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Strengthening food security through alternative carbohydrates in the city-state of Singapore

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Strengthening food security, in places where land and natural resources are limited or no longer available, is challenging. This is especially true for the production of staple food carbohydrates. Unlike some alternative foods, such as cultured meats, producing food carbohydrates using conventional agri-food approaches requires many natural resources, which are not available in some regions such as Singapore. Therefore, we must develop new, sustainable methods to enhance the quantity and nutritional quality of foods rich in carbohydrates. In this article, we review current developments in food security in the city-state of Singapore and emphasize the essential role of food carbohydrates in the food security plan. We discuss technology developments (i.e., indoor vertical farming, urban farming) used to enhance crop quality and production. We also make a few recommendations such as exploring underutilized and unconventional crops that are resilient and nutrient-dense, identifying hidden resources in local ecosystems (i.e., revalorizing agri-food processing by-products), and producing alternative carbohydrates (i.e., microbial and synthetic carbohydrates). Experience and approaches developed in Singapore provide an example to other regions and may inspire creativity in securing food availability.

KEYWORDS

food security, Singapore, food availability, alternative carbohydrates, microbial carbohydrate, indoor farm, synthetic carbohydrate, urban farming

1. Introduction

The world today faces an increasing demand for food. Nearly 9–10% (approximately 720 to 810 million) of the global population went hungry in 2020 (FAO, IFAD, UNICEF, WFP, and WHO, 2021). The world's population is expected to increase to 9.9 billion by 2050 (Population Reference Bureau, 2020). At its current food consumption pattern, the world will have a 70% increase in food demand in 50 years (Food and Agriculture Organization, 2009). However, food production and supply are not rising sufficiently to meet the projected need. In addition, environmental challenges, such as climate change, further put food production at risk. In the absence of effective adaptation, the global yield of food crops (Bichetti et al., 2021) could decline by nearly 30% by 2050 (Hobert and Negra, 2020).

The rapid increase of urbanization also raises challenges in food security. More than 55% of the global population lives in urban areas (United Nations Department of Economic and Social Affairs, 2018), and nearly 80% of the population worldwide uses imported foods for at least a portion of their meals. The value of food imports has tripled since the beginning of the century (Bichetti et al., 2021). However, the high cost does not guarantee food availability. The reliance on foreign supplies for major nutrients is risky for food security. The COVID-19 pandemic and the war between Russia and Ukraine have interrupted the global food supply chain and threaten food security in many countries. In addition to the concern of food availability, nutrition security in urban areas involves tackling the coexistence of overnutrition (i.e., overweight) and malnutrition (i.e., deficiency of micronutrients). Urbanization influences food systems and diets, which tend to include a high proportion of unhealthy foods and sugar-based beverages (Nguyen et al., 2021). A sedentary lifestyle further elevates health risks. As a result, city-states, such as Singapore, face the challenge of stabilizing food availability and nutrition quality.

Singapore currently produces less than 10% of its food supply due to limited natural resources (Singapore Food Agency, 2020). Aside from growing food locally, the country diversifies its importing sources and also produces food overseas to secure the food supply chain. Singapore's approaches have been very successful. The country was ranked first in 2018 and 2019 by the Global Food Security Index (GFSI), which examined food affordability, accessibility, and quality (Economist Intelligence Unit, 2018, 2019). However, when natural resources and resilience were added to the score criteria, the rank of Singapore dropped to 29th out of 100 countries (Economist Intelligence Unit, 2020).

To strengthen its food security and resiliency, Singapore has set a national goal ("30 by 30") to increase its local food production from less than 10 to 30% by 2030 to meet nutritional needs. The government also implemented the Singapore Food Story R&D Plan to develop technologies in areas of sustainable urban food production, sustainable future foods such as advanced biotech-based protein production, and for food science safety and innovation (Singapore Food Agency, 2022). A significant effort has been invested in technology development. Stakeholders have quickly accelerated the transformation of the food industry into advanced manufacturing, particularly in producing plant and cultivated meat and dairy alternatives to formulate alternative proteins into popular local cuisines that stimulate consumers' interest and acceptance (Quek, 2022). In addition to prioritizing production, Singapore took regulatory leadership and became the first nation to approve the commercial sale of cultivated meat products (International Trade Administration, 2021). The approval enables the availability of alternative proteins for the consumers in Singapore. Singapore demonstrates a successful case in implementing these advances through the integration of science, technology, economics, consumer education, and novel food regulations and policies.

Perhaps a more significant challenge to increasing food security in Singapore is obtaining alternative sources of vital energy and nutrients. This article recommends and discusses a few potential solutions to support food carbohydrate security, including developing innovative food production technology, exploring underutilized crops with greater resilience and nutrients, identifying hidden resources in local agri-food systems, and producing alternative carbohydrates, such as microbial carbohydrates and synthetic glucans. The adaption of new food systems and the initiatives taken in Singapore could be applied to other regions and inspire more innovative approaches to strengthen food security in the world.

2. Role of carbohydrates in food security

Carbohydrates, proteins, and lipids are macronutrients, which provide the human body with vital energy, and carbohydrate-based foods are recognized as nutritious and healthy. Carbohydrates first appear in our life as part of complementary feeding during weaning (Lin and Nichols, 2017). Rice is given to young children in a great quantity in Asia and Africa. Western India has a tradition of feeding infants with arrowroot. In the United States, infant cereals or baby finger foods made of rice, oats, maize, and wheat are popular. Parents observe the benefits of complementary feeding with starch-based foods as they see their children grow (Lin and Nichols, 2017). The Eatwell Guide in England comments that starchy foods are a good source of energy and the main source of a range of nutrients in our diet (Public Health England, 2019). The dietary guideline encourages "choosing higher fiber or wholegrain varieties, such as wholewheat pasta and brown rice, or [to] simply leave the skins on potatoes" (Public Health England, 2019). Glycemic carbohydrates are the primary caloric energy for our brain, central nervous system, kidneys, and heart muscles (Vannucci and Vannucci, 2000; Myers et al., 2021). Some indigestible and non-digestible carbohydrates, such as dietary fiber, are substrates of gut microbial fermentation and are essential to human health. Carbohydrate-based foods also provide non-carbohydrate nutrients, including proteins, vitamins B, C, and E (Kulp and Ponte, 2000), minerals (i.e., potassium, iron, magnesium, zinc, and selenium), and phytochemicals (e.g., β-carotene, polyphenols; McKevith, 2004; Zaheer and Akhtar, 2016; Saini et al., 2021). For example, grains supply carbohydrates and are also a primary protein source in human diets. Wheat is a popular grain and offers nearly one-fifth of the calories and proteins consumed worldwide (Daba et al., 2020; Poutanen et al., 2021). However, excessive consumption of carbohydrates creates health concerns in some populations. The long-term overconsumption of sugars and rapidly digestible starch-based foods is associated with some hyperglycemia-related diseases, such as type 2 diabetes and obesity. Low-carbohydrate diets, which restrict the energy supply received from carbohydrates and lead to quick weight loss, are popular with some groups (Gómez-Maqueo et al., 2023). However, the nutritional functions of carbohydrates go beyond their role as energy sources and involve providing some biological functions. Glycoconjugates (e.g., glycoproteins and glycolipids) operate as messengers of critical information and are involved in receptor structure, recognition sites, blood clotting regulation, and lectin interactions (Murray, 2003). Long-term carbohydrate restriction is linked to complications such as heart arrhythmias, impairment of cardiac contractile function, kidney damage, lipid abnormalities, increased cancer risk, impairment of physical activity, osteoporosis, and sudden death (Bilsborough and Crowe, 2003). Removing carbohydrates from regular diets or overconsuming carbohydrates with poor nutritional quality contributes to health risks.

According to the Food and Agriculture Organization of the United Nations, "Food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious foods that meet their dietary needs and food preferences for an active and healthy lifestyle" (Food and Agriculture Organization, 2006). Historically, carbohydrate staple foods (e.g., rice, wheat, potatoes) have played a fundamental role in food security. Rice, maize, and wheat make up 2/3 of global human food consumption, and rice alone provides more than 21% of global caloric needs. Besides grain-based staple foods, root (i.e., potato) and fruit (i.e., banana and plantain) crops are consumed by over 3 billion people in developing countries (Scott, 2021). Cultivating carbohydrate staples transformed nomadic hunter-gatherers into settled farmers, spawned the first urban centers, and built empires and dynasties (Callaway, 2014). Existing challenges today involve effectively producing sufficient carbohydrate foods and processing them in such a way that would support healthy diets.

3. Challenges in strengthening carbohydrate food security with limited natural resources in Singapore

In the 1970s, 9% of Singapore's total population (approximately 175,000 people) was engaged in agricultural activities. Due to urbanization and industrialization, the food system was gradually restructured with limited self-production (Singapore Food Agency, 2020). Currently, Singapore produces few staple carbohydrate foods; the primary self-produced products are eggs, fish, and leafy vegetables (Singapore Food Agency, 2020). Less than 1% of Singapore's land, which is only approximately 72 square kilometers, is available for food production (Mullen, 2020). However, conventional cultivation of carbohydrate-rich crops requires the luxury of land space. Furthermore, the long planting season of staple crops restricts the use of land from multiple production cycles. There are also many difficulties in terms of climate. Typical tropical weather consistently has high temperatures and abundant rainfall. In recent years, Singapore has experienced hotter temperatures with increased amounts of rain (Adeline et al., 2021), which further challenges the agronomic management of maintaining crop quality, yields, and disease resilience. The self-production cost (e.g., energy and space renting) in Singapore is often much higher than that in neighboring countries, such as Malaysia, Indonesia, and India. The production cost is reflected in the product price, which is less competitive than imported crops.

Like many urban regions, Singapore faces challenges in nutrition security. Nearly 28% of the elderly (above 55 years old) were at risk of malnutrition in Singapore due to low mobility and poor health (Nagpaul et al., 2020). Some migrant workers suffer from hidden hunger. One study found that the long-term imbalanced diets of migrant workers in Singapore, consisting primarily of white rice with few other foods, resulted in a deficiency of vitamins A and B, iron, zinc, and folic acid (BBC, 2016). The Singapore Ministry of Health declared "war on diabetes" in 2016. Singapore's high prevalence of diabetes was once only next to the United States among developed countries. The disease is projected to affect one in two residents in Singapore by 2050 (Ministry of Health, 2019). A food-focused strategy was promoted to increase the accessibility to healthier food options, such as brown rice and low-sugar beverages (Ministry of Health, 2019).

Despite many obstacles to local production, Singapore continues to prioritize the increase in self-production as a vital buffer for when the global food supply chain is interrupted (Teng, 2020). Non-conventional approaches are needed to produce accessible, affordable, and nutrient-rich carbohydrates. Figure 1 illustrates Singapore's strategies and the recommendations from this article.

4. Production with innovative technology

Singapore is globally recognized in innovation and technology. Beyond its leadership in digital competitiveness (e.g., artificial intelligence, cloud computing, and quantum computing), developing innovative farming technologies is crucial for growing food in a productive, sustainable, and climate-resilient manner. Indoor farming and urban farming have continued to advance in Singapore with the support of innovative technologies.

4.1. Indoor vertical farming

Indoor farming is a resource-conserving method where food is produced in closed recycling and controlled systems with a minimized negative impact on the environment. It is immune to environmental stresses (e.g., rainfalls, drought) and is sustainable in that it utilizes water and energy with advanced technology. Hydroponics, aeroponics, and aquaponics are popular farming methods, which either recycle or minimize the use of water. A hydroponic system supplies plants with nutrients *via* a thin stream of water running through the roots. An aeroponic system sprays a nutrient-containing mist onto the roots in an enclosed root chamber, using 70% less water than hydroponics (Masyk and Fritz, 2017). In aquaponics, fresh-water fish, such as tilapia, generate nitrogen-based waste to supply plant growth. One kilogram of fish can produce approximately seven kilograms of vegetables in such a system. Vertical farming has rapidly developed in Western countries, such as the United States. It is projected to grow approximately 24% between 2018 and 2024 and is expected to be worth $3 billion in US dollars by 2024 (Arizton, 2019; LeBlanc, 2020). Vertical farming, unlike conventional, horizontally constructed greenhouses, is particularly favorable to urban areas like Singapore. Vertical farming can potentially expand food production on ships or offshore landfilled areas. Therefore, Singapore is one of several Asian countries (i.e., Japan, China, South Korea, Taiwan, and Thailand) with a significant number of vertical farms (Piechowiak, 2022).

Indoor farming requires much science and technology development to close the knowledge gap for elevating yield, quality, and sustainability. Much technology development is invested in lighting, temperature control, irrigation systems, and water recycling. Lighting is costly, but the development of LED lighting has decreased energy consumption by at least 75% and lasts 25 times longer than incandescent and fluorescent lighting (Breene, 2016; Energy, 2022). Supplementing artificial light with natural light further decreases the cost and excess heat generated from LED lights (Asiabanpour et al., 2018). Manipulating light wavelengths (blue, red, and white) impacts the photosynthesis rate and maximizes crop growth (Lin et al., 2013). Furthermore, modular towers designed with rotating growing racks improves and evenly distributes light, irrigation, and airflow (Al-Kodmany, 2018). In addition, the application of infrared-light-absorbing curtains mitigates heat (Panasonic, 2021). Novel techniques can manipulate plant growth and, therefore, can also alter crop quality. Moisture sensors, for example, are used to gage the degree of photosynthesis (Panasonic, 2021), which directly impacts crop growth. Researchers, such as those at the newly established Research Center on Sustainable Urban Farming in Singapore, have begun genetically modifying crops to become more suitable for an indoor growing environment while also enhancing the nutritional quality.

Indoor farms in Singapore are primarily used to grow vegetables that have a short turnover and adapt well to a hydroponic system without soil. Cultivating staple food crops is more challenging than vegetables. However, research has shown great yields of some staple

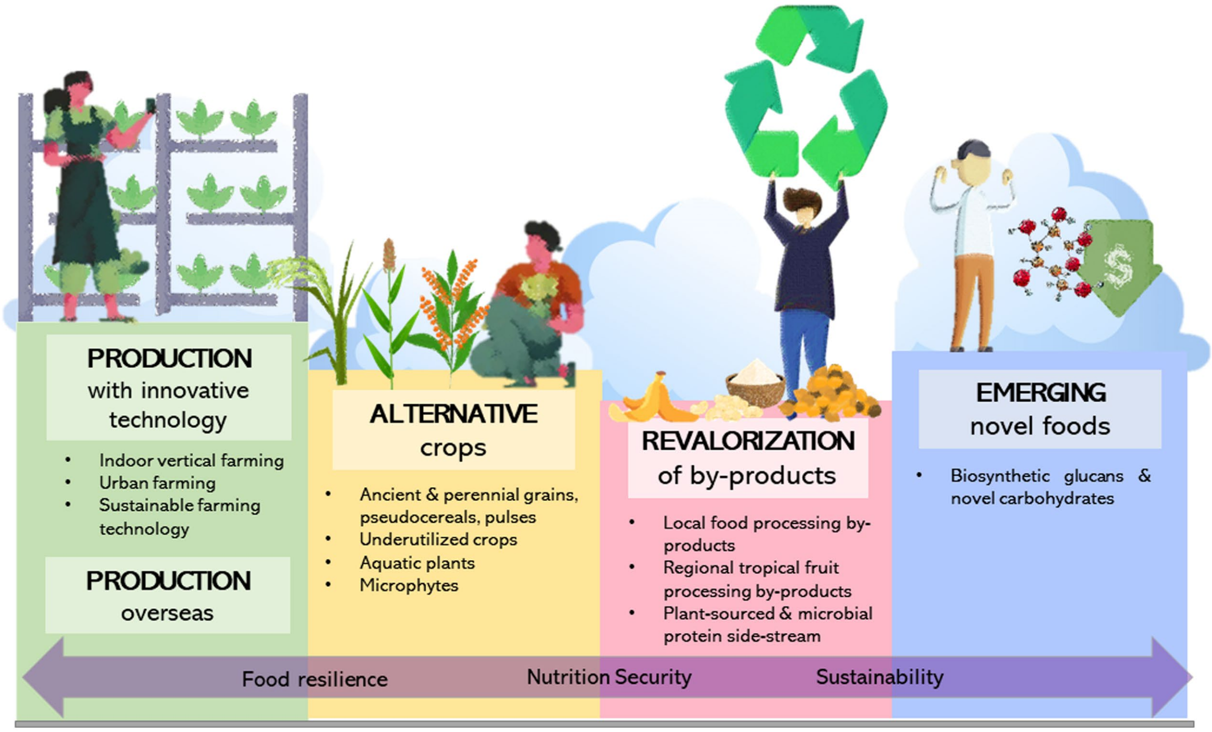

FIGURE 1
Strategies in producing food carbohydrates with limited natural resources.

crops cultivated *via* advanced technology. Rice is an essential crop that provides up to 76% of the caloric intake of Southern Asians. The yield of indoor-farmed rice may be elevated to five times that of the traditional paddy-grown rice through increased harvest cycles (Kiernan, 2018). Potatoes are an environmentally sustainable crop. Research has shown potatoes provide more food energy, require less water and land, and their production involves fewer greenhouse gas emissions than most other crops (Food and Agriculture Organization of the United Nations, 2009). Utilizing indoor farms, the US National Aeronautics and Space Administration (NASA) produced potatoes (175 t/ha) with twice the best yield of potatoes grown in traditional fields (89 t/ha) or greenhouses. Indoor vertical farmed wheat is also projected to reach 600 times (~700 t/ha) more grains than traditional farming (3.2 t/ha) through the crop simulation tool DSSAT-NWheat, which simulates field conditions of one hectare of land and optimizes temperature, light, carbon dioxide levels to obtain a maximum harvest for a 10-floor vertical farm (Asseng et al., 2020). The success of indoor farming opens a new era of sustainable food production on a grand scale.

4.2. Urban farming

Urban farming is a food production strategy conducted in household and commercial settings. Residents are encouraged to grow food at home and in the community for self-supply. Some policies have been implemented for commercialization in Singapore to promote sustainable production. For example, the first standard requires agronomic management to grow farm products that can be labeled as clean and green (Enterprise Singapore, 2020). Approximately 36 urban commercial farms with an average of 5.2 hectares have been established in Singapore. In addition, schools, backyards, and rooftop gardens are utilized for more planting for consumption and education (AgriFarming, 2021).

Leafy vegetables, herbs, and fruits are popular crops; carrots, bananas, sapodilla, guava, custard apple, and ginger are also grown at these farms. Some urban farms (e.g., Bollywood Veggies in Singapore) are experimenting with staple crops, such as rice, sweet potato, cassava, and pumpkin (The Smart Local, 2019). Technology development can further turn urban farming into a significant source of production. For example, using recycled rainfall in a drip irrigation system enables three harvest cycles of rice in one year. With advanced technology, it is projected that Singapore could supply some of its own rice needs as early as 2030 (Temasek Foundation, 2021).

Despite the efforts and advances made in urban farming and indoor farming development in Singapore, some challenges remain. Urban farming production is not economically competitive with the imported foods produced in a conventional food system. Production quantity is rising, but its sustainability (i.e., water usage) and efficiency (i.e., production per literate of water) require comprehensive and standardized assessments. For example, some hidden costs (e.g., post-harvesting management with a small-scale production) and product quality (e.g., nutrition density, sensory attributes) need to be considered along with labor, water, electricity, infrastructure, etc. In addition, urban farming outdoors in a tropical region is highly vulnerable to diseases and infections that requires additional agronomic management to maintain crop health. Nevertheless, recent assessment reports demonstrate the promising future of urban farming and indoor farming to strengthen food security in Singapore (Wood et al., 2020; Song et al., 2022). Governmental support along with funds and collaboration from the private sector promotes increased participation. Furthermore, urban farming raises awareness of food resilience and increases food production in a small area. In Singapore, urban farming also provides social benefits, such as education, youth development, and skills and workforce training. Expanding current urban and indoor farming development to include carbohydrate-based crops would increase the availability of these essential food sources.

5. Future potential for Singapore

5.1. Production of underutilized and unconventional crops

The world production of staple crops focuses primarily on maize, rice, and wheat. These staple crops supply caloric energy. They are also the primary materials of carbohydrate-based ingredients, such as maltodextrin and syrups. Non-conventional (alternative) carbohydrates offer a way to increase self-supplied nutrients and ingredients. Unlike rice, many alternative crops have high sustainability, high resilience to harsh environments, and significant nutritional value. These crops include ancient grains, pseudocereals, perennial grains, pulses, and unconventional tropical crops (Li et al., 2020; Table 1). Ancient grains refer to grains with few changes over the last few hundred years. Pseudocereals are plants with starch-rich seeds and function similarly to cereal grains in food applications. Pseudocereals such as buckwheat, quinoa, and amaranth (Table 1) are less frequently utilized in Western countries and are often included in the ancient grain category. However, many are not new to South Asians, such as buckwheat and amaranth. Perennial crops offer a higher level of ecological intensification in agriculture. In contrast to modern wheat and other grains, perennial crops do not need to be re-seeded or re-planted every year. Therefore, the planting method of perennial crops protects soil from erosion, nutrition loss, and damage due to microorganisms. In terms of nutritional values, whole grains offer higher nutritional quality with rich dietary fiber, lower starch digestibility, and greater micronutrients. Most of these grains are rich in essential amino acids, essential fatty acids, minerals, and vitamins and are free of gluten (Schoenlechner and Bender, 2020). Overconsuming rapidly digestible starchy food is associated with some health risks, such as diabetes and obesity. Increasing the consumption ratio from rapidly digestible carbohydrates (e.g., polished white rice, sweet bread) to carbohydrate-based foods with great nutritional quality, such as whole grains, will strengthen nutrition security in Singapore. The food applications of alternative grains are simple since many are similar to modern grains, such as wheat, barley, and rice. Table 1 tabulated some applications of ancient grains as well as other underutilized and unconventional crops. Some of these grains (e.g., millet, and quinoa) are found in local grocery stores, indicating the acceptance and demand of those grains in Singapore.

Singapore is humid, with consistently high temperatures, which makes cultivating tropical crops feasible. Some underutilized or unconventional tropical root and rhizome crops are resilient to environmental change and require minimal agronomic management. Starches produced from canna (*Canna edulis*), chufa sedge (*Cyperus esculentus*), air yam (*Dioscorea bulbifera*), white ginger lily (*Hedychium coronarium*), malanga (*Xanthosoma sagittifolium*), and kithul (*Caryota urens*) are candidates as substitutes for some commercial starches and chemically modified starches (Sudheesh et al., 2019; Dos Santos and De Francisco, 2020; Table 1). Canna starch has been broadly used in oriental desserts as a thickening agent, and the starch of white ginger lily has a high amount of amylose with low paste viscosity. Kithul stem has abundant starch, which has been broadly studied to promote the rural economy in Sir Lanka. Unlike alternative grains, tropical crops greatly vary from one to another. Therefore, much research is required to commercialize these underutilized crops into novel or alternative foods and ingredients desirable to consumers. Starches in these alternative crops are worth researching for novel functionalities or properties. These unconventional starches may be good candidates for replacing conventional chemically modified starches and may be used as "clean label" starch ingredients.

Tropical regions also have a high diversity of nutritious fruits with abundant carbohydrates and micronutrients, such as vitamins, minerals, and antioxidants. Breadfruit (*Artocarpus altilis* S. Park. Fosb), wood apple (*Limonia acidissima* L.), monkey jack (*Artocarpus lakoocha* Roxb.), marang fruit (*Artocarpus odoratissimus*), gumihan (*Artocarpus sericarpus*), and nam-nam (*Cynometra cauliflora*) have the potential to provide alternative carbohydrates (Table 1). Breadfruit is native in Malaysia and Indonesia. Nearly 75% of the dry weight of breadfruit is starch. Both breadfruit starch and breadfruit flour could be commercialized to replace some chemically modified starch (Adebowale et al., 2005; Nwokocha and Williams, 2011). Wood apple trees are able to grow on saline waste and neglected lands (Kumar and Deen, 2017), and wood apple is suitable for processing into jam, jellies, and preserves. Monkey jack is another crop containing abundant carbohydrates and also rich in proteins, vitamins (e.g., vitamin C and vitamin A precursor, β-carotene), and minerals (e.g., sodium, potassium, iron, copper, manganese, and phosphorus; Yadav et al., 2018). Marang fruit is often referred to as an "athlete's fruit" due to the abundance of starch and micronutrients, which are essential for athletic performance and muscle growth. Gumihan is a very sweet fruit that grows well in humid tropical weather. Nam-nam is native to Malaysia and is used for preparing sambal, compote, or fruit salad.

Pulse-based foods are excellent sources of proteins and carbohydrates, which generally have slowly digestible carbohydrates and are rich in dietary fiber. Pulses also contain abundant micronutrients, such as flavonoids, polyphenols, terpenes, and lectins (Reynoso-Camacho et al., 2006). Despite its popularity, only a few legumes (i.e., pea, soybean) are introduced to the global market. There are many varieties of pulses that are native or cultivated in the South Asian continent and Indo-Pacific regions (Nayak et al., 2022), and many of them are nutritious to humans and resilient in harsh environments (Table 1). The winged bean (*Psophocarpus tetragonolobus*) is a tropical legume that grows well in hot and humid equatorial regions, such as the Philippines, Indonesia, Thailand, and Sri Lanka. The immature pod of the winged bean is consumed raw, pickled, or cooked (e.g., stir-fried, boiled). Horse gram (*Macrotyloma uniflorum*) is tolerant to drought and salinity (Reddy and Reddy, 2005) and is easily found in Malaysia and India. Horse gram, which is similar to other legumes, consists of nearly 60% carbohydrates and 18–25% protein and also contains abundant minerals (i.e., iron, molybdenum, phosphorus) and other micronutrients (i.e., carotene, thiamine, riboflavin, niacin, and vitamin C; Prasad and Singh, 2015).

Black gram (*Vigna mungo*) and rice bean (*Vigna umbellatta*) also have a high nutritional value, and mung bean (*Vigna mungo*), which has been a part of Chinese diets for over 2,000 years, is consumed in sprouts, soups, or desserts. Singapore is experienced in overseas farming and is very active in researching product and ingredient development with sustainable manufacturing techniques. Converting these underutilized roots (or rhizomes), fruit, and legumes into alternative ingredients for Asian foods would not only supply Singapore but benefit others.

Aquatic plants are another alternative approach to increasing food production. Many aquatic plants have abundant carbohydrates and are popular food materials in oriental cuisines, such as lotus (*Nelumbo nucifera*), wild rice (genus *Zizania*), water chestnuts (*Eleocharis dulcis*), water caltrop (*Trapa natans, Trapa bicornis*, or *Trapa rossica*) and duckweed (*Lemna minor*; Table 1). Lotus has a high economic value due to its demand in Chinese communities. The entire lotus plant, including the seed, rhizome, stem, and flowers, are valuable in oriental cuisines, for medical use, and beverages (e.g., lotus flower tea, lotus flour drink). Wild rice is an ancient grain and has become popular in Western countries due to its nutrients and taste, and its stem, known as jiāobái, serves as a vegetable in oriental meals. Water chestnut is not a "nut" but is a bulbotuber with a crisp texture. Water chestnuts are consumed in salads or with fruit, or they are cooked with other food materials. Water caltrop, which is prevalent in China and Taiwan is another ancient crop and has been part of human diets for over 3,000 years (Lu et al., 2021). The fruit of water caltrop contains a single, large (averaging 5–7 centimeters in diameter), edible starchy seed with a unique tapered shape and two elongated, curved, dropping spines. Duckweed (*Lemna minor*), a small aquatic plant, grows rapidly and densely. It serves as an alternative protein source as well as an alternative carbohydrate. Duckweed is suitable for humans and livestock, and various varieties have different ratios of macronutrients.

TABLE 1 Examples of applications of underutilized or unconventional crops.

Category	Crops	Scientific name	Selected applications
Ancient grains	Sorghum	*Sorghum bicolor*	Porridge, soups, and stews
	Teff	*Eragrostis tef*	Porridge
	Millet	*Pennisetum glaucum*	Porridge, sauces, and stews
	Quinoa	*Chenopodium quinoa*	Salads, beverages, snacks
	Amaranth	Genus *Amaranthus*	Porridge, patties (tikki), and stews
Roots and rhizomes	Canna	*Canna edulis*	Consumed raw, boiled, and baked
	Chufa sedge	*Cyperus esculentus*	Beverages and bread
	Air yam	*Dioscorea bulbifera*	Chips, fries, stews
	White ginger lily	*Hedychium coronarium*	Stews
	Malanga	*Xanthosoma sagittifolium*	Mashed, roasted, and fried, and used in soups
	Kithul	*Caryota urens*	Flour is used in porridge and desserts
Pulses	Winged bean	*Psophocarpus tetragonolobus*	Stews and salads
	Horse gram	*Macrotyloma uniflorum*	Porridge, soups, and salads
	Mung bean	*Vigna radiata*	Soups, sauces, stews, and salads
	Black gram	*Vigna mungo*	Soups, sauces, stews, and salads
	Rice bean	*Vigna umbellatta*	Soups, sauces, and stews
Aquatic plants	Lotus	*Nelumbo nucifera*	Stews, soups, tea, and used as a vegetable in meals
	Wild rice	Genus *Zizania*	Consumed as a vegetable (starchy vegetable)
	Water chestnuts	*Eleocharis dulcis*	Consumed raw and stir-fried, and used for drinks, stews, and soups, salads, pickled, and candied
	Water caltrop	*Trapa natans*, *Trapa bicornis* or *Trapa rossica*	Cooked snacks, stir-fries, dumpling stuffing, stirred into rice, and in vegetable dishes
	Duckweed	*Lemna minor*	Boiled or roasted
Fruits	Breadfruit	*Artocarpus altilis*	Processed into flour and consumed boiled, steamed, baked, and fried
	Wood apple	*Limonia acidissima*	Juice, chutney, ice cream, and jams
	Monkey jack	*Artocarpus lakoocha*	Curry, pickled, and consumed fresh
	Marang fruit	*Artocarpus odoratissimus*	Jams and consumed fresh
	Gumihan	*Artocarpus sericarpus*	Consumed fresh
	Nam-nam	*Cynometra cauliflora*	Pickled and consumed fresh

5.2. Development of microbial carbohydrates

Microphytes, such as algae, are another potential alternative crop source. Although it is not yet fit for human consumption, producing starch from photosynthetic microorganisms (e.g., microalgae) has been an alternative way to substitute maize for biofuel production (Chen et al., 2013). Microalgae grow rapidly in various aquatic environments, such as fresh-water, saline water, and wastewater. It has a high capacity to absorb carbon dioxide and is highly efficient at using light energy for photosynthesis (Guimarães, 2012). Therefore, microalgae accumulate and produce starch rapidly, and their starch content depends on species and cultivation conditions. Red algae are a microalgae that produces a unique polysaccharide, Floridian starch, which has a high degree of branched molecular structures. Floridian starch has a low gelatinization temperature, low viscosity, and high resistance to retrogradation, which are all of interest to the processed food industry (Yu et al., 2002). Microalgae starch may have comparable characteristics to commercial products (e.g., maize starch). Starch extracted from *Klebsormidium flaccidum* is similar to maize starch in its ratio of amylose to amylopectin, swelling capability, and solubility, despite its small granule size of approximately 1 μm (Ramli et al., 2020).

Marine photosynthetic bacteria, such as cyanobacteria, have been used for centuries to produce high-value ingredients and nutritional supplements. Although most cyanobacteria produce glycogen, several species (e.g., *Cyanobacterium* sp. NBRC 102756, *Cyanothece* sp. ATCC 51142, *Caynobacterium* sp. CLg1) produce insoluble polysaccharide granules (Nakamura et al., 2005; Deschamps et al., 2008), which is highly analogous to cereal amylopectin with its tandem–cluster structure (Suzuki et al., 2013). From a sustainability perspective, phylum, such as cyanobacteria, could have a distinct advantage for large-scale cultivation as they can be cultivated in seawater.

Yeast strictly produces glycogen, which is a branched glucose polymer, unlike amylopectin, without cluster structure and cannot form insoluble granules like starch. These microorganisms store glycogen in tiny soluble particles in the cytoplasm rather than in large insoluble granules, as with photosynthetic organisms. However, a recent study showed the feasibility of recreating the synthesis of starch granules in a common yeast culture (*Saccharomyces cerevisiae*; Pfister et al., 2016). Genetically engineered yeast was purged of its endogenous glycogen-metabolic enzymes to be able to express the core Arabidopsis starch-biosynthesis pathway. The result produced dense, insoluble granules with a starch-like semi-crystalline organization.

Among non-conventional carbohydrate resources, microphytes may best suit Singapore and similar environments. Its vigorous aquaculture industry has abundant resources for supporting the cultivation of microphytes suitable for saline water. Technology, which has been developed to enhance microbial protein production, has rapidly advanced in Singapore and therefore, can facilitate the indoor cultivation of microbial carbohydrates. With limited land space and natural resources to grow conventional higher plants, novel microbial carbohydrates would have unlimited potential for developing alternative foods and ingredients. However, some macrophytes and microbial carbohydrates are new to human diets. Substantial research on food safety, regulatory processes, and consumer acceptance must be conducted.

5.3. Development of synthetic carbohydrates

Starch is the primary glycemic carbohydrate in human diets. However, the structure of starch granules is complicated in that, even today, a successful synthesis of a starch granule has not been documented. Nevertheless, carbohydrate biosynthesis is not a new science, and some glucans with relatively small molecules were developed and commercialized as food ingredients. Most synthetic glucans are developed by modifying starch, starch derivatives (e.g., maltodextrins), and sucrose. Isomaltulose, dextrans, neo-amylose, alternans, and alternan-oligosaccharides are either commercially or bio-technically modified or synthesized from sucrose (Xue et al., 2022). Pullulan and cyclic cluster dextrins are produced from starch, and cyclodextrins are made from melt condensation of glucose and sorbitol in an acidic environment (Miao et al., 2018). Some α-glucans are produced from non-starch sources. Naturally, isomaltooligosaccharides are found in various fermented foods, such as miso, sake, and soy sauce, although commercial isomaltooligosaccharides are produced from starch hydrolysates through enzymatic modifications (Gangoiti et al., 2020). Agricultural post-harvest and food processing by-products, such as corn stalks, rice brans, and fruit skins, are carbon-rich materials for developing novel food carbohydrates. Xylitol, a non-cariogenic sweetener, is primarily produced by the chemical hydrogenation of xylose, which is obtained from natural resources, such as nutshells, wood hydrolysates (e.g., sulfite waste liquor), or corn cobs hydrolyzed in acid (Vandamme and Soetaert, 1995).

Novel glucans cannot yet replace starch in providing caloric energy, but they provide different technical properties and nutritional functionalities needed in the processed food industry (Table 2). Low-calorie foods, prebiotics, resistant or slowly digestible starch, and immunity-related functions (e.g., fungal β-glucans) are essential from a health perspective. Oligomers or polysaccharides generated from biotechnical production are often used as texture stabilizers in food applications, such as thickeners (xanthan gum–produced by bacteria), gelling agents (gallant gum–produced by bacteria), and glazing agents (e.g., polydextrose–synthesized through melt condensation reaction). Fermentation techniques and biotechnology are primary tools for developing novel (biosynthesis) glucans, and many reactions rely on enzymes and catalysts. Researchers recently reported the synthesis of glucans toward the goal of producing artificial starch (Cai et al., 2021). The researchers successfully used an inorganic catalyst and engineered recombinant enzymes to convert inorganic carbon sources into glucans. Although, much research is still needed to create a starch granule, the study demonstrated the necessity of exploring novel enzymes for alternative food production. These carbohydrate sources show great promise and may be key to providing cost-effective and accessible alternative carbohydrate sources. Nevertheless, the production of alternative carbohydrates and the use of novel enzymes must meet consumer health regulations, and safety and toxicology examinations must be incorporated into the research plan.

5.4. Revalorization of agri-food processing by-products

Many food processing by-products are landfilled even though many nutrients (i.e., starch, lipids, proteins) are retained in those by-products. Even a small island state like Singapore has a great quantity of nutrient-rich by-products. In 2021, Singapore produced almost 800,000 tons of food waste and recycled approximately 20% of it (Figure 2). The top four waste streams in Singapore are spent grains, okara, bread, and spent coffee waste (National Environment Agency, 2021). Singapore actively researches innovative solutions to revalorize food processing by-products (National Environment Agency, 2021), and some food applications have become available on the market (Table 2). Okara is a soybean processing by-product consisting of approximately 4% carbohydrates, 6% proteins, and 2% lipids, and the quantity produced in Singapore yearly is around 83,000 tons (National Environment Agency, 2021). Okara is blended into food formulation ingredients for beverages, confectionery, mock meat products, soy cheese, energy bars, crackers, bread, and noodles. Okara is also directly processed into probiotic beverages through fermentation with various biocatalysts (Vong and Liu, 2019). Coffee ground waste can be converted into alcoholic drinks (Liu et al., 2021). Food processing by-products are generated in small food processors throughout Singapore under hot (25–32°C) and humid conditions (~80%, sometimes 100% during prolonged periods of rains), and the main challenge to utilizing food processing by-products is contamination and pasteurization. Another difficulty is that many processors cannot immediately process or adequately store the by-products. On-site cost- and space-saving processing to conserve the materials for further processing is essential for utilizing those materials (Table 3).

Singapore is located close to countries with active agricultural industries (i.e., Thailand), especially those with tropical fruit production, such as banana, pineapple, durian, rambutan, and jackfruit. Technology development utilizing fruit processing by-products in Singapore creates an opportunity to partner with processors to strengthen food security as well as to enhance sustainable manufacturing. Typical by-products are seeds, peels, husks, stems, leaves, and immature fruits, and these portions of fruit usually contain much carbohydrate as well as proteins, lipids, and micronutrients. Seeds from jackfruits, durians, and rambutans are large, and contain approximately 26–80% carbohydrates (Eiamwat et al., 2016; Baraheng and Karrila, 2019). The starch in jackfruit seed offers a firm and elastic

TABLE 2 Technological and nutritional functionality of α-glucans in foods.

Ingredients	Functionality
Isomaltulose	Sweetener
Isomaltooligosaccharides	Sweetener, anti-caries, prebiotic, soluble dietary fiber
Resistant maltodextrins	Bulking agent, soluble dietary fiber
Polydextrose	Bulking agent, glazing agent, humectant, stabilizer, thickener, soluble dietary fiber
Pullulan	Filler, glazing agent, film-forming, thickener, binder
Cyclodextrins	Encapsulating agent, masking taste
Dextran	Thickener, cholesterol-lowering agent, emulsifier, stabilizer, humectant, texture agent, anti-crystallizing agent
Neo-amylose	Insoluble dietary fiber
Cyclic cluster dextrins	Spray-drying aid, slowly digestible carbohydrate, taste improver
Alternan	Bulking agent, binder
Alternan-oligosaccharides	Prebiotic, modulating blood sugar
Low-amylose starch	Gelling agent, texture stabilizer
Low-digestible starch	Prebiotic, modulating blood sugar

Vandamme and Soetaert (1995), Miao et al. (2018), Gangoiti et al. (2020), and Xue et al. (2022).

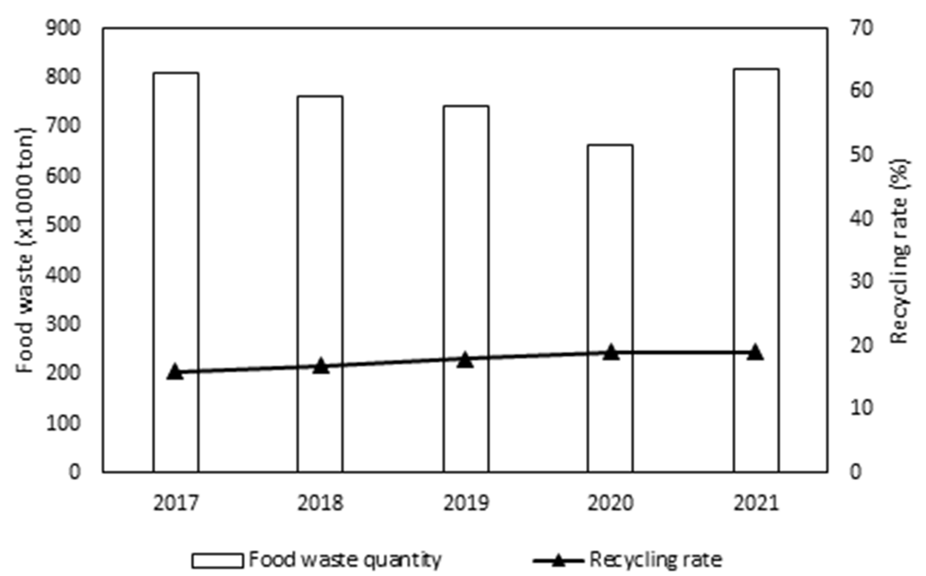

FIGURE 2
Food waste generated (×1,000 ton) and recycling rate (% of total food waste from total generated food waste) in Singapore from 2017 to 2021. Recreated based on data in (National Environment Agency, 2021).

TABLE 3 Commercial products made from the revalorization of agri-food processing by-products in the Singapore region.

By-products	Commercial products	Product highlights	Ref
Spent grains	Noodles	High-protein noodles made of spent barley	Neo (2021)
	Yeast substrate	Beer yeast substrate made of spent brewery grains	Evans (2022)
	Snack	High-protein chip snack made of spent brewery grains	Lee (2021)
Okara	Beverage	Non-dairy probiotic drink	Lim (2021)
	Bakery	Ingredient high in dietary fiber for baking	The Straits Times (2017)
	Energy bars	Granola bars made with okara and oats	Bean My Day (2022)
	Crackers	Baked crackers made with okara and rice	ZenMarket (2021)
	Noodles		Good Food World (2022)
Bread and spent coffee waste	Beer	Ale infused with surplus bread and upcycled coffee grounds	Tan (2022)
Jackfruit seeds	Flour	Ingredient used for baking and soups	Nature Loc (2022)
Pineapple stems and peels	Supplements	Supplement rich in dietary fiber	Cheng (2022)
Green banana	Flour	Ingredient for cooking, baking, and making smoothies.	

texture, while flours made from green bananas have slow starch digestibility (Vatanasuchart et al., 2012; Kumar et al., 2019). Noodles made from jackfruit seed flour and green banana flour have received much positive response, and green banana flour has been distributed in local markets in Singapore. Pineapple stems and peels are very nutritious, with sugars and vitamins as well as dietary fiber and polyphenols, which both aid in the healthy growth of gut microbiota (Campos et al., 2020). Much research is in progress studying how to utilize these hidden food resources in functional foods and ingredients in Singapore. A challenge in revalorizing unconventional portions of fruit is coping with undesirable components, such as endogenous toxic compounds (e.g., alkaloids), chemicals from agronomy practices (e.g., pesticides), or compounds with unpleasant taste (e.g., bitterness). Fermentation and other biotechnology are helpful in removing undesirable components. Food safety and toxicology must be considered while developing products from non-conventional materials.

Singapore invests a significant effort in alternative protein production, and both microbial and plant-based protein production generate a substantial amount of carbohydrates. Protein extract from legumes (e.g., peas, chickpeas) generates a considerable portion of starch and fiber. In addition, carbohydrates generated from microbial protein production, such as β-glucans and chitin, have much potential for functional ingredient development. Technology development to extract and modify these carbohydrate-rich by-products will effectively enhance their functionality and application for local food development.

6. Conclusion

Hunger is real; hidden hunger is not negligible, and food carbohydrates are essential to both. Whether the location is on an island like Singapore or a vast territory, natural resources are not unlimited. The current agri-food system and consumption patterns are not sustainable for feeding a growing global population. Conventional local production faces many limitations, and innovative approaches outside local agri-food systems may unearth some solutions. Sustainably utilizing local resources with novel technology can build basic production infrastructure. Collaboration with local stakeholders and partnerships with global food suppliers create a greater chance of success in strengthening food resilience and nutrition security.

Author contributions

AL: conceptualization, supervision, writing–original draft, and reviewing and editing. AG-M: conceptualization and writing–original draft. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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