/100 g) (Countdown, 2021). The reason is that short shelf-life costs more money than processing. Therefore, innovative processing that extends shelf-life without nutritional loss is needed. In this sense, fermentation of fruit puree by probiotic bacteria can be a solution, as demonstrated for pear kefir (Hampton et al., 2021).

2.3 Innovative Food Sources of Carbohydrates

2.3.1 Starch

Innovative sources of starch promise to deliver high amounts of carbohydrates with moderate GI and low footprint. Starting from cereals (corn, rice, wheat) and starchy tubers and roots (potatoes, tapioca, yam) novel products are rising (Table 2.3). Rice, tapioca, and yams have been around and consumed for centuries in their original forms or processed into traditional food products such as rice noodles, tapioca flour in baking, and purple yam (ube) flavoured desserts.

Fig. 2.2 Representative sources of sugar: traditional (sucrose) and innovative (date syrup, Stevia)

Table 2.3 Innovative food sources of starch: raw materials, bioavailability (glycemic index) and sustainability (water and carbon footprint)

Products	Raw materials	Bioavailability	Sustainability	
		Glycemic index	Water footprint (L water/kg product)	Carbon footprint (kg CO_2/kg product)
Functional chips	Corn	55	1,222	0.48
		Yang et al. (2006)	Mekonnen and Hoekstra (2010)	Zhang et al. (2017)
Malt Flour	Wheat	66	1,827	0.75
		Chaturvedi et al (1997)	Mekonnen and Hoekstra (2010)	Zhang et al. (2017)
Resistant starch	Potatoes	78	287	0.25
		Atkinson et al. (2008)	Mekonnen and Hoekstra (2010)	Svubure et al. (2018)
Rice bran in a tube	Rice	73	2,500	1.3-2.3
		Atkinson et al. (2008)	Mekonnen and Hoekstra (2010)	Xu et al. (2013)
Boba/Tapioca balls	Tapioca	70	3,106	0.56-0.64
		Foster-Powell et al. (2002)	Mekonnen and Hoekstra (2010)	Usubharatana and Phungrassami (2015)
Edible packaging film	Yam	44	343	0.88
		Ampofo et al. (2021)	Mekonnen and Hoekstra (2010)	Go (2009)

However, the world is constantly evolving and developing hence these traditional raw materials are also used in more new and innovative food products.

The Daily Crave chips are made of corn flour that claims clean label and high nutrition. High-quality starch is delivered as well as protein and some micronutrient. Some varieties are glutenfree. By adding up extra vegetable flour and natural condiments that people are familiar with, their taste is also naturally flavoured (Food Navigator USA, 2019). BriesSpecialty malt flour is made of whole wheat flours milled from natural malt. It has non-GMO and clean-labelled ingredients that are from natural materials and used to offer natural colour and flavour adjustment. It only adds malt to increase the whole grain content and lower the GI value. Light colour flour indicates mild to intense flavour and dark flour has a deeper flavour (Food Navigator USA, 2019). The resistant starch derived from potatoes is classified as RS2. It is non-digestible in the small intestine but fermented in the large intestine. It promotes digestive health and insulin and glycaemic response due to the low GI value. Also, it performs well in boosting butyrate, which helps to promote satiety, protect against endothelial dysfunction, and control blood sugar (Food Navigator USA, 2020a, b).

An innovative food product made from rice is the “Nuka” rice bran in a tube packaging made by Kohsei Foods Co., Ltd. This food innovation is targeting the upcycling market trend with more focus on providing more convenience for consumers. It is one form of upcycling because it uses the bran of rice, a part of the rice kernel, which is the by-product of rice milling (Friedman, 2013). Rice bran has been used in food products for some time but this “Nuka” rice bran in a tube can be considered an innovative food product because the packaging it comes in is new and the company only started selling them in January 2021, so it is very recent. The product has been manufactured in a compact and easy-to-use packaging that enables its users to add flavour to their fish or meat in a hygienic way by squeezing the tube packaging. Rice bran is rich in micronutrients like oryzanols, tocopherols, tocotrienols, and phytosterols as well as 15% protein content and 50% carbohydrate dietary fibres like beta-glucan, pectin, and gum (Nagendra et al., 2011). This fermented “Nuka” rice bran improves the health of the intestine which makes it very good for gut health and boosting the immune system (PR Distribution, 2021).

Boba is a pearl-shaped food product made from tapioca that has recently seen an upsurge in demand. Boba’s dark colour comes from the brown sugar used to make the balls and is known for its very chewy texture (Min et al., 2017). The global boba drinks market was valued at 5.3 billion USD in 2018 and is estimated to reach 11 billion USD by the end of 2025, implying a CAGR of 9.3% from 2019 to 2025 (Market Watch, 2021a). In April 2021, there have been news saying that there is currently a boba shortage in the United States due to supply chain and logistics disruptions; e-commerce sales of boba have surged due to rising demand but lack of dockworkers and drivers are holding up these boba from getting into the boba drink retailers (Janse, 2021). Boba is entirely plant-based making it vegan-friendly. Boba itself does not have any nutritious value besides being loaded with carbohydrate and sugar, if it was made with sugar, however consumption of boba with tea may contain other nutrients and antioxidant benefits depending on the type of tea used (Min et al., 2017).

An innovative product made from yams is edible film packaging and food coating. In 2020, the global edible films and coating market was valued at 2.6 billion USD and is predicted to grow at a CAGR of 7.64% from 2021 to 2026 (Globe News Wire, 2021). This innovative product is targeting the sustainability market trend because there is an increasing demand to move away from plastics to more sustainable packaging and biodegradable coatings from renewable resources. One experiment done on this yam edible film packaging for food coatings blends purple yam starch, chitosan, and glycerol to create films with homogenous surface and greater thermal stability (da Costa et al., 2020). This edible yam packaging increases the shelf-life of fresh fruits, reducing weight loss and oxidation upon storage (da Costa et al., 2020). However, as this product is still at the early stages of innovation, there is very little information regarding price, sensory, nutritional values, etc. Further research and development on this is definitely something to be looked into as this innovation does have great potential and environmental as well as socioeconomic benefits.

The GI of cooked corn is around 55 (Yang et al., 2006), so it is medium-low GI food. The GI of wheat is 66 (Chaturvedi et al., 1997), which is slightly higher than corn, but still the medium. Boiled potato has a relatively high GI, which counts for 78 (Atkinson et al., 2008). There are few reasons why GI varies. Firstly, potatoes have high starch content in the dry matter, of which 60–80% is starch. Its starch is made of numerous glucose and mainly in the form of amylopectin (Robertson et al., 2018). Also, its fibre content is low, which is about 1.4 g/100 g (Food Composition Data, 2019). Fibre is the component of food that is non-digestible by the human body, thus the low content of fibre increases the GI value. On the contrary, corn and wheat have a much lower GI. Conventionally cultivated wheat contains 60–75% starch (Shevkani et al., 2017), which is slightly lower than that in potato. The composition of the starch is amylose to amylopectin is 0.25:0.75 (Zi et al., 2018). Carbohydrate in cooked corn only counts for 16.7 g/100 g, and its starch is composed of about 25−30% amylose (Amin, 2017), which is even higher than wheat grains. The highest 5 g/100 g fibre among three materials also contributes to the low GI (Food Composition Data, 2019). All the reasons make the potato the highest GI, wheat the medium GI and corn the medium-low GI.

White rice has a high glycaemic index due to its high amylopectin to amylose ratio, post-harvest whitening-polishing, and shorter required cooking time (Boers et al., 2015). Amylopectin is a branched and long polymer of glucose units whereas amylose is a linear and shorter polymer of glucose units. Starches with higher amylose content have a higher gelatinisation temperature which forms complexes with lipids thus reducing the gut enzymes' access to starch (Boers et al., 2015). This means starches with higher amylose content tend to have lower GI values. Tapioca also has a high GI and the reasons for this are similar to the reasons white rice has a high GI. Tapioca has a very low amylose content but a high amylopectin content, similar to white rice, which leads to lower gelatinization temperature making the starch more easily digested and absorbed by the gut into the blood (Charles et al., 2005). Cassava root only has a GI value of 46 when cooked but because tapioca is made by grinding the cassava root into a powder, this increases the surface area to starch ratio which leads to increased rate of digestion thus increasing the GI (Boers et al., 2015; Charles et al., 2005; Nnadi & Keshinro, 2016). Yam has an amylose content of 30%, which is higher than that of rice or tapioca, making it a lower GI food compared to rice and tapioca (Freitas et al., 2004). The cooking method of the yam also plays an important role in determining its GI value. Table 2.1 shows the GI value of yam that is boiled; boiling, followed by cooling, prompts the formation of resistant starches which slows down the digestion rate thus lowering the GI of the yam (Ampofo et al., 2021).

In general, low-GI foods are healthier and recommended for everyone especially those with diabetes so yam would be a good option as a source of carbohydrate. However, in certain cases, high-GI foods are needed; rice and tapioca are good sources of carbohydrates for athletes, especially those doing lots of endurance sports, who need high GI foods to promote rapid glycogen metabolism and to quickly replace the carbohydrates lost during the physical activity (Murray & Rosenbloom, 2018).

The GI, when used in conjunction with in vitro measures of carbohydrate bioavailability, can provide a more comprehensive picture of the real carbohydrate bioavailability of a food ingredient or product (Englyst & Englyst, 2005).

Like a two-sided coin, high GI food have both advantages and disadvantages. Since the high GI food increases the blood sugar content and provides energy immediately, some athletes could have it around strenuous training to replenish the glycogen and provide enough ATP for consumption. Meanwhile, high sugar level could improve cognitive performance and brain activity, as a result, if some people are doing mental work, when they need novel ideas, the supplement of high GI food would be beneficial. However, without the glycogen being consumed, the blood sugar spike it causes might lead to more synthesis of fat, and thus the potential risks of obesity, cardiovascular diseases, and type II diabetes. Instead, the low GI food releases the sugar and increases the blood sugar level at a controllable speed. For people who have more sedentary work or no need for immediate energy, low GI food is preferred. Whether high GI food is beneficial or harmful depends on individual needs.

In terms of sustainability, the total water footprint of corn is 1,222 L/kg, with 947, 81 and 194 litres of green, blue and grey water respectively. The green, blue and grey water for wheat are 1,277, 342 and 207 L/kg, respectively, with the total water consumption is 1,827 L/kg of wheat. Potato has the lowest water footprint among the three products, which is only 287 L/kg. The three contributors are quite low as well: 191, 33 and 63 L/kg (Mekonnen & Hoekstra, 2010). Blue water footprint is the volume of surface and groundwater evaporated as a result of the production of the raw material; green water footprint is the volume of rainwater consumed in the production of the raw material; grey water footprint is the volume of freshwater needed to dilute pollutants, so the water used to produce the raw material meets quality standards (Mekonnen & Hoekstra, 2010).

As for cereals, they generally have a medium water footprint (~1,600 L/kg), however, as shown, maize has a relatively low water footprint among the cereals. The reason why water footprint is different is that different parts of plants are harvested. Potato is the starchy stem of the potato plants, at which all the nutrients are stored, other parts of the plants do not need much energy or water to grow. While the cereals do not have such a structure, only the seeds, the minor part, are harvested and the rest is ditched. Potato has a short harvest time, which is approximately 120 days after planting (Liu et al., 2003). The harvest time for maize varies from 80 days to 120 days (Ashley, 2001). However, it might take 300 days to harvest wheat (HCGA, 2008). That is why cereals have a higher water footprint than potatoes. Yam is the most sustainable crop with only 343 L of water needed to grow 1 kg of it. Rice comes in next at a global average of 2,500 L of water needed to grow 1 kg of it. Tapioca has the highest water footprint of 3,106 L/kg among the three crops because to get the tapioca, the cassava plant needs to undergo some processes; cassava itself has an average water footprint of only 622 L/kg (Mekonnen & Hoekstra, 2010; Situmorang & Manik, 2018). Rice comes in third place and tapioca starch and buckwheat tie for last place with water footprints of over 3,100 L/kg (Mekonnen & Hoekstra, 2010). However, it is worth noting that these water footprint figures are only global averages and the real water footprints of these crops vary based on several factors such as the variety of the crop, the cultivation method used to grow the crop, where the crop is grown, conditions of the environment where the crop is grown, and many more (Yao et al., 2017).

Carbon footprint is a complementary parameter. The carbon emission of potato is 251 Kg CO_2/t harvested (Svubure et al., 2018), and that of cereals are higher, which are 480 Kg CO_2/t and 750 Kg CO_2/t respectively (Zhang et al., 2017). Land use can be used to measure the resource consumed by the crops as well. The yields of potatoes of 90 t/ha are theoretically possible recently (Plant & Food Research, 2013). By contrast, the average yields of corn were 11.8 t/ha in NZ in 2016 (FAR, 2016). The yield of wheat is generally lower than 10 t/ha (FAR, 2010). In a word, potatoes have a very low resource consumption, it shows environmental sustainability, while rice, corn and wheat consume more resources in producing. Yam edible film resulted in higher carbon emissions, likely due to the extensive processing required to obtain such a product (0.88 kg/kg product) (Go, 2009).

2.3.2 Sugar

When it comes to sugar and sweeteners, the amount of research has steadily increased in the past decades, following a 3-step growth. At first, the focus was on non-nutritive synthetic sweeteners, such as aspartame and acesulfame-K, which taste sweet without providing calories (Shankar et al., 2013). Then, the attention moved to non-nutritive sweeteners extracted from plants, such as Stevia and Allulose (Tan et al., 2019). Most recently, nutritive sweeteners (sweet ingredients that deliver calories) have grown in popularity, with products such as agave syrup and date syrup being used more extensively in food manufacturing (Djaoud et al., 2020; Ozuna et al., 2020). The aim of this chapter is carbohydrates for energy, therefore emphasis will be given to nutritive sweeteners, while the non-nutritive counterparts will be included in the discussion due to their high popularity in food formulations.

The past decade was the time of Stevia, when the world became well aware of this new sweetener. What drew attention was two characteristics: extremely high sweetness (150–300 times that of sucrose) and low caloric intake, close to 0 kcal/g (Ashwell, 2015; Wang et al., 2020). Stevia is the commercial name for a pair of glycosides, stevioside and rebaudioside, extracted from the leaves of *Stevia rebaudiana*, a plant found mostly in Brazil and Paraguay (Ashwell, 2015; Wang et al., 2020). Unlike other non-nutritive sweeteners, Stevia does not express strong bitter aftertaste, thanks to its structure and to novel extraction technologies. The water and carbon footprints are about 95% lower than those of sucrose (Ashwell, 2015).

One interesting product is Allulose, a naturally occurring monosaccharide extracted from corn. The market demand for Allulose is booming, with a predicted compound annual growth rate (CAGR) of 14.8% between 2021 and 2027 (Market Watch, 2021b). It is the product of an enzymatic conversion of fructose from corn, delivering sweetness with low calories (0.4 cal/g), which is one-tenth of sucrose that is usually added to make food sweet, and without the loss of upfront sweetness of sucrose, the quality of sweetness or the mouthfeel. However, allulose is three times more expensive than sucrose but still cheaper than the sweetener erythritol. It is important to observe that a successful sweetener must be sweet, cheap and easy to label (Food Navigator USA, 2020b). Being a product of corn, the environmental impact is equal or greater to that of corn (Table 2.4).

Nowadays, syrups are becoming a popular choice as sweeteners: due to the presence of soluble fibers, they provide lower glycemic index than sucrose and higher water binding abilities, making food texture juicier and more pleasant. Agave syrup has grown in popularity over the past 15 years. It is extracted from the leaves of *Agave tequilana* and related plants. The high fructose content allows for its high sweetness (about 1.5 times that of sucrose) at low glycemic index: 11–27 (Espinosa-Andrews et al., 2021; Foster-Powell et al., 2002). The bright yellow appearance resembles that of honey and allows for several applications. When darker colour is needed, date syrup can be a proper choice. This ingredient is new, thus limited research information is available. Sucrose replacement with date syrup in sponge cake resulted in darker, moister product, with sweet, slightly acidic taste (Bhuian et al., 2020). The newest entry is quinoa syrup. Industrial sources present it as mildly sweet, with a delicate bitter aftertaste (Food Navigator, 2021). Quinoa needs low water input (349–877 L water/kg product) (Scanlin & Lewis, 2017) but its processing does result in relevant carbon emissions (1.5 kg CO_2/kg product) (Eco chain, 2020) thus having a mixed environmental impact. Limited geographical availability suggest better impact when used locally rather than upon import.

Another interesting innovation is the result of the upcycling trend. Sweeteners can be extracted from the spent grains, a by-product of the beer industry. The process is simple: applying high temperature, mechanical stress and water, the fibre can be hydrolysed into xylo-olygosaccharides, which are then dried into a powder, without the need for additives (Swart et al., 2021). Their sweetness and caloric value are comparable to those of sucrose, but with lower GI (47) (Kyung et al., 2014) and lower environmental impact (Cimini & Moresi, 2016; Mekonnen & Hoekstra, 2010). Since the raw material is a by-product, it is removed from landfill to be used for food production. Therefore, the carbon footprint of spent grains was calculated to be only 0.02 kg CO_2/kg product (Cimini & Moresi, 2016), lower than that of traditional sweeteners such as sucrose (0.2–0.5 kg CO_2/kg product) (Rein, 2011).

Table 2.4 Innovative food sources of sugar: raw materials, bioavailability (glycemic index) and sustainability (water and carbon footprint)

Products	Raw materials	Bioavailability	Sustainability	
		Glycemic index	Water footprint (L water/kg product)	Carbon footprint (kg CO_2/kg product)
Allulose	Corn	No impact	1,222	0.48
		Tan et al. (2019)	Mekonnen and Hoekstra (2010)	Zhang et al. (2017)
Stevia	Stevia (Eupatorium rebaudianum)	No Impact	83	0.14
		Wang et al. (2020)	Ashwell (2015)	Ashwell (2015)
Agave syrup	Agave	11–27	6,549	0.10
		Espinosa-Andrews et al. (2021)	Healabel (2021)	Healabel (2021)
Date syrup	Dates	Not available	2,277	1.1
			Mekonnen and Hoekstra (2010)	Healabel (2021)
Quinoa syrup	Quinoa	Not available	394–877	1.5
			Scanlin and Lewis (2017)	Eco Chain (2020)
Sweeteners from spent grains	Barley malt	54–60	1,950	0.02 (spent grains)
		Kyung et al. (2014)	Mekonnen and Hoekstra (2010)	Cimini and Moresi (2016)

2.4 Conclusions

In closing, energy can be obtained from a wide variety of carbohydrate-based foods. For the majority of the population low glycemic index is preferred, therefore indicating pasta, rolled oats and noodles as good choices. Environmentally, pasta presents the lowest footprint among starch sources and it is highly acceptable, being cheap and neutral in taste. New popular starch-based products are malt flour and boba balls (used in snack food Boba Tea). Traditional sugary foods that have low impact on glycemia and the environment are fruits, followed by syrups when enhanced shelf-life is required. Data seems to indicate that extrusion technologies can lower the glycemic impact of starch-based foods, while fermentation can be a valuable tool to preserve fruit, thus guaranteeing a wholesome source of sugar. Finally, interesting innovations allow for the development of sustainable sweeteners that are either nutritive (xylo-olygosaccharides from brewers spent grains) or non-nutritive (allulose from corn).

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