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# Technology innovations for food security in Singapore: A case study of future food systems for an increasingly natural resource-scarce world

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## ABSTRACT

*Background:* Food security is becoming an increasingly important global issue. Anthropogenic factors such as rapid urbanization and industrialization have strained finite resources like land and water. Therefore, against the impending threat of food security, the world can no longer rely on traditional methods to meet its needs. Instead, more creative and technologically advanced methods must be adopted to maximise diminishing natural resources. Singapore is a good case study of a small city-state that is trying to increase its own self-production of food using technology.

*Scope and approach:* This review highlights the technologies that Singapore have adopted in enhancing food security given its limitation in natural resources. These methodologies serve as a case study that can be used as a reference point in light of the increasingly finite natural resources. The review also presents the advantages of these techniques as well as challenges that need to be overcome for them to be more widely adopted.

*Key findings and conclusion:* To increase self-production of food and enhance its food security, Singapore has employed the use of technologies such as vertical farming and aquaponics in urban farming, nutrient recovery from food waste, biodegradable food packaging from durian rinds, natural preservatives, insect farming, microalgae and cultivated meat as alternative protein sources. These technologies workaround Singapore's land and natural resource constraints, which many countries around the world can adapt. However, many of them are still relatively nascent with numerous challenges, which have to be addressed before they can be widely accepted and implemented.

## 1. Introduction

According to FAO (Food and Agriculture Organization of the United Nations), IFAD (International Fund for Agricultural Development) and WFP (World Food Program), food security is defined as “a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life” (McGuire, 2015).

With the world's population projected to increase from the current 7.7 billion to 9.2 billion in 2050, food security is becoming an increasingly important global issue. Apart from the increase in population, changing consumer palate, climate change and natural resource scarcity make meeting the increased demand for food even more challenging.

Food demand estimates across 10 global economic models were compared and it was found that food demand increases by 59–98% from 2005 to 2050 (Valin et al., 2014). This is a slightly higher figure from the most recent projection from FAO of 54% from 2005 to 2007. The authors also noted that the food demand for animal calories varies even more from 61% to 144% due to differences in income, price elasticities as well as demand system specifications. Although the projections of food demand by 2050 vary greatly across different studies, the fact that we are facing an imminent increase in food demand is undeniable.

China is the world's largest food producer that accounted for 29.1% of global rice production, 20% of maize production as well as 16.9% of wheat production in 2009. In the last 50 years, China was able to increase its crop yield per unit area through the use of planting technologies such as chemical fertilizers, pest and weed control, and

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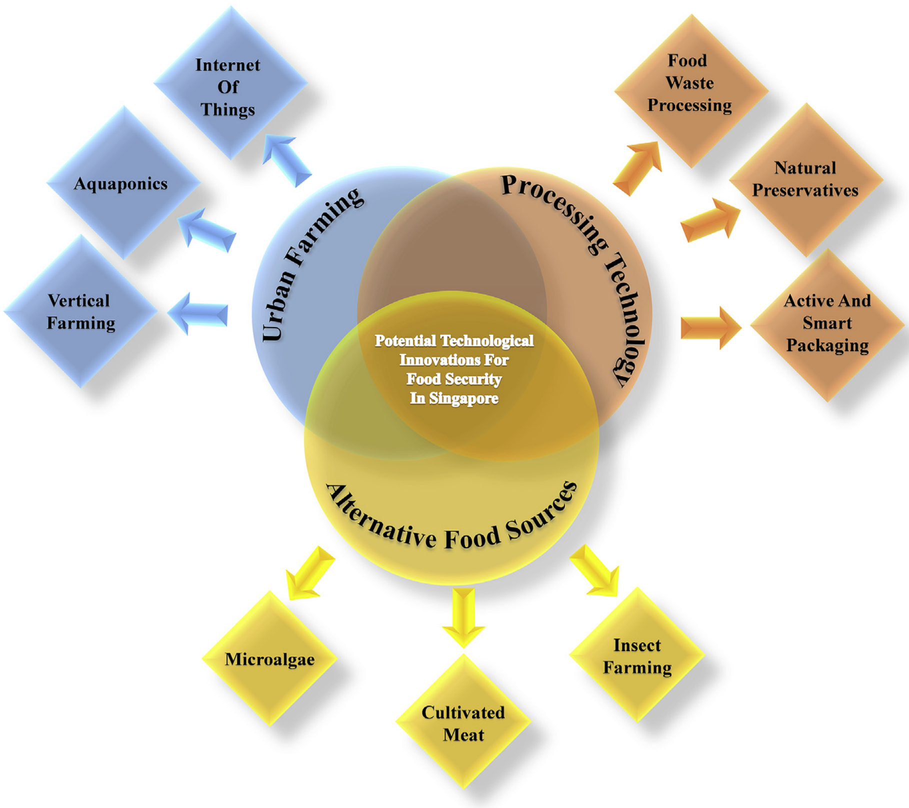


**Fig. 1.** Overview of the main areas in enhancing food security in Singapore.

irrigation (Fan et al., 2011). However, over the past 10 years, yields of rice and maize have been steadily declining due to factors such as poor soil quality, nutrient usage efficiency and water management (Dawe et al., 2000). Similarly, according to Takle et al. (2013), agriculture in USA is also facing constraints such as availability of arable land and freshwater. Another challenge faced in USA is in coping with climate change, which can directly affect crops and livestock productivity or indirectly affect income from agricultural production and food prices due to food availability. Fan et al. (2011) also noted that moving forward; it would be challenging to continue increasing crop yields through the methods mentioned previously due to decreasing arable land that can be attributed to rapid industrialization and urbanization. In this regard, a study conducted by Bren d'Amour et al. (2017) showed that urban expansion would result in a 1.8 to 2.4% loss of global croplands. In addition, usage of chemical fertilizers has to be reduced as their overuse has led to environmental pollution, which can aggravate climate issues. More recently, the Coronavirus Disease 2019 (COVID-19) pandemic also highlighted an urgent need to enhance food security. The United Nations (UN) remarked that the pandemic would “unleash a food security crisis not seen since the Great Recession” (Tiensin, Kalibata, & Cole, 2020). Therefore, against the impending threat of food security, countries can no longer rely on traditional methods such as the increase of primary production using traditional farming techniques. Instead, more creative and technologically advanced methods must be adopted to maximise diminishing natural resources. Singapore is a good case study of a small city-state with limited natural resources that is striving to increase its own self-production of food using technology.

In Singapore, rapid economic development has seen its population increased by 87% from 3.047 million to 5.7 million in 2019 (Department of Statistic Singapore, 2019). This increase has been met by a rapid decline in the amount of land allocated for agriculture. In 1965, Singapore was partially self-sufficient in food supply with farmlands occupying approximately 25% of land. However, by 2014, farmlands occupied less than 1% of the land in Singapore. Hence, Singapore is reliant on the 160 countries which it imports food from (Ludher, 2016).

According to a study titled “Environmental Impact of Key Food Items in Singapore” conducted by the Agency of Science Technology and Research (A*STAR) and Deloitte that was published in 2019, the total food consumption per capita in 2019 is approximately 365 kg compared to 363 kg in 2009. Although the overall increase was minimal, a breakdown of the food consumptions across different categories showed that consumption of vegetables, fruits, chicken, pork and eggs increased significantly while that of rice reduced drastically. This shows that the population is increasingly health conscious and eating more healthily. Therefore, the food security strategies adopted should not only focus on quantity but the quality of the food as well. Apart from the changing food demand, an estimated 763,100 tonnes of food waste was generated within Singapore in 2018. To mitigate the environmental effects of food wastage, reduction of food wastage through technological means will be required. Also, if innovations can convert such food waste into food for consumers, they will provide another food source to enhance Singapore's food security.

The key elements of Singapore's food security include availability of food from either domestic production or global market, accessibility of food by consumers, affordability, and safety as well as nutrition standards for consumers. According to the Global Food Security Index 2019, Singapore is ranked top based on the criteria of food affordability, availability, quality and safety. However, its rank would drop to 12 if climate change and natural resource risk were taken into consideration (Global Food Security Index, 2019). This is due to the fact that Singapore imports over 90% of its food supply which leaves it vulnerable to trade and supply chain disruptions that can cause food prices to increase (Ludher, 2016). The current COVID-19 pandemic perfectly reflects Singapore's vulnerability in food security with supermarkets running short of essential items and general increase in food prices.

Similarly, climate change may cause severe flooding and droughts in neighbouring countries such as Thailand and Indonesia, which can cause crop failure and in turn affect supply. According to the latest data in March 2020, Singapore imported S$2.093 billion and S$1.087 billion worth of food from Indonesia and Thailand respectively, which makes up almost 10% of its total food import when combined ("Singapore Imports of Food & Live Animals," 2020).

Therefore, technology innovations are key to enhance food security in Singapore. Such technologies may include vertical farming, aquaponics and internet-driven agriculture, technology-driven food waste management (zero waste food processing) as well as platform technology to develop alternative and unconventional food sources.

Taken together, Singapore's strategies for enhancing food security can be redefined to include 3 main areas: urban farming, processing technology and alternative food sources (Fig. 1). Urban farming encompasses vertical farming, aquaponics and internet of things while processing technology would focus on food waste valorisation, natural preservatives and smart packaging. Lastly, alternative food sources would look into the areas of insect farming, microalgae and cultivated meat. Despite limited land available for agriculture, technology-driven farming practices should provide the nation with a buffer zone to tide over sudden disruption in food supply from other countries. Processing technology should lead to less food wastage and thus reduce its impact on climate change and secure food resources, while alternative food and nutrition sources can potentially reduce reliance on food import. Table 1 provides a snapshot of the technology innovations that Singapore has adopted for food security as well as challenges and future prospective.

To the best of our knowledge, reviews that provide a broad-based view on the technologies that can be adopted across the different facets of food security are currently lacking. Most reviews are specific to one area such as agriculture, food waste or even specific crops. Therefore, the focus of this review is to highlight the technology innovations in urban farming, processing technology to reduce food wastage and spoilage, and alternative food sources that Singapore has adopted in addressing the rising challenge of food security. This would serve as a case study for the increasingly natural resource-scarce world that we are living in. This review would also address some of the challenges facing these fledging technologies that have to be solved for them to be more widely adopted.

## 2. Urban farming

Light, temperature, plant nutrition, air relative humidity and composition are important physiological and environmental factors that dictate plant quality and productivity. Over the past 50 years, urban farming had undergone significant evolution from simple covers, to greenhouses, and finally to sophisticated, environmentally controlled plant factories (Ting, Lin, & Davidson, 2016).

In March 2019, the Singapore government announced the "30 by 30" strategy which aims to increase its food production from 10% to 30% by 2030 (Paul Teng & Montesclaros, 2019). To meet this target, Singapore would have to adopt new technologies to maximise crop yields from the limited land spaces. Some of these innovations such as vertical farming have already been adopted by the nation while others such as aquaponics and AI assisted smart agriculture are in their infancy (Fig. 2).

### 2.1. Vertical farming

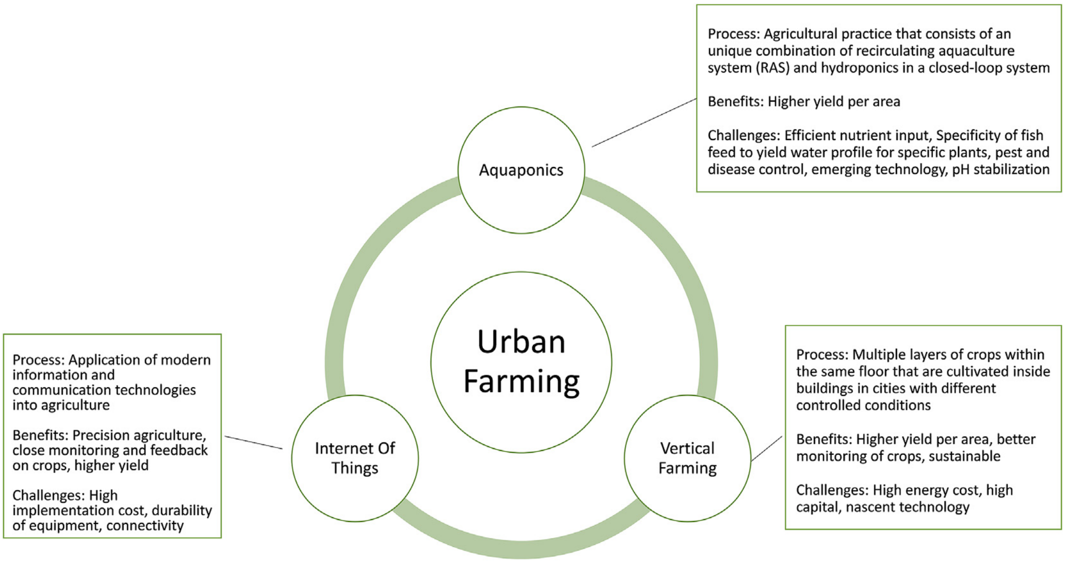
Vertical farming refers to the cultivation of vegetables, fruits and grains in vertically stacked layers inside of a building in cities and urban areas in which the conditions of different floors are controlled to grow different types of crops (Al-Chalabi, 2015). Due to its limited land space, vertical farming is especially relevant to the primary production in Singapore. The adoption of this technology is gaining traction as the number of indoor vertical farms has increased from 6 in 2016 to 26 in 2018 (Lou, 2018).

Typically, vertical farms employ a combination of recycled water, air-temperature and humidity control, solar panel lighting or controlled 24 h LED lighting to minimize seasonality and reduce cost of production. In certain cases, plants are grown under soilless conditions with nutrients fed through a solution that flow past the plant roots (Benke & Tomkins, 2017). In Singapore, different companies employed slightly different techniques in the execution of vertical farming although the general concepts are the same. For instance, Sky Green, Singapore's first commercial vertical farm utilizes the award winning "A-Go-Gro" technology for its vertical farms. Customizable modular towers are used to house the vegetables which are in turn planted on rotating racks powered by recycled water-pulley system that deploy rainwater collected from its overhead reservoirs. The rotating system helped to ensure equal distribution of sunlight, air flow and irrigation (Al-Kodmany,

**Table 1**

Summary of technology innovations and their impacts on food security in Singapore.

| Area of Innovation | Techniques | Materials | Challenges | Future Prospective |
|---|---|---|---|---|
| Urban farming | ● Vertical farming | ● Vegetables | ● Energy consumption<br>● High capital cost | ● Higher yield per unit area |
| | ● Aquaponics | ● Vegetables and Fish | ● Efficient fish waste solubilisation<br>● Pest and disease control<br>● pH stabilization | ● Sustainability and cost effective<br>● Higher yield per unit area |
| | ● IOT | ● Nanosensors<br>● Integrated control systems | ● Durability of equipment<br>● Energy consumption<br>● Connectivity<br>● Data Management | ● Better monitoring of crop growth<br>● More efficient usage of resources |
| Processing technology | ● Food waste valorisation | ● BSG<br>● Okara | ● Upscaling feasibility<br>● Cost of production | ● Reduction in food waste disposal |
| | ● Biodegradable packaging | ● Durian rinds | ● Cellulose purity | ● Reduction in plastic waste |
| | ● Natural preservatives | ● Flavonoid from yeast | ● Upscaling feasibility | ● Reduction in use of synthetic preservatives |
| | ● Smart packaging with nanotechnology | ● Chemical, gas and biosensors | ● Performance of thin film electronics | ● Increased food safety |
| Alternative food sources | ● Insect farming | ● Insects such as black soldier fly, crickets and mealworms | ● Reliance on manual labour<br>● Microbial degradation of insects | ● Alternative protein source |
| | ● Microalgae culture | ● Microalgae | ● Practical harvesting techniques | |
| | ● Cultivated meat | ● Stem cells | ● Low-cost culture media | |



Process: Agricultural practice that consists of an unique combination of recirculating aquaculture system (RAS) and hydroponics in a closed-loop system

Benefits: Higher yield per area

Challenges: Efficient nutrient input, Specificity of fish feed to yield water profile for specific plants, pest and disease control, emerging technology, pH stabilization

Process: Application of modern information and communication technologies into agriculture

Benefits: Precision agriculture, close monitoring and feedback on crops, higher yield

Challenges: High implementation cost, durability of equipment, connectivity

Process: Multiple layers of crops within the same floor that are cultivated inside buildings in cities with different controlled conditions

Benefits: Higher yield per area, better monitoring of crops, sustainable

Challenges: High energy cost, high capital, nascent technology

**Fig. 2.** Overview of the process, benefits and challenges of different technologies in urban farming utilized in Singapore.

2018). In another example, Sustenir Agriculture also uses a modular tower design with LED lightings. Nutrients are tube-fed to the vegetables while $CO_2$ is provided from the air-conditioning ducts with temperatures being controlled to be between 14 °C and 22 °C (Khew, 2016).

Although still a nascent technology, there are numerous benefits and opportunities to vertical farming that could significantly change the agricultural landscape. Firstly, due to its vertical nature, productivity per unit area of cultivated land is enhanced. It was reported that lettuce production was 13.8 times higher when grown using vertical farming compared to traditional farming (Touliatos, Dodd, & McAinsh, 2016). Similarly, the Den Bosch verti-farm was reported to be able to achieve 3 times more crop yields compared to traditional farming methods (Besthorn, 2013). On top of that, vertical farming could also produce multiple types of crops simultaneously on different levels while in traditional farming, only 1 crop can be produced at a time.

Another advantage of vertical farming is its resistance to seasonal climate changes and natural disasters. This is because in vertical farming, not only are the crops grown indoors where they are shielded from the environment as well as hazardous pests, the ideal conditions required for optimum growth such as heating, lighting, moisture content, humidity and nutrients can be controlled and customized for different crops (as per the methodologies adopted by Sky Green and Sustenir Agriculture). This would allow for multiple harvest in a year compared to traditional farming where there is typically only 1 harvest a year (Germer et al., 2011).

Another area that vertical farming can benefit the environment is the reduction in usage of fossil fuels. Traditional farming consumes huge amount of fossil fuels during transportation and storage. For instance, Besthorn (2013) stated that in America, 20% of fossil fuels are consumed for farming activities. It is well known that combustion of fossil fuels contributes greatly to global warming. It was reported that in 2015, 45% of $CO_2$ emissions came from coal burning, 35% from oil burning, and 20% originated from natural gas burning (Al-Ghussain, 2019). Since the target consumers of crops produced by vertical farming are living near the farms, there would be less requirement for long haul transportation, which would cut down fuel consumption. Transportation of crops also brings along other potential problems such as spoilage and infestation which can affect the environment due to methane emission (Williams & Wikström, 2011).

Although there are many benefits to vertical farming compared to traditional farming, there are also challenges that need to be overcome for it to be fully embraced. One of it is the energy consumption, which is closely related to carbon footprint. Since vertical farming in buildings has less access to natural light on top of the fact that there exist a light intensity gradient from the top of the building to the bottom (Touliatos et al., 2016), artificial lighting would need to be supplemented which translates into higher capital and energy cost. Al-Chalabi (2015) reported that currently, vertically grown crops have a higher energy consumption compared to conventionally grown ones. A simulation performed by Banerjee and Adenaeuer (2014) postulated that vertically produced vegetables would likely require 14 GWh of power per hectare of land per year, while according to Himanshu, Kumar, and K (2012), traditional farming only requires 1.75 GWh of power per hectare of land per year. Similarly, Kalantari, Mohd tahir, Akbari Joni, and Fatemi (2017) mentioned that if the whole agricultural industry in the US adopts a vertical approach, the energy required would be 8 times that of all the energy produced by all the power plants annually. Proper energy usage and planning would be needed for vertical farming to be fully feasible. For example, light-emitting diode (LED) is the preferred choice for vertical farming due to lower energy consumption, better reliability and brightness as well as its suitability for greenhouse agriculture (Kozai, 2016). LED lights can also be switched on and off intermittently as required for the plants based on the relationship between Photosynthetically Active Radiation (PAR) and biomass which correlates the conversion of absorbed light energy into biomass for crops (Leblon, Guerif, & Baret, 1991). Al-Chalabi (2015) also hypothesized that if the energy required for vertical farms is from renewable sources such as solar energy, the carbon footprint generated could be comparable to conventional farming methods. Furthermore, the rotating vertical rack concept pioneered by Sky Green can help to ensure even distribution of sunlight/LED light for the vegetables. Another area that requires much attention is in the implementation of automation. This could potentially lead to a decrease in contamination due to less handling from workers. It can also reduce cost of production, as less workers are required to manage the farm. Automation requires different domains of information technologies such as perception (sensing and data acquisition), reasoning and learning (mathematical and statistical methodologies), communication (delivery platforms such as wireless and local area network), task planning and execution (involving control logic, robotics and flexible automation workcells), and systems integration (providing computation resources and capabilities of system informatics, modelling and analysis). Successful implementation of automation would require more research into the different domains and how they can be integrated to achieve system optimization. It is also important to understand the appropriate levels of machine intelligence required (Ting et al., 2016). In addition, consumer acceptance of vertically produced vegetables should also be evaluated. A study conducted by Jürkenbeck, Heumann, and Spiller (2019) reported that there were 2 factors, namely sustainability and naturalness of the produce, affecting the consumer acceptability. Most of the people surveyed were not aware of what vertical farming is. Despite the lack of knowledge, many of the participants rated vertical farming systems as sustainable. Participants also weakly agreed vertical agriculture is not too artificial, which is a critical factor in their tendency to purchase.

Overall, vertical farming holds great potential in terms of meeting the food demand of our rising population, although there are still teething issues due to its technical infancy. In terms of sustainability, the vertical farming model is able to achieve enhanced ease of maintenance, improved ergonomics, automation and space efficiency. However, there are also issues that can impact sustainability such as high capital costs requirement and profitability (mainly due to high-energy requirements). The economic factors provide a significant barrier to a wider adoption of vertical farming and its sustainability. Further research and innovations would be required for vertical farming to be more widely accepted and practiced.

### 2.2. Aquaponics

Aquaponics is an agricultural method that leverages the symbiotic relationship between fish and plants in a unique combination of recirculating aquaculture system (RAS) and hydroponics in a closed-loop system (Goddek et al., 2015). In conventional hydroponics, required macro and micronutrients are supplied to the plants in a nutrient solution under soil-less conditions (Treftz, 2016). However, in an aquaponics system, fish sludge that is rich in nutrients is used for plant growth. The basic idea of aquaponics is to provide fish with feed of the right composition, ammonia from fish urine and gill excretion are then converted into nitrates via nitrification by nitroso-bacteria (convert ammonia into nitrites) and nitro-bacteria (convert nitrites to nitrates). Nitrate rich water is then channelled to the hydroponic beds where the plants would essentially act as water reprocessing units by removing nitrates from the water for growth. The “depleted” water is transferred back into the aquaculture where the cycle repeats. Hence, in aquaponics, water is recirculated around the system in a close loop (Graber & Junge, 2009).

Aquaponics presents advantages such as reduced land usage due to potential for vertical implementation, less weeds growth, less ongoing maintenance, less usage of water due to circular nature and moveable infrastructure. From an economic standpoint, it has the potential to generate more profits from two components for the producers: fish and vegetables. Also, the fish and crops produced are appealing to the consumers' demand for safe food produced in an environmentally responsible way (Blidariu & Grozea, 2011).

According to Junge, König, Villarroel, Komives, and Jijakli (2017), aquaponics only started garnering widespread attention in 2010 and can be termed an “emerging technology”, while Kotzen, Emerenciano, Moheimani, and Burnell (2019) considered it to be at the mid-stage of development. As such, worldwide adoption of aquaponics are modest at best (McHunu, Lagerwall, & Senzanje, 2019). In recent years, several companies in Singapore have started to adopt aquaponics technology. For example, according to its website, Metro Farm has successfully commercialised a full-scale aquaponics farm spanning 7000 ft$^2$ at Kranji as well as a 3000 ft$^2$ aquaponics prototype system at Punggol. In another example, Orchidville has implemented a 600 m$^2$ aquaponics farm at Sungei Tengah that can rear 8000 rosa and romaine lettuce heads as well as 8000 fish at any one time, the fresh produce and fish are subsequently served at a restaurant beside the farm (Boh, 2017). There are also 6 agrotechnology parks in Singapore spanning 1465 ha that houses modern farms that utilize advanced technologies for intensive farming practices. The country has further announced a new 18 ha Agri-Food Innovation Park at Sungei Kadut that will consolidate the high-tech farms in Singapore (Ai-Lien, 2019; SFA, 2019). Co (2019) also reported that aquaponics farms were installed on the rooftop of both Fairmont Singapore and Swissotel The Stamford. The latter is said to be able to produce up to 1200 kg of vegetables such as water spinach, different types of lettuces, numerous different mints and 350 kg of tilapias monthly for the hotel's kitchens, which is approximately 30% and 10% of the hotel's daily requirement for vegetables and fish respectively. That being said, the owner of the farm also remarked that aquaponics is difficult to sustain due to several factors such as temperature control, lack of sunlight, excessive wind and moisture of air. This is could possibly account for the relatively slow implementation of aquaponics around the world as although aquaponics is acknowledged as one of the 10 technologies that could change our lives by the European Union Parliament, there are still many challenges that need to be overcome for it to contribute significantly to food security (Junge et al., 2017).

The main challenge for commercial aquaponics is to overcome its multi-disciplinarity, since it requires expertise from environmental, civil, mechanical engineering as well as knowledge in biochemistry, biotechnology, aquatic biology, process control, economics, finance and marketing. Some of the main technical challenges are highlighted below.

Firstly, for aquaponics to be a sustainable system for food production, nutrients input have to be used efficiently with minimal discard to achieve a zero discharge recirculating system (Boxman, Nystrom, Ergas, Main, & Trotz, 2018). Insoluble materials such as fish excreta represent inefficiency in the current aquaponics system. As such, more research would be required on fish waste solubilisation, which is rich in ammonia that is critical to the aquaponics system. Vermicomposting could be a solution in mineralizing organic materials (fish excreta) thereby achieving the objective of converting all fish feeds into plant biomass (Torri & Puelles, 2010). The composition of fish feed also plays an important role in the efficacy of aquaponics since it would affect the nutritional profile of the water (Martins, Eding, & Verreth, 2011). It has been reported that aquaponics systems relying solely on fish feed to supply nutrients have low levels of phosphorous, iron, potassium, manganese and sulfur (Roosta & Hamidpour, 2011). A study conducted by Nozzi, Graber, Schmautz, Mathis, and Junge (2018) utilized 3 identical aquaponics set-up with different supplementation schemes. In general, it was found that different plants exhibited high yields under different schemes. For example, lettuce grew best when weekly supplementation of iron, potassium and phosphorus was provided, while mushroom herbs grew well without any nutrient supplementation. The goal in aquaponics is to find the perfect feed composition for specific types of fish that would yield a water profile that is as close as possible to the hydroculture requirements of specific plants. This is because, if the water lacks certain nutrients, inorganic minerals would need to be added into the system, which would translate into additional cost and affect its sustainability. Therein also lies the challenge of finding the perfect fish-plant couple where the nutrient profile provided by the fish excreta and the nutrients required by the plants overlaps significantly.

Pest and disease control is another challenging aspect of aquaponics that requires attention. By default, aquaponics systems contain more microflora compared to hydroponics due to the breeding of fish as well as the nitrifying autotrophic bacteria in the biofiltration units. Pesticides used in conventional hydroponics cannot be used in aquaponics due to their toxicity to the fish and the nitrifying bacteria (Blidariu & Grozea, 2011). At the same time, due to the need to maintain the nitrifying biofilm, antibiotics and fungicides cannot be used for fish pathogen control. Furthermore, usage of antibiotics for plant applications is not permitted. These constraints necessitate the use of innovative pest control methods such as the use of microorganisms with biological control properties or plant extracts with antimicrobial properties (Gurjar, Ali, Akhtar, & Singh, 2012). Furthermore, according to Yavuzcan Yildiz, Radosavljevic, Parisi, and Cvetkovikj (2019), one of the main concerns for food safety in aquaponics is the fear of pathogen transfer in sludge from fish to plants. However, based on previous studies, there are minimal risks present. Potential microbes in aquaponics system include bacteria, archaea, fungi, viruses and protists in different compositions. To prevent the proliferation of pathogens, disinfecting protocol such as treating water with ultraviolet light combined with ozone can be employed. There is also the potential risk of having diseased fish in the aquaponics system. To mitigate the food safety risks due to diseased fish in the system, biological control methods such as the use of filter-feeding, filtering organism, beneficial microorganisms as probiotics in fish feed or use of effective medicinal plants against pathogens can be employed.

Another important facet of aquaponics is in pH stabilization. One of the most commonly reared fish species in aquaponics is nile tilapia (Oreochromis). This species is chosen for its robustness that allows it to tolerate wide environmental conditions. However, it is important to note that nile tilapia is also a relatively low value fresh water fish which is produced cheaply through non-aquaponic culture. Nile tilapia has optimum growth performance at pH from 7.0 to 9.0 while the nitrifying bacteria have optimum pH ranging from 7.5 to 8.3. Hydroponics plants perform optimally at pH 5.8 to 6.2 (Yep & Zheng, 2019). Such discrepancies in optimum pH mean that some organism's growth would have to be compromised in favour of others depending on which is more critical. In general, most reviewers recommended a more neutral pH from 6.8 to 7.0 in favour of the nitrification process. pH of the aquaponics system tends to decrease overtime due to the acidity producing nitrification process which supersedes the increase in pH during root uptake of nitrates. The most commonly used method to maintain pH is the addition of carbonate and hydroxide to the system (Rakocy, 2012). Alternatively, some new technologies can be introduced into the field of aquaponics such as the introduction of the fluidized lime-bed reactor which involves the controlled addition of dissolved limestone into the acidic system to continuously raise its pH (Goddek et al., 2015).

Currently, aquaculture stands as the main method of fish farming. However, aquaponics has features and potential (such as its ability to go vertical) that are well suited for urban and land scarce area like Singapore as it allows for intensive production of fresh and high quality plants and fish in small spaces such as rooftops. There are evidences of several local companies taking up the challenge of implementing more aquaponics farms around the country although as highlighted, there are still numerous issues and challenges which require further research before it can live up to its potential in alleviating the problems of food security.

### 2.3. Internet of things (IOT) based smart agriculture

As the world becomes increasingly reliant on technology, internet of things (IOT) is a buzzword that is garnering more and more attention. It is estimated that IOT could potentially grow into a market worth 7.1 trillion by 2020 (Wortmann & Flüchter, 2015). The applications of IOT are broad and affect virtually all areas of life, for example the AI industry (development of intelligent product systems) and blockchain technology.

Agriculture is an industry that is beginning to adopt IOT technologies, which would enable farmers to enhance productivity and reduce wastage. Precision agriculture is one of the most promising concepts that has arisen in recent years and is expected to enhance food security in a sustainable way (Zhang, Wang, & Wang, 2002). The main aim of precision engineering is to improve and optimize agricultural processes to maximise production. It requires fast, reliable and distributed measurements to give farmers holistic and detailed overview of the situation across the cultivation area as well as coordination of different automated hardware to optimize the use of energy, water and pest control measures for optimum plant growth (Tzounis, Katsoulas, Bartzanas, & Kittas, 2017).

Recently wireless sensing technology is being used in agriculture to monitor environmental parameters such as temperature, humidity and illumination to provide optimal crop growth conditions (Srbinovska, Gavrovski, Dimcev, Krkoleva, & Borozan, 2015). For example, an IOT enabled garden system was developed whereby a controller is connected to light, temperature and soil moisture sensors together with an integrated Wi-Fi module. The system would be able to tell farmers what kind of vegetables grow best on the soil and send messages to the farmers' smart phones when in need of water and light. It also has voice-recognition capabilities as well as the ability to access specific information and make logical deductions (Ray, 2017).

With its "30 by 30" goal in sight, Singapore has started to incorporate IOT into its urban farming scene. For example, researchers from the Singapore-Massachusetts Institute of Technology (MIT) alliance for Research and Technology (SMART) have found a method of monitoring the growth of plant at a molecular level by injecting nanoparticles into the plant. These nanosensors would be able to detect minor changes in the plant ranging from temperature to growth impact by soil acidity to pest infestations and diseases. With this technology, urban farmers in Singapore would be able to detect diseases and pests before they are visible. Moreover with such real-time data available, farmers would be able to better monitor the growth of crops in terms of what is working and what is not (Teh, 2019). CrowdFarmX is a local company that is the world's first cooperative farming platform on blockchain. It aims to connect farmers to the global market as well as provide them with the technological expertises to increase their productivity. These expertises include physical shared services hubs that provide IOT monitoring systems and data analysis on climates and soil condition. Farmers are also connected to agronomists and technologists through the platform to help them develop advanced farming protocols and automate their farming practices (Shiao, 2019).

Adoption of IOT in agriculture comes with its own set of challenges. Firstly, the sensors used at the cultivation sites have to be robust enough to endure harsh environmental conditions such as solar radiation, extreme temperatures (high temperature in Singapore), rain and humidity, winds as well as vibrations. Not only should they be durable enough to function for a prolonged period, they should be able to function well under those conditions as well. Power consumption can be an issue since these IOT equipment requires power sources, which can increase the production cost of the vegetables. Therefore, appropriate programming tools and low-power capabilities are required to reduce the overall production cost. Lastly, the large number of connected sensors and devices can produce a huge amount of data which can easily overwhelm small scale server infrastructure (Atzori, Iera, & Morabito, 2010).

These new technologies can be adopted into urban agriculture such as vertical farming and aquaponics (smart urban agriculture) which could potentially increase crop yield and reduce cost of production such as energy and water usage that can help Singapore inch closer to its "30 by 30" goals as well as minimize environmental impacts.

## 3. Processing Technology

Processing technology encompasses food processing, food waste processing as well as food packaging technologies. The technologies employed across multiple facets of the processes within the food industry seek to provide abundant, safe and nutritious food for the world. Food processing involves the deliberate altering of food before it becomes available for consumption. Additionally, food processing improves nutritional profile, extends shelf life, and enhances sensory characteristics and safety of food. Many food processing techniques such as pasteurizing, pickling, canning, salting, extrusion and milling are well known while new methods like high-pressure processing, pulses electric field, cool plasma and UV irradiation are getting increasing attention. However, in recent years, technology innovations in Singapore are more focused on the areas of food waste processing and packaging technologies. Therefore, this review would focus on the aforementioned areas. Fig. 3 provides a graphical summary of the processes, challenges and benefits of each area.

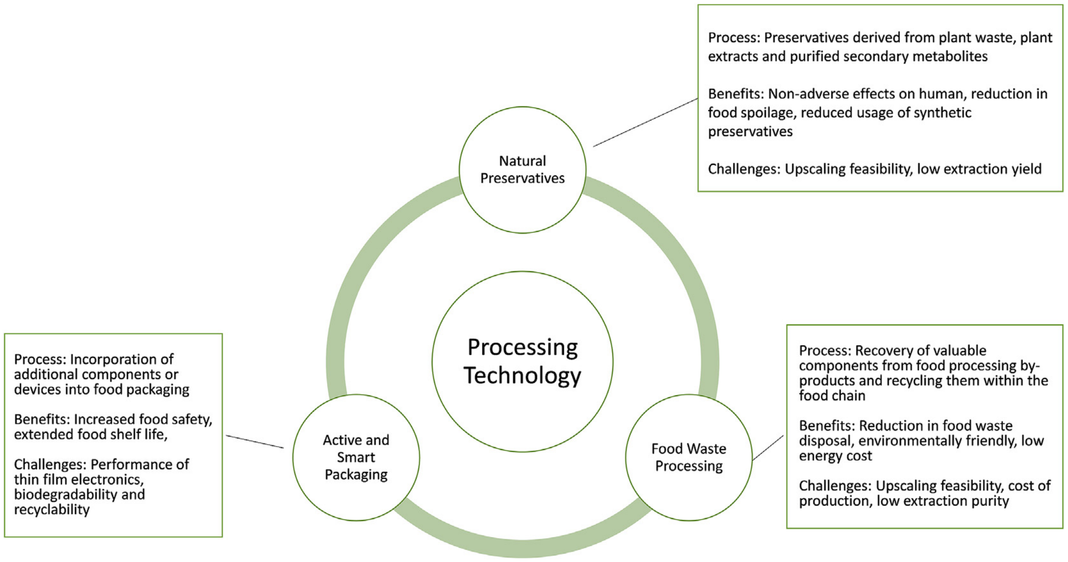


**Fig. 3.** Overview of the process, benefits and challenges of the different aspects of processing technology utilized in Singapore.

### *3.1. Food waste processing*

Food waste processing involves the recovery of valuable components from food processing by-products and recycling them within the food chain. According to FAO, approximately 1.3 billion tonnes of food produced for human consumption goes to waste annually. This staggering figure amounts to more than one-third of the total food produced worldwide. These losses would lead to wastage of resources such as water, land space, labour and capital. Typically, food wastage and losses occur due to inefficiencies in harvesting techniques as well as inadequate storage and transportation facilities (FAO, 2019).

As mentioned, in Singapore, roughly 763,100 tonnes of food waste were generated in 2018. Of these, only 17% were recycled while the rest were incinerated and disposed of in landfills (NEA, 2019). Disposal of such huge quantities of food waste would lead to undesirable effects on the environment since incineration of municipal solid waste which contains waste from biological origin emits $CO_2$ (Rabl, Spadaro, & Zoughaib, 2008). Therein lies the biggest problem that food waste contributes to: climate change. Venkat (2011) noted that avoidable food waste produces greenhouse emissions that are at least equivalent to 113 million metric tonnes of $CO_2$, which makes up 2% of the total greenhouse emissions in US alone. Similarly, Hiç, Pradhan, Rybski, and Kropp (2016) reported that greenhouse gases due to food wastage had increased by 300% between 1965 and 2010. In the context of food security, climate changes can adversely affect global primary production due to higher frequency of natural disasters, which can lead to increased crop failure in turn affecting worldwide food supply. As such, there is a need to reduce the amount of food waste disposed through the using of technology. However, it is important to note that fibrous food wastes such as okara, brewer's spent grain, bamboo shoots and vegetables still contain residue after reuse due to the presence of insoluble dietary fibre such as cellulose and lignin, which would leave a carbon footprint when disposed. Therefore, zero-waste processing technology has to be adopted in order to minimize the carbon footprint of food waste. The following section provides examples about the processing technologies that can be applied to food waste that are developed in Singapore such as the extraction of nutrients from brewer's spent grain (BSG) into a culture medium, usage of okara to create a probiotic beverage, fabricating of biodegradable food packaging using durian rinds and natural preservatives.

#### *3.1.1. Brewer's spent grain*

One of the side stream products from food processing is known at brewer's spent grain (BSG). According to Mussatto (2014), in the beer manufacturing industry, large quantities of food by-products are generated of which 85% consist of BSG. The other by-products are mainly spent hobs and surplus yeast. The annual global production of BSG is estimated to be 38.6 million tonnes. On a dry basis, BSG is made up of fibres, which consist of cellulose, arabinoxylan, lignin, and protein. Currently, the bulk of BSG generated is managed by its usage as animal feed mainly for cattle as well as other alternative uses such as fuel source in energy combustion and mushroom cultivations (Mussatto, Dragone, & Roberto, 2006). The rest is disposed of in landfills which as mentioned is an unsustainable option that can severely impact global food supply due to climate change (Buffington, 2014).

One of the challenges to valorise BSG lies in its husky physical property combined with high amount of cellulose and hemicellulose, which can bind onto proteins and other nutrients thereby making extraction difficult. Physical, biological, chemical pre-treatment or a combined treatment method can be employed to better harness the nutrients in BSG. Physical pre-treatment or sometimes a combination of physical and thermal pre-treatment are mainly used to reduce the size and deform the crystalline cellulose structure of BSG through extrusion, milling, grinding, microwave radiation and ultrasound (Buffington, 2014; Lynch, Steffen, & Arendt, 2016). The size reduction would increase the surface area of BSG, which would better allow enzyme or acid entry into the lignocelluloses. Chemical methods include steam explosion, ammonia fibre explosion, sulfur dioxide explosion as well as the addition of lime and acid (Ivanova et al., 2017). However, the main disadvantage of chemical methods is the formation of toxic compounds. Biological treatment involves the use of commercial enzymes or microorganisms. One advantage of enzymatic treatment is that its use does not generate toxic compounds (Sindhu, Binod, & Pandey, 2016). In a study by Niemi, Martins, Buchert, and Faulds (2013), it was reported that pre-treating milled BSG with a carbohydrase mix from *Humicola insolens* considerably improve the subsequent protein solubilisation in the residual biomass. However, it should be noted that in general, the main disadvantage of using commercial enzymes in pre-treatment is its high cost especially in large scale processing.

A lower cost option to utilize BSG through biological means is the use of fermentation using microorganisms. Employing the right strains of microorganisms that produce enzymes such as cellulases, proteases and lipases would achieve similar effects to commercial enzymes at a fraction of the cost. In Singapore, various research institutions and local companies have been exploring the valorisation of BSG across various applications. For instance, Cooray, Lee, and Chen (2017) reported that fermentation of BSG by *Rhizopus oligosporus* was able to enhance its nutritional content which can be extracted into a liquid phase to produce a novel culture media for *Rhodosporidium toruloides* and *Saccharomyces cerevisiae.* The media derived from BSG was found to be competitive to commercial media in terms of supporting yeast growth. Tan, Mok, Lee, Kim, and Chen (2019) proposed the use of fermented BSG as a food ingredient after solid-state microbial fermentation with *Bacillus subtilis.* It was found that the process increases the various amino acids, fatty acids, total phenolic content as well as antioxidant activity. In another example, food wastes such as BSG and okara were used as feed for microalgae culture as an alternate source of protein. Microalgae-based proteins have lower land requirement compared to other sources of proteins. For example, microalgae requires less than 2.5 $m^2$ per kg of protein compared to 47–64 $m^2$ per kg for pork, 42–52 $m^2$ for chicken and 144–258 $m^2$ for beef (Caporgno & Mathys, 2018). UglyGood, a local company is also exploring the use of BSG to produce bio-based cleaning products such as floor cleaners and multi-purpose solutions (Chiang, 2019).

Overall, biological treatment methods are more environmentally friendly compared to chemical methods as they do not generate toxic compounds and produce fewer inhibitors as a result of milder processing conditions on top of its lower energy requirement compared to physical methods.

### 3.1.2. Okara

Another food processing side stream product is the soybean residue, known as okara. It is the pulp left behind from soybean after soymilk and soybean curd processing. Global production of okara is estimated to be around 14 million tonnes every year with 10,000 tonnes being produced in Singapore annually (Li, Qiao, & Lu, 2012). Dry okara contains about 50% fibre, 25% protein, 10% lipids as well as other soy components such as isoflavones, phytosterols, lignans, saponins, coumestans, and phytates (Li et al., 2012). Similar to BSG, numerous methods such as chemical or enzymatic treatment, microorganism fermentation, high pressure and micronization treatments had been employed to valorise okara (Li et al., 2012).

The most cost effective method to valorise okara is the use of microbial fermentation. This technique is able to convert insoluble fibres into soluble fibres, which would aid in the extraction of nutrients. For instance, fermentation of okara using *Lactobacillus* was shown to increase the amount of soluble fibres by 15%. This fermentation process provided an acidic environment in which the glycosidic linkages of the polysaccharides were broken down and hence insoluble fibres are converted into soluble fibres. Other nutritional contents such as isoflavones, crude protein and water soluble substances were also enhanced (Tu et al., 2007).

In recent years, okara has been the subject of much interest in Singapore. For example, Vong and Liu (2019) used a combination of different biocatalyst in the fermentation of okara to create a novel probiotic beverage. Firstly, carbohydrase was added to convert the insoluble fibres into soluble fibres. The okara hydrolysate was then fermented with *Lactobacillus paracasei* and *Lindnera saturnus* to increase its free amino acids, isoflavone aglycones and fruity esters content. The probiotics were also able to remain viable when stored at 5 °C for 6 weeks. Mok, Tan, Lee, Kim, and Chen (2019) employed the use of *Bacillus subtilis* which is known to produce several enzymes such as cellulases, proteases and lipases in solid-state fermentation of okara to increase its nutritional value. It was found that amino acids, fatty acids as well as antioxidant activity were enhanced after fermentation. In another work, Kim (2019) developed a nutrient-rich culture medium using okara as substrate for the growth of *Phaeodactylum tricornutum*, a microalgae strain. The author reported that the biomass obtained in the okara culture medium is twice the amount obtained when using commercial culture medium.

### 3.1.3. Biodegradable food packaging

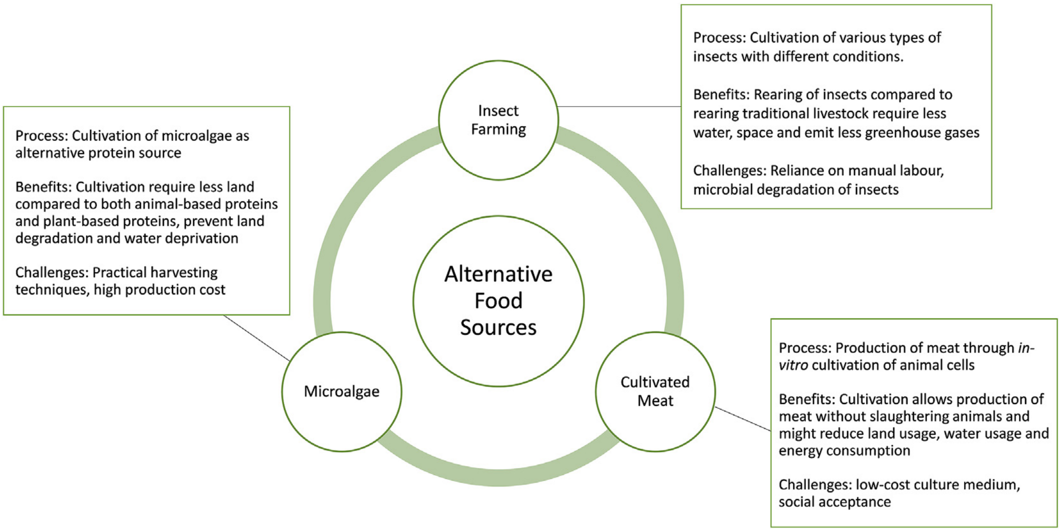
As mentioned previously, although valorisation of food waste can be a good way to extract valuable compounds, the residues left behind still create carbon footprints. One strategy to mitigate this is the development of biodegradable food packaging through the extraction of compostable, biodegradable polymers such as fibres, starch, cellulose and lignin from plant based food waste (Zhao, Lyu, Lee, Cui, & Chen, 2019). Not only would this minimize food waste disposal, it would also alleviate the global problem of plastic waste disposal, which are getting widespread attention.

Durian is a common fruit consumed in Southeast Asia countries and there is a huge amount of durian rinds disposed annually with up to 6 million of them consumed in Singapore alone annually (Khoe, 2018). Durian rinds, which are generally disposed, are rich in components such as hemicellulose, cellulose, lignin and phenolic compounds, which can serve as low-cost resources that can be used to produce biodegradable food packaging. On a dry basis, durian rind was reported to contain 31–36% cellulose, 10–11% lignin and 15–19% hemicellulose. A study in Singapore successfully extracted cellulose of high purity from durian rinds and utilized the cellulose to produce food packaging films (Zhao et al., 2019). Durian-rind cellulose film was reported to have high tensile strength, high rigidity, and smooth surface, excellent transparency and is also 100% biodegradable. Despite the advantages of converting durian-rinds into films, a more thorough evaluation would be required to determine if it would actually prevent the deterioration of food quality. Furthermore, food migration tests would have to be conducted to ensure that no chemicals are migrated to the food. Similarly, a technology firm in Singapore recently developed fully biodegradable drinking straws from the bacterial fermentation of plant-based oils and sugars. Apart from biodegradable straws, the biopolymers can also be used to fabricate cutlery, cup lids as well as food packaging (Liu, 2019).

## 3.2. Natural preservatives

Apart from ensuring the abundance of food, food security also entails the provision of safe food for the population. The use of preservatives is one of the most common methods to prevent spoilage of food. Currently, most of the preservatives used in the food industry are synthetic such as benzoates, sorbates and nitrates. However, synthetic food preservatives were reported to have adverse effects on human health such as allergy reactions, headaches and even cancer (Bondi, Laukov, de Niederhausern, Messi, & Papadopoulou, 2017; Ng, Lyu, Mark, & Chen, 2019). On the other hand, natural preservatives, which can be derived from plant extracts, food waste, purified secondary metabolites, are perceived as better and safer compared to synthetic food preservatives (Erginkaya & Konuray, 2017; Ng et al., 2019). In a study conducted using a genetically engineered strain *Saccharomyces cerevisiae* Y26 that produces naringenin, Ng et al. (2019) was able to obtain antimicrobial phenolic metabolites that exhibited strong antimicrobial properties which can be used as natural food preservatives. Cherries and blackcurrants were also found to be able to produce natural preservatives. Nowak, Czyzowska, Efenberger, and Krala (2016) reported that 2 distinct groups of polyphenols present in blackcurrants and cherries were identified as phenolic acids and flavonoids that include epigallocatechin and glycosides of quercetin as well as kaempferol. Other sources of natural preservatives from plant extracts include blueberry, garlic and mustard (Erginkaya & Konuray, 2017).

In summary, the various types of food waste generated in different processes had been explored widely to be reused in nutrient recovery through several methods. Food waste has also been used to create biodegradable food packaging which can reduce global plastic waste. In addition, development of natural preservatives would potentially help to extend shelf life of food and contribute to improving food security.



Process: Cultivation of various types of insects with different conditions.

Benefits: Rearing of insects compared to rearing traditional livestock require less water, space and emit less greenhouse gases

Challenges: Reliance on manual labour, microbial degradation of insects

Process: Cultivation of microalgae as alternative protein source

Benefits: Cultivation require less land compared to both animal-based proteins and plant-based proteins, prevent land degradation and water deprivation

Challenges: Practical harvesting techniques, high production cost

Process: Production of meat through *in-vitro* cultivation of animal cells

Benefits: Cultivation allows production of meat without slaughtering animals and might reduce land usage, water usage and energy consumption

Challenges: low-cost culture medium, social acceptance

**Fig. 4.** Overview of the process, benefits and challenges of different alternative food sources explored in Singapore*
Colours should be used for Figs. 1, Fig. 2, Figs. 3 and 4. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

### *3.3. Active and smart packaging*

As the population becomes increasingly affluent and well informed, there is a growing concern for better food safety, which drives the need for innovations in food packaging. With new technologies in food packaging, not only would there be safer food, there would also be a reduction in food spoilage thereby improving food security. Active packaging incorporates additional components into the packaging to provide safer food by maintaining or extending the food quality and shelf life (Biji, Ravishankar, Mohan, & Srinivasa Gopal, 2015). The techniques employed in active packaging include control of moisture, oxidation, microbial growth, ethylene removal and odour absorption (Ghoshal, 2018). For example, A*STAR in Singapore created a polymeric packaging material based on nanotechnology. By introducing silicate from natural sources into the gaps between the polymers, the oxygen barrier of food packaging can be enhanced which would prevent premature food spoilage. Oxygen-scavenging nanofillers can also be added into the packaging to remove remnant oxygen inside the packaging which can enhance shelf life (Neo, 2019).

Smart packaging is another technology in food packaging that has a different working principle compared to active packaging. According to Ghoshal (2018), smart packaging can be classified into simple smart packaging, interactive or responsive smart packaging. These packaging have devices such as sensors and indicators to judge the internal and external environment of package, identify the changes on food condition, as well as inform these changes to consumers. In addition to the common components, interactive smart packaging also contains response mechanisms that can neutralize hazardous changes occurring in the food.

### *3.4. Challenges in processing technology*

Most of the technologies highlighted are relatively new and generally performed at lab scale. Therefore, one of the main challenges is to scale up these processes. For example, with respect to food waste valorisation, BSG and okara are usually fermented under solid-state condition. At industrial scale, this would result in non-uniform fermentation due to the temperature gradient effect within the solid substrate. One way of mitigating this is the use of tray bioreactors where substrates are laid out onto each tray thinly which would minimize the effects of temperature gradient (Durand, 2003). However, such setups are space consuming which is unsuitable for countries like Singapore where spaces are at a premium.

Another important challenge concerning biodegradable food packaging is to obtain cellulose of high purity from the substrates. It is difficult to attain cellulose of high purity due to its conjunction with lignin and hemicellulose in the substrate. Zhao et al. (2019) suggested a 2-step purification process using sodium chlorite and hydrogen peroxide to remove lignin and hemicellulose. Using this method, cellulose of purity up to 90.4% was obtained. However, since the main application of cellulose extracted from food waste is for food packaging, the effects of chemicals added during the extraction process on the human body have to be investigated.

Active and smart packaging comes with its own set of challenges as well. According to Schaefer and Cheung (2018), smart packaging requires further development in terms of improving the performance of thin film electronics as well as its integration into food packaging. Most of the development on biosensors are limited to preliminary proof of concepts studies and require further works for practical implementation. More work would be required on the biodegradability and recyclability of the sensors and communication functionalities as the implementation of smart packaging will still generate waste (Schaefer & Cheung, 2018). For active packaging, more research work would be required in the development of active compounds to be incorporated into packaging.

## 4. Alternative food sources

As mentioned, with the rising population becoming increasingly affluent and educated, there is a need to produce not only more food, but also food of healthier origin. Therefore, moving forward, it is important to cater to the changing dietary preferences of the population by using ingredients that are more natural. It is also important to develop alternative food and nutrition sources such as insect proteins, microalgae and cultivated meat (Fig. 4) to add on to existing food supply. Insect farming may also be used to provide supplementary feed to livestock, which can indirectly impact food security. According to Hartmann and Siegrist (2017), animal protein production requires high amount of agricultural land, water and energy which would only increase as the global population and demand for food increase. Currently, meat production is estimated to be approximately 200 million tonnes which is slated to potentially increase to 470 million tonnes by 2050 (Liguori et al., 2015). The increase in animal protein production to meet the increasing demand would deplete resources rapidly and adversely affect the environment in the long run.

### 4.1. Insect farming

Due to the huge demand in natural resources (land and water) required to grow livestock for protein, interest in insects as an alternative protein source has been increasing. Insects were found to be highly nutritious in terms of essential amino acids, vitamins, mineral, fats and have been consumed by humans since ancient times (Hartmann & Siegrist, 2017; B. A.; Rumpold & Schluter, 2013). A study reported that the quality of insect as a protein source was comparable to soy protein (Vangsoe, Thogersen, Bertram, Heckmann, & Hansen, 2018). This will allow insects to be a potential solution to the issue of providing sufficient food for the populations.

There are a total of approximately 2000 edible insect species reported, which were consumed in eggs, larvae, pupae, nymphs or some in adult forms (Anankware, Fening, Osekre, & Obeng-Ofori, 2015; Dobermann, Swift, & Field, 2017). Insects can be obtained by harvesting from the nature or from insect farming (Dobermann et al., 2017). The more commonly consumed insects in the world are beetles, caterpillars, bees, wasps, ants, grasshoppers, locust, crickets, cicadas, leafhoppers, plant hoppers, scale insects, true bugs, termites and dragonflies (Van Huis et al., 2013). 31% of the total insect consumption globally was reported to be the consumption of beetles (Van Huis et al., 2013).

According to Anankware et al. (2015), apart from direct consumption of edible insects in the wild, insect farming can potentially serve as an alternative source of protein to traditional livestock. The cultivation of insects as protein source would have several advantages over traditional livestock. For instance, less $CO_2$, $CH_4$, $N_2O$, and $NH_3$ emissions were found from rearing insects compared to conventional livestock due to the insects' respiration, metabolism and their faeces (Van Huis & Oonincx, 2017). In terms of land usage, the production of mealworms only required about 10% of the land used compared to that of beef (Oonincx & de Boer, 2012). Similarly, mealworm production requires approximately 5 times less water compared to beef production (Van Huis & Oonincx, 2017). In comparison to chicken production, mealworms require approximately 2–3 times less land and almost half the water footprint per gram of protein (Miglietta, De Leo, Ruberti, & Massari, 2015; Oonincx & de Boer, 2012).

Singapore has also taken its first step into the use of insects as alternative protein source. Insect farming in Singapore is still an emerging technology that requires further large-scale development. Asia Insect Farm Solutions is a local start-up that attempts to transform crickets into a nutritious flour-like product that can be used to replace conventional flour (Paulo & Ong, 2020). Crickets were chosen for several reasons. Firstly, they have lower carbon footprint compared to traditional livestock. They also require less water and land space compared to chicken. Crickets are also more efficient in converting feed into muscle mass due to them being poikilothermic, which means that they do not need to use energy from the feed to maintain their body temperature (Van Huis & Oonincx, 2017).

Apart from serving as alternate protein source, insects can also help to combat food wastage by converting them into other products. Insectta is a local black soldier fly farm established in 2018. Currently, approximately 500 kg of food waste from food suppliers, homes and food stalls are consumed and converted into plant fertilizers as well as fish and animal feed by 100 kg of black soldier fly larvae. St-Hilaire et al. (2007) reported that black soldier fly could replace up to 50% of fishmeal used to produce rainbow trout. Similarly, the fertilizers produced can be combined with a hydroponics system in a closed-loop to grow crops such as kale, lettuce and other vegetables (Boh, 2018). The conversion of food waste into animal feed and fertilizers could be a potentially effective method to reduce food wastage since the larvae are able to eat up to 4 times their body weight. As this technique is relatively new in Singapore, the output is currently not at a significant scale. However, according to Surendra, Olivier, Tomberlin, Jha, and Khanal (2016), approximately 100,000 tonnes of food waste can be converted into 10,000 tonnes of animal feed based on a reported feed conversion ratio for black soldier fly larvae of approximately 10–15. As mentioned, reduction in food wastage can help to alleviate climate issues, which can affect primary production.

Although insect farming is a potentially viable choice to reduce food wastage, it has issues based on the optimization of farming techniques (Dobermann et al., 2017). The majority of insect farming is reliant on manual labour to feed, collect, clean and rehouse. The usage of manual labour instead of automation is costly and would lead to higher insect protein prices (Birgit A. Rumpold & Schlüter, 2013). Therefore, in order to reduce production costs, automation technologies have to be developed. Such technologies include monitoring devices, mechanical removal systems of dead or diseased insects, continuous rearing systems, harvesting devices, sanitation procedures for management of diseased and processing units for separation of proteins (Birgit A. Rumpold & Schlüter, 2013). Other means of cost reduction will include the development of cheap rearing substrates as well as innovations in production technologies incorporating cost-effective production systems. Another challenge in the execution of insect farming is the presence of potentially harmful ingredients or the microbial degradation of insects, which could present significant health risks for humans. Insects are vulnerable to microbiological hazards in the absence of proper heat treatment or storage facilities (Klunder, Wolkers-Rooijackers, Korpela, & Nout, 2012). To reduce the microbial contamination of insects, processes such as powdering of the insects, heating, drying, UV treating, acidifying, pasteurizing can be incorporated (Y. S. Wang & Shelomi, 2017).

### 4.2. Microalgae

Another interesting alternative protein source is microalgae. In fact, microalgae have been explored as food and proposed as possible alternative protein sources since the 1950s (Vigani et al., 2015). Microalgae are mainly autotrophic organisms found in marine and freshwater but some species have been found to be heterotrophic (Chacón-Lee & González-Mariño, 2010; Pleissner, Lam, Sun, & Lin, 2013). It is abundant in several nutrients such as essential amino acids, fatty acids, carotenoids, fibres, B vitamins, iron and calcium (Hayes et al., 2017; Vigani et al., 2015). It was also reported to possess antioxidant, antidiabetic, antiallergenic as well as anti-inflammatory properties (Hayes et al., 2017). The cultivation of microalgae-based proteins requires less land compared to both animal-based proteins and plant-based proteins (Caporgno & Mathys, 2018). It also contributes to the environment by preventing land degradation and water deprivation.

An interesting study by Pleissner et al. (2013) found that food waste hydrolysate can be used as culture medium in heterotrophic microalgae cultivation. A medium rich in nutrients through fungal hydrolysis of food waste was determined to be viable in the cultivation two heterotrophic microalgae species, *Schizochytrium mangrovei* and *Chlorella pyrenoidosa*. Kitchen wastewater was also reported to possibly serve as a nutrient source for cultivation of *Phaeodactylum strain E70* (X. Wang et al., 2020).

Microalgae products in the market come in form of dried algae, which are sold directly and used as sources of proteins and carbohydrates (Ruiz et al., 2016). Other high value compounds such as antioxidants, proteins, fatty acids and docosahexanoic acid (DHA) can also be extracted from microalgae (Borowitzka, 2013). The more commonly consumed microalgae species are the *Chlorella*, *Spirulina, Dunaliella, Haematococcus,* and *Schizochytrium*, which are certified as Generally Recognized as Safe (GRAS) (Hayes et al., 2017; Vigani et al., 2015).

There are also recent developments in the microalgae scene in Singapore. It was reported that researchers were able to utilize the nutrients in a culture medium derived from okara to grow microalgae that can produce up to 3 times the yield when compared to commercial medium at a tenth of the cost. Most interestingly, the microalgae were able to grow in the absence of sunlight which is ideal for urban cities like Singapore as it allows for indoor farming (Zhuo, 2019). Such microalgae species can be cultivated in a dark environment as they utilize the organic carbon, such as glucose, that are available in the culture medium in the absence of sunlight (Yen, Hu, Chen, & Chang, 2014). Moreover, these microalgae are able to produce proteins, vitamins and minerals which many photosynthetic strains and plants are unable to (Zhuo, 2019). In another development, local start-up, Sophie's Bionutrients won the annual Liveability Challenge in 2019 for its technology in producing food grade microalgae as alternate protein source. The company is now actively developing the technology for commercialization (Liu, 2019).

The main challenge in large scale culturing of microalgae is in finding a low-cost, high-efficiency harvesting technique. This is due to a myriad of reasons such as the size of microalgae cells, small density differential between cells and culture medium which makes separation difficult, low cell concentration, high ionic strength in salt and brackish water as well as the need to manage large volume of culture medium (Chacón-Lee & González-Mariño, 2010). Currently, no single harvesting method that is suitable for every scenario. As such, there is much work ahead in terms of innovating and optimizing the systems to achieve higher productivity and cost effectiveness when harvesting the microalgae. However, Caporgno and Mathys (2018) noted that from an economic standpoint, the lack of optimization in microalgae based protein production compared to traditional protein sources hinders its ability to attract investors to fund further developments. Nevertheless, despite the challenges, microalgae hold much economic attraction as the products that can be extracted such as β-carotene, astaxanthin and phycocyanin can fetch hundreds to thousands of euro per kg depending on purity.

### 4.3. *Cultivated meat*

Cultivated meat refers to the production of meat through *in-vitro* cultivation of animal cells, rather than slaughtering of animals. In general, a biopsy is first taken from a live animal. Stem cells are then obtained by cutting the muscles. These stem cells have the ability to not only proliferate, but can also transform themselves into other types of cells such as muscle and fat cells. The stem cells are grown in culture medium, typically containing fetal bovine serum (FBS). As the cells proliferate, they would form myotubes which can then grow into muscle tissues (Chriki & Hocquette, 2020).

Although still a nascent technology, cultivated meat, if successfully implemented, could be a potential environmentally sustainable protein source to satisfy the growing global demand for meat products (Verbeke et al., 2015). Based on a study by Post (2012), cultivated meat production can potentially reduce land usage, water usage and energy consumption by 99%, 90% and 40% respectively. In this regard, Singapore has also explored the potential of cultivated meat. Shiok Meats, a start-up in Singapore, is Southeast Asia's first cultivated meat company that focuses on crustaceans. The company was able to produce minced meat of shrimp using its stem cells and turn them into shrimp dumplings (Lawton, 2020). A*STAR's Bioprocessing Technology Institute (BFI) has also began trials on culturing meat using existing technology in stem cells bioengineering and bioproduction (Begum, 2019).

Although cultivated meat holds much potential in enhancing food security, there is still a major roadblock that needs to be overcome for it to be economically viable. Current methods of culturing stem cells utilize commercial culture medium such as L-15 and M-199 with supplementation of FBS. These media are prohibitively expensive and would greatly impede commercialization of cultivated meat. Despite decades of research into finding a low-cost, well-defined growth medium for expansion of stems cells, none have been identified till date (Thorrez & Vandenburgh, 2019). Another challenge in cultivated meat is in the difficulty in producing real muscles, which comprise of organized fibres, blood vessels, nerves, connective tissues and fat cells. The production of a thick piece of meat would be difficult due to the need to perfuse oxygen inside the meat to mimic the diffusion of oxygen in real tissues (Chriki & Hocquette, 2020). Apart from the technological challenges, cultivated meat also has social acceptance challenges. Cultivated meat can have associations with cloning, transgenesis and other unknown risks (Bhat & Fayaz, 2011). Also, some common objections to cultivated meats include unnaturalness, safety, inferior taste and texture (Bryant & Barnett, 2018).

All things considered, cultivated meat presents a promising look into a potential future where animal proteins are replaced or supplemented by lab-grown alternatives. However, it is important to note that this technology is extremely recent and the main challenge of finding a low-cost but yet effective culture medium has to be solved to achieve commercial viability.

## 5. Conclusion

As we march towards 2050, natural resources are going to become increasingly precious commodities. With the rise in global population and urbanization, there would be decreasing amount of natural resources such as land for food production using traditional methods. For instance, India is slated to become one of the most land-scarce countries around the world by 2050 due to rapid urbanization (Shukla, 2017). Therefore, there is an urgent need for technological innovations in the context of food security that maximizes the diminishing land and natural resources around the world to produce sufficient, safe and nutritious food for the population. Singapore, with its lack of land space and natural resources, is a good example on how to achieve the balance between resources and food supply.

As mentioned, Singapore is extremely reliant on other countries to meet its food requirement (imports more than 90% of its food supply) which makes it susceptible to supply chain issues that can cause price fluctuations. As such, Singapore has to make use of technology innovations to better insulate itself against food security problems. The "30 by 30" goal prescribed by SFA is the perfect launching pad for the adoption of technologies in the 3 main areas of food security in Singapore.

There is increasing number of vertical and roof tops farms, which are ideal for land scarce countries like Singapore since the yield per area is higher than traditional agriculture. Aquaponics is another emerging technology that has started to gain traction in Singapore such as the rooftop aquaponics farm at Swissotel The Stamford. Numerous researches are also being done to address the large amount of food waste in Singapore. Some examples include the use of BSG to obtain a culture medium for yeast growth, utilizing okara as food ingredients and probiotic beverages, and the use of durian rinds to produce biodegradable food packaging. Natural preservatives from genetically modified yeasts were developed to enhance the safety and shelf life of food. Companies in Singapore are also looking into alternative protein sources such as insect farming, cultivated meat and microalgae, which could potentially alleviate pressure on livestock.

Although Singapore has taken steps to combat the issue of food security, many of these technologies are still relatively new and there are challenges ahead that require solving before they will be more widely used. Lackadaisical approach to innovating new solutions in these key areas would potentially put more pressure on food systems. The most pressing issue is the need to upscale the many innovations within the areas of urban farming, processing technology and alternative food sources in an economically and environmentally sustainable way. Other areas to be further examined include cost analysis and optimization for the respective areas. Methodologies to increase product yield and the acceptance level of companies and consumers in adapting into these new innovations should also be evaluated.

It is also important to note that there are many other different methods that Singapore is looking into to meet its “30 by 30” objectives. Such methods can include plant-based protein, food safety technology and intensive aquaculture. Nevertheless, this review strives to provide a broad overview on the more emerging technologies that could potentially have more upside in meeting the increased food demand.

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## Declaration of competing interest

The authors declare that there is no conflict of interest.

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## References

Ai-Lien, C. (2019). *Singapore opening up land and opportunities for agri-tech ventures.* The Straits Times. Retrieved from https://www.straitstimes.com/singapore/spore-opening-up-land-and-opportunities-for-agri-tech-ventures.

Al-Chalabi, M. (2015). Vertical farming: Skyscraper sustainability? *Sustainable Cities and Society, 18*, 74–77. https://doi.org/10.1016/j.scs.2015.06.003.

Al-Ghussain, L. (2019). Global warming: Review on driving forces and mitigation. *Environmental Progress & Sustainable Energy, 38*(1), 13–21. https://doi.org/10.1002/ep.13041.

Al-Kodmany, K. (2018). The vertical farm: A review of developments and implications for the vertical city. *Buildings, 8*(2), 24.

Anankware, P., Fening, K. O., Osekre, E., & Obeng-Ofori, D. (2015). Insects as food and feed: A review. *International Journal of Agriculture: Research and Review, 3*(1), 143–151.

Atzori, L., Iera, A., & Morabito, G. (2010). The internet of things: A survey. *Computer Networks, 54*(15), 2787–2805. https://doi.org/10.1016/j.comnet.2010.05.010.

Banerjee, C., & Adenaeuer, L. (2014). Up, up and away!. *The Economics of Vertical Farming, 2*(1), 21. https://doi.org/10.5296/jas.v2i1.4526.

Begum, S. (2019, 28/03/2019). *Beefing up efforts to grow meat in labs. The straits times.* Retrieved from https://www.straitstimes.com/singapore/beefing-up-efforts-to-grow-meat-in-labs.

Benke, K., & Tomkins, B. (2017). Future food-production systems: Vertical farming and controlled-environment agriculture. *Sustainability: Science, Practice and Policy, 13*(1), 13–26. https://doi.org/10.1080/15487733.2017.1394054.

Besthorn, F. H. (2013). Vertical farming: Social work and sustainable urban agriculture in an age of global food crises. *Australian Social Work, 66*(2), 187–203. https://doi.org/10.1080/0312407X.2012.716448.

Bhat, Z. F., & Fayaz, H. (2011). Prospectus of cultured meat—advancing meat alternatives. *Journal of Food Science & Technology, 48*(2), 125–140. https://doi.org/10.1007/s13197-010-0198-7.

Biji, K. B., Ravishankar, C. N., Mohan, C. O., & Srinivasa Gopal, T. K. (2015). Smart packaging systems for food applications: A review. *Journal of Food Science & Technology, 52*(10), 6125–6135. https://doi.org/10.1007/s13197-015-1766-7.

Blidariu, F., & Grozea, A. (2011). Increasing the economical efficiency and sustainability of indoor fish farming by means of aquaponics-review. *Scientific Papers: Animal Science and Biotechnologies, 44*(2).

Boh, S. (2017). *A vegetable, fish farming system that is truly green. The Straits Times*. Retrieved from https://www.straitstimes.com/singapore/a-vegetable-fish-farming-system-that-is-truly-green.

Boh, S. (2018). *Using insect army to fight food waste. The Straits Times.* 16/03/2019 https://www.straitstimes.com/singapore/using-insect-army-to-fight-food-waste.

Bondi, M., Laukov, A., de Niederhausern, S., Messi, P., & Papadopoulou, C. (2017). Natural preservatives to improve food quality and safety. *Journal of Food Quality, 2017*, 3. https://doi.org/10.1155/2017/1090932.

Borowitzka, M. A. (2013). High-value products from microalgae—their development and commercialisation. *Journal of Applied Phycology, 25*(3), 743–756. https://doi.org/10.1007/s10811-013-9983-9.

Boxman, S. E., Nystrom, M., Ergas, S. J., Main, K. L., & Trotz, M. A. (2018). Evaluation of water treatment capacity, nutrient cycling, and biomass production in a marine aquaponic system. *Ecological Engineering, 120*, 299–310. https://doi.org/10.1016/j.ecoleng.2018.06.003.

Bren d'Amour, C., Reitsma, F., Baiocchi, G., Barthel, S., Güneralp, B., Erb, K.-H., … Seto, K. C. (2017). Future urban land expansion and implications for global croplands. *Proceedings of the National Academy of Sciences, 114*(34), 8939. https://doi.org/10.1073/pnas.1606036114.

Bryant, C., & Barnett, J. (2018). Consumer acceptance of cultured meat: A systematic review. *Meat Science, 143*, 8–17. https://doi.org/10.1016/j.meatsci.2018.04.008.

Buffington, J. (2014). The economic potential of brewer's spent grain (BSG) as a biomass feedstock. *Advances in Chemical Engineering and Science, 4*(3), 308–318. https://doi.org/10.4236/aces.2014.43034.

Caporgno, M. P., & Mathys, A. (2018). Trends in microalgae incorporation into innovative food products with potential health benefits. *Front Nutr, 5*, 58. https://doi.org/10.3389/fnut.2018.00058.

Chacón-Lee, T. L., & González-Mariño, G. E. (2010). Microalgae for “healthy” foods—possibilities and challenges. *Comprehensive Reviews in Food Science and Food Safety, 9*(6), 655–675. https://doi.org/10.1111/j.1541-4337.2010.00132.x.

Chiang, T. S. (2019). *The eco-preneurs. The Business times.* Retrieved from https://www.businesstimes.com.sg/lifestyle/feature/the-eco-preneurs.

Chriki, S., & Hocquette, J.-F. (2020). The myth of cultured meat: A review. *Front Nutr, 7*(7), https://doi.org/10.3389/fnut.2020.00007.

Co, C. (2019). *Aquaponics farming: How two hotels are looking to boost their sustainable practices.* 17/11/2019 https://www.channelnewsasia.com/news/singapore/aquaponics-rooftop-farm-fairmont-swissotel-stamford-hotels-12082350.

Cooray, S. T., Lee, J. J. L., & Chen, W. N. (2017). Evaluation of brewers' spent grain as a novel media for yeast growth. *AMB Express, 7*(1), 117. https://doi.org/10.1186/s13568-017-0414-1.

Dawe, D., Dobermann, A., Moya, P., Abdulrachman, S., Singh, B., Lal, P., … Zhen, Q. X. (2000). How widespread are yield declines in long-term rice experiments in Asia? *Field Crops Research, 66*(2), 175–193. https://doi.org/10.1016/S0378-4290(00)00075-7.

Department of Statistic Singapore (2019). *Singapore population.* Retrieved from https://www.singstat.gov.sg/modules/infographics/population.

Dobermann, D., Swift, J. A., & Field, L. M. (2017). Opportunities and hurdles of edible insects for food and feed. *Nutrition Bulletin, 42*(4), 293–308. https://doi.org/10.1111/nbu.12291.

Durand, A. (2003). Bioreactor designs for solid state fermentation. *Biochemical Engineering Journal, 13*(2), 113–125. https://doi.org/10.1016/S1369-703X(02)00124-9.

Erginkaya, Z., & Konuray, G. (2017). Natural preservatives: An alternative for chemical preservative used in foods. *World Academy of science, Engineering and technology. International Journal of Biological, Biomolecular, Agricultural, Food and Biotechnological Engineering, 11*(4), 311–316. https://doi.org/10.5281/zenodo.1130043.

Fan, M., Shen, J., Yuan, L., Jiang, R., Chen, X., Davies, W. J., et al. (2011). Improving crop productivity and resource use efficiency to ensure food security and environmental quality in China. *Journal of Experimental Botany, 63*(1), 13–24. https://doi.org/10.1093/jxb/err248.

FAO (2019). *Food loss and food waste.* Retrieved from http://www.fao.org/food-loss-and-food-waste/en/.

Germer, J., Sauerborn, J., Asch, F., Boer, J., Schreiber, J., Weber, G., et al. (2011). Skyfarming an ecological innovation to enhance global food security. *Journal für Verbraucherschutz und Lebensmittelsicherheit, 6*, 237–251. https://doi.org/10.1007/s00003-011-0691-6.

Ghoshal, G. (2018). Chapter 10 - recent trends in active, smart, and intelligent packaging for food products. In A. M. Grumezescu, & A. M. Holban (Eds.). *Food packaging and preservation* (pp. 343–374). Academic Press.

Global Food Security Index (2020). Retrieved from https://foodsecurityindex.eiu.com/Country/Details#Singapore.

Goddek, S., Delaide, B., Mankasingh, U., Ragnarsdottir, K., Jijakli, M., & Thorarinsdottir, R. (2015). Challenges of sustainable and commercial aquaponics. *Sustainability, 7*, 4199–4224. https://doi.org/10.3390/su7044199.

Graber, A., & Junge, R. (2009). Aquaponic Systems: Nutrient recycling from fish wastewater by vegetable production. *Desalination, 246*(1), 147–156. https://doi.org/10.1016/j.desal.2008.03.048.

Gurjar, M., Ali, S., Akhtar, M., & Singh, K. (2012). Efficacy of plant extracts in plant disease management. *Agricultural Sciences, 3*(3), 425–433. https://doi.org/10.4236/as.2012.33050.

Hartmann, C., & Siegrist, M. (2017). Insects as food: Perception and acceptance. Findings from current research. *Ernahrungs Umschau, 64*(3), 44–50. https://doi.org/10.4455/eu.2017.010.

Hayes, M., Skomedal, H., Skjånes, K., Mazur-Marzec, H., Toruńska-Sitarz, A., Catala, M., … García-Vaquero, M. (2017). 15 - microalgal proteins for feed, food and health. In C. Gonzalez-Fernandez, & R. Muñoz (Eds.). *Microalgae-based biofuels and bioproducts* (pp. 347–368). Woodhead Publishing.

Himanshu, S., Kumar, S., A, K., & K, G. (2012). Energy economics assessment of crops in traditional and mechanized farming. *International Research Journal of Environment Sciences, 1*(5) 2319-1414.

Hiç, C., Pradhan, P., Rybski, D., & Kropp, J. P. (2016). Food surplus and its climate burdens. *Environmental Science and Technology, 50*(8), 4269–4277. https://doi.org/10.1021/acs.est.5b05088.

Ivanova, K., Denkova, R., Kostov, G., Petrova, T., Bakalov, I., Ruscova, M., et al. (2017). Extrusion of brewers' spent grains and application in the production of functional food. Characteristics of spent grains and optimization of extrusion. *Journal of the Institute of Brewing, 123*(4), 544–552. https://doi.org/10.1002/jib.448.

Junge, R., König, B., Villarroel, M., Komives, T., & Jijakli, M. (2017). Strategic points in aquaponics. *Water, 9*, 182. https://doi.org/10.3390/w9030182.

Jürkenbeck, K., Heumann, A., & Spiller, A. (2019). Sustainability matters: Consumer acceptance of different vertical farming systems. *Sustainability, 11*(15), 4052. https://doi.org/10.3390/su11154052.

Kalantari, F., Mohd tahir, O., Akbari Joni, R., & Fatemi, E. (2017). Opportunities and challenges in sustainability of vertical farming: A review. *Journal of Landscape Ecology, 11*(1), https://doi.org/10.1515/jlecol-2017-0016.

Khew, C. (2016). *High-tech farmers cropping up.* The Straits Times. Retrieved from https://www.straitstimes.com/singapore/high-tech-farmers-cropping-up.

Khoe, W. J. (2018). *More durians rolling in this year: AVA data. The straits times*. 20/07/2019 https://www.straitstimes.com/singapore/more-durians-rolling-in-this-year-ava-data.

Kim, J. (2019). *Transforming okara into a microalgae culture medium*Thesis Nanyang Technological University. Retrieved from https://hdl.handle.net/10220/49477.

Klunder, H. C., Wolkers-Rooijackers, J., Korpela, J. M., & Nout, M. J. R. (2012). Microbiological aspects of processing and storage of edible insects. *Food Control, 26*(2), 628–631. https://doi.org/10.1016/j.foodcont.2012.02.013.

Kotzen, B., Emerenciano, M. G. C., Moheimani, N., & Burnell, G. M. (2019). Aquaponics: Alternative types and approaches. In S. Goddek, A. Joyce, B. Kotzen, & G. M. Burnell (Eds.). *Aquaponics food production systems: Combined aquaculture and hydroponic production technologies for the future* (pp. 301–330). Cham: Springer International Publishing.

Kozai, T. (2016). Why LED lighting for urban agriculture? In T. Kozai, K. Fujiwara, & E. S. Runkle (Eds.). *LED lighting for urban agriculture* (pp. 3–18). Singapore: Springer Singapore.

Lawton, G. (2020). The food revolution starts here. *New Scientist, 245*(3270), 39–43. https://doi.org/10.1016/S0262-4079(20)30411-5.

Leblon, B., Guerif, M., & Baret, F. (1991). The use of remotely sensed data in estimation of PAR use efficiency and biomass production of flooded rice. *Remote Sensing of Environment, 38*(2), 147–158. https://doi.org/10.1016/0034-4257(91)90076-I.

Liguori, R., Soccol, C. R., Vandenberghe, L. P.d. S., Woiciechowski, A. L., Ionata, E., Marcolongo, L., et al. (2015). Selection of the strain Lactobacillus acidophilus ATCC 43121 and its application to brewers' spent grain conversion into lactic acid. *BioMed Research International, 2015*. https://doi.org/10.1155/2015/240231 9.

Li, B., Qiao, M., & Lu, F. (2012). Composition, nutrition, and utilization of okara (soybean residue). *Food Reviews International, 28*(3), 231–252. https://doi.org/10.1080/87559129.2011.595023.

Liu, V. (2019). *Food tech start-up Sophie's Kitchen wins $1m at green challenge.* The Straits Times. 08/06/2019 https://www.straitstimes.com/singapore/food-tech-start-up-wins-green-challenge.

Lou, D. W. (2018). *Strawberries grown in Singapore vertical farm make debut. The straits times*. 20/06/2018 https://www.straitstimes.com/singapore/strawberries-grown-in-singapore-vertical-farm-make-debut.

Ludher, E. K., Deakin, M., Diamantini, D., & Borreli, N. (2016). Singapore's smart governance of food. In D. D.a. N. B. Mark Deakin (Ed.). *The governance of city food systems: Case studies from around the world*. Fondazione Giangiacomo Feltrinelli.

Lynch, K. M., Steffen, E. J., & Arendt, E. K. (2016). Brewers' spent grain: A review with an emphasis on food and health. *Journal of the Institute of Brewing, 122*(4), 553–568. https://doi.org/10.1002/jib.363.

Martins, C. I. M., Eding, E. H., & Verreth, J. A. J. (2011). The effect of recirculating aquaculture systems on the concentrations of heavy metals in culture water and tissues of Nile tilapia Oreochromis niloticus. *Food Chemistry, 126*(3), 1001–1005. https://doi.org/10.1016/j.foodchem.2010.11.108.

McGuire, S. (2015). FAO, IFAD, and WFP. The state of food insecurity in the world 2015: Meeting the 2015 international hunger targets: Taking stock of uneven progress. Rome: FAO, 2015. *Advances in Nutrition, 6*(5), 623–624. https://doi.org/10.3945/an.115.009936.

McHunu, N., Lagerwall, G., & Senzanje, A. (2019). Aquaponics model specific to South African conditions. *South African Journal of Agricultural Extension, 47*(1), 73–91. https://doi.org/10.17159/2413-3221/2019/v47n1a491.

Miglietta, P. P., De Leo, F., Ruberti, M., & Massari, S. (2015). Mealworms for food: A water footprint perspective. *Water, 7*(11), 6190–6203.

Mok, W. K., Tan, Y. X., Lee, J., Kim, J., & Chen, W. N. (2019). A metabolomic approach to understand the solid-state fermentation of okara using Bacillus subtilis WX-17 for enhanced nutritional profile. *AMB Express, 9*(1), 60. https://doi.org/10.1186/s13568-019-0786-5.

Mussatto, S. I. (2014). Brewer's spent grain: A valuable feedstock for industrial applications. *Journal of the Science of Food and Agriculture, 94*(7), 1264–1275. https://doi.org/10.1002/jsfa.6486.

Mussatto, S. I., Dragone, G., & Roberto, I. C. (2006). Brewers' spent grain: Generation, characteristics and potential applications. *Journal of Cereal Science, 43*(1), 1–14. https://doi.org/10.1016/j.jcs.2005.06.001.

NEA (2019). *Waste statistics and overall recycling.* https://www.nea.gov.sg/our-services/waste-management/waste-statistics-and-overall-recycling.

Neo, P. (2019). *Science-based packaging: Intelligent nanotech-based material from Singapore could create 'huge demand' from food firms.* 14/08/2019 https://www.foodnavigator-asia.com/Article/2019/08/02/Science-based-packaging-Intelligent-nanotech-based-material-from-Singapore-could-create-huge-demand-from-food-firms.

Ng, K. R., Lyu, X., Mark, R., & Chen, W. N. (2019). Antimicrobial and antioxidant activities of phenolic metabolites from flavonoid-producing yeast: Potential as natural food preservatives. *Food Chemistry, 270*, 123–129. https://doi.org/10.1016/j.foodchem.2018.07.077.

Niemi, P., Martins, D., Buchert, J., & Faulds, C. B. (2013). Pre-hydrolysis with carbohydrases facilitates the release of protein from brewer's spent grain. *Bioresource Technology, 136*, 529–534. https://doi.org/10.1016/j.biortech.2013.03.076.

Nowak, A., Czyzowska, A., Efenberger, M., & Krala, L. (2016). Polyphenolic extracts of cherry (Prunus cerasus L.) and blackcurrant (Ribes nigrum L.) leaves as natural preservatives in meat products. *Food Microbiology, 59*, 142–149. https://doi.org/10.1016/j.fm.2016.06.004.

Nozzi, V., Graber, A., Schmautz, Z., Mathis, A., & Junge, R. (2018). Nutrient management in aquaponics: Comparison of three approaches for cultivating lettuce, mint and mushroom herb. *Agronomy, 8*(3), 27. https://doi.org/10.3390/agronomy8030027.

Oonincx, D. G. A. B., & de Boer, I. J. M. (2012). Environmental impact of the production of mealworms as a protein source for humans – a life cycle assessment. *PloS One, 7*(12), Article e51145. https://doi.org/10.1371/journal.pone.0051145.

Paulo, D. A., & Ong, L. (2020). *Crickets, algae, soya discard — 3 foods of the future, made in Singapore* (International Edition). . 11/01/2020 https://www.channelnewsasia.com/news/cnainsider/crickets-algae-soya-discard-3-future-foods-made-in-singapore-12252394.

Pleissner, D., Lam, W. C., Sun, Z., & Lin, C. S. K. (2013). Food waste as nutrient source in heterotrophic microalgae cultivation. *Bioresource Technology, 137*, 139–146. https://doi.org/10.1016/j.biortech.2013.03.088.

Post, M. J. (2012). Cultured meat from stem cells: Challenges and prospects. *Meat Science, 92*(3), 297–301. https://doi.org/10.1016/j.meatsci.2012.04.008.

Rabl, A., Spadaro, J. V., & Zoughaib, A. (2008). Environmental impacts and costs of solid waste: A comparison of landfill and incineration. *Waste Management & Research, 26*(2), 147–162. https://doi.org/10.1177/0734242X07080755.

Rakocy, J. E. (2012). Aquaponics—integrating fish and plant culture. In J. H. Tidwell (Ed.). *Aquaculture production systems* (pp. 344–386). John Wiley & Sons, Inc.

Ray, P. P. (2017). Internet of things for smart agriculture: Technologies, practices and future direction. *Journal of Ambient Intelligence and Smart Environments, 9*, 395–420. https://doi.org/10.3233/AIS-170440.

Roosta, H. R., & Hamidpour, M. (2011). Effects of foliar application of some macro- and micro-nutrients on tomato plants in aquaponic and hydroponic systems. *Scientia Horticulturae, 129*(3), 396–402. https://doi.org/10.1016/j.scienta.2011.04.006.

Ruiz, J., Olivieri, G., de Vree, J., Bosma, R., Willems, P., Reith, J. H., ... Barbosa, M. J. (2016). Towards industrial products from microalgae. *Energy & Environmental Science, 9*(10), 3036–3043. https://doi.org/10.1039/C6EE01493C.

Rumpold, B. A., & Schluter, O. K. (2013). Nutritional composition and safety aspects of edible insects. *Molecular Nutrition & Food Research, 57*(5), 802–823. https://doi.org/10.1002/mnfr.201200735.

Rumpold, B. A., & Schlüter, O. K. (2013). Potential and challenges of insects as an innovative source for food and feed production. *Innovative Food Science & Emerging Technologies, 17*, 1–11. https://doi.org/10.1016/j.ifset.2012.11.005.

Schaefer, D., & Cheung, W. M. (2018). Smart packaging: Opportunities and challenges. *Procedia CIRP, 72*, 1022–1027. https://doi.org/10.1016/j.procir.2018.03.240.

SFA (2019). *Food farms.* https://www.sfa.gov.sg/food-farming/food-farms/farming-in-singapore.

Shiao, V. (2019). *The future of farming. The Business Times.* https://www.businesstimes.com.sg/magazines/the-sme-magazine-januaryfebruary-2019/the-future-of-farming.

Shukla, A. (2017). *India to Be amongst most land scarce countries by 2050: Survey.* http://www.businessworld.in/article/India-To-Be-Amongst-Most-Land-Scarce-Countries-By-2050-Survey/31-01-2017-112208/.

Sindhu, R., Binod, P., & Pandey, A. (2016). Biological pretreatment of lignocellulosic biomass – an overview. *Bioresource Technology, 199*, 76–82. https://doi.org/10.1016/j.biortech.2015.08.030.

Singapore Imports of Food, & Animals, L. (2020). https://tradingeconomics.com/singapore/imports-of-food-live-animals.

Srbinovska, M., Gavrovski, C., Dimcev, V., Krkoleva, A., & Borozan, V. (2015). Environmental parameters monitoring in precision agriculture using wireless sensor networks. *Journal of Cleaner Production, 88*, 297–307. https://doi.org/10.1016/j.jclepro.2014.04.036.

St-Hilaire, S., Sheppard, C., Tomberlin, J. K., Irving, S., Newton, L., McGuire, M. A., ... Sealey, W. (2007). Fly prepupae as a feedstuff for rainbow trout, Oncorhynchus mykiss. *Journal of the World Aquaculture Society, 38*(1), 59–67. https://doi.org/10.1111/j.1749-7345.2006.00073.x.

Surendra, K., Olivier, R., Tomberlin, J. K., Jha, R., & Khanal, S. K. (2016). Bioconversion of organic wastes into biodiesel and animal feed via insect farming. *Renewable Energy, 98*, 197–202. https://doi.org/10.1016/j.renene.2016.03.022.

Takle, E., Gustafson, D., Beachy, R., Nelson, G., Mason-D'Croz, D., & Palazzo, A. (2013). US food security and climate change: Agricultural futures. *Economics, 7*. https://doi.org/10.5018/economics-ejournal.ja.2013-34.

Tan, Y. X., Mok, W. K., Lee, J., Kim, J., & Chen, W. N. (2019). Solid state fermentation of brewers' spent grains for improved nutritional profile using Bacillus subtilis WX-17. *Fermentation, 5*(3), 52. https://doi.org/10.3390/fermentation5030052.

Teh, C. (2019). Tiny sensors allowing observation of plant growth may help urban farms. *The Straits Times*. 17/08/2019 https://www.straitstimes.com/singapore/tiny-sensors-allowing-observation-of-plant-growth-may-help-urban-farms.

Teng, P., & Montesclaros, J. (2019). *Singapore's '30 by 30' food production target: Is it feasible? Today*. 9/4/2019 https://www.todayonline.com/commentary/singapores-30-30-food-production-target-it-feasible.

Thorrez, L., & Vandenburgh, H. (2019). Challenges in the quest for 'clean meat'. *Nature Biotechnology, 37*(3), 215–216. https://doi.org/10.1038/s41587-019-0043-0.

Tiensin, H., Kalibata, A., & Cole, M. (2020). *Ensuring food security in the era of COVID-19*. 08/04/2020 https://www.un.org/sustainabledevelopment/blog/2020/04/ensuring-food-security-covid-19/.

Ting, K. C., Lin, T., & Davidson, P. C. (2016). Integrated Urban controlled environment agriculture systems. In T. Kozai, K. Fujiwara, & E. S. Runkle (Eds.). *LED lighting for urban agriculture* (pp. 19–36). Singapore: Springer Singapore.

Torri, S., & Puelles, M. (2010). Use of vermiculture technology for waste management and environmental remediation in Argentina. *International Journal of Environmental Engineering, 10*(3/4), 239–254. https://doi.org/10.1504/IJGENVI.2010.037269.

Touliatos, D., Dodd, I. C., & McAinsh, M. (2016). Vertical farming increases lettuce yield per unit area compared to conventional horizontal hydroponics. *Food and Energy Security, 5*(3), 184–191. https://doi.org/10.1002/fes3.83.

Treftz, C. (2016). Hydroponics: Potential for augmenting sustainable food production in non-arable regions. *Nutrition & Food Science, 46*(5), 672–684. https://doi.org/10.1108/NFS-10-2015-0118.

Tu, Z., Li, J., Ruan, R., Liu, C., Wang, H., & Wu, D. (2007). Process for increasing soluble dietary fiber content of soybean meals. *Nongye Gongcheng Xuebao/Transactions of the Chinese Society of Agricultural Engineering, 23*(5), 246–250. https://doi.org/10.3969/j.issn.1002-6819.2007.5.048.

Tzounis, A., Katsoulas, N., Bartzanas, T., & Kittas, C. (2017). Internet of Things in agriculture, recent advances and future challenges. *Biosystems Engineering, 164*, 31–48. https://doi.org/10.1016/j.biosystemseng.2017.09.007.

Valin, H., Sands, R. D., van der Mensbrugghe, D., Nelson, G. C., Ahammad, H., Blanc, E., ... Willenbockel, D. (2014). The future of food demand: Understanding differences in global economic models. *Agricultural Economics, 45*(1), 51–67. https://doi.org/10.1111/agec.12089.

Van Huis, A., & Oonincx, D. G. A. B. (2017). The environmental sustainability of insects as food and feed. A review. *Agronomy for Sustainable Development, 37*(5), 43. https://doi.org/10.1007/s13593-017-0452-8.

Van Huis, A., Van Itterbeeck, J., Klunder, H., Mertens, E., Halloran, A., Muir, G., et al. (2013). *Edible insects: Future prospects for food and feed security.* Food and Agriculture Organization of the United Nations.

Vangsoe, M. T., Thogersen, R., Bertram, H. C., Heckmann, L.-H. L., & Hansen, M. (2018). Ingestion of insect protein isolate enhances blood amino acid concentrations similar to soy protein in A human trial. *Nutrients, 10*(10), 1357. https://doi.org/10.3390/nu10101357.

Venkat, K. (2011). The climate change and economic impacts of food waste in the United States. *International Journal on Food System Dynamics, 2*(4), 431–446. https://doi.org/10.18461/ijfsd.v2i4.247.

Verbeke, W., Marcu, A., Rutsaert, P., Gaspar, R., Seibt, B., Fletcher, D., et al. (2015). 'Would you eat cultured meat?': Consumers' reactions and attitude formation in Belgium, Portugal and the United Kingdom. *Meat Science, 102*, 49–58. https://doi.org/10.1016/j.meatsci.2014.11.013.

Vigani, M., Parisi, C., Rodríguez-Cerezo, E., Barbosa, M. J., Sijtsma, L., Ploeg, M., et al. (2015). Food and feed products from micro-algae: Market opportunities and challenges for the EU. *Trends in Food Science & Technology, 42*(1), 81–92. https://doi.org/10.1016/j.tifs.2014.12.004.

Vong, W. C., & Liu, S.-Q. (2019). The effects of carbohydrase, probiotic Lactobacillus paracasei and yeast Lindnera saturnus on the composition of a novel okara (soybean residue) functional beverage. *LWT, 100*, 196–204. https://doi.org/10.1016/j.lwt.2018.10.059.

Wang, X., Balamurugan, S., Liu, S.-F., Zhang, M.-M., Yang, W.-D., Liu, J.-S., ... Lin, C. S. K. (2020). Enhanced polyunsaturated fatty acid production using food wastes and biofuels byproducts by an evolved strain of Phaeodactylum tricornutum. *Bioresource Technology, 296*, 122351. https://doi.org/10.1016/j.biortech.2019.122351.

Wang, Y. S., & Shelomi, M. (2017). Review of black soldier fly (hermetia illucens) as animal feed and human food. *Foods, 6*(10), https://doi.org/10.3390/foods6100091.

Williams, H., & Wikström, F. (2011). Environmental impact of packaging and food losses in a life cycle perspective: A comparative analysis of five food items. *Journal of Cleaner Production, 19*(1), 43–48. https://doi.org/10.1016/j.jclepro.2010.08.008.

Wortmann, F., & Flüchter, K. (2015). Internet of things. *Business & Information Systems Engineering, 57*(3), 221–224. https://doi.org/10.1007/s12599-015-0383-3.

Yavuzcan Yildiz, H., Radosavljevic, V., Parisi, G., & Cvetkovikj, A. (2019). Insight into risks in aquatic animal health in aquaponics. In S. Goddek, A. Joyce, B. Kotzen, & G. M. Burnell (Eds.). *Aquaponics food production systems: Combined aquaculture and hydroponic production technologies for the future* (pp. 435–452). Cham: Springer International Publishing.

Yen, H.-W., Hu, I. C., Chen, C.-Y., & Chang, J.-S. (2014). Chapter 2 - design of photobioreactors for algal cultivation. In A. Pandey, D.-J. Lee, Y. Chisti, & C. R. Soccol (Eds.). *Biofuels from algae* (pp. 23–45). Amsterdam: Elsevier.

Yep, B., & Zheng, Y. (2019). Aquaponic trends and challenges – a review. *Journal of Cleaner Production, 228*, 1586–1599. https://doi.org/10.1016/j.jclepro.2019.04.290.

Zhang, N., Wang, M., & Wang, N. (2002). Precision agriculture—a worldwide overview. *Computers and Electronics in Agriculture, 36*(2), 113–132. https://doi.org/10.1016/S0168-1699(02)00096-0.

Zhao, G., Lyu, X., Lee, J., Cui, X., & Chen, W.-N. (2019). Biodegradable and transparent cellulose film prepared eco-friendly from durian rind for packaging application. *Food Packaging and Shelf Life, 21*, 100345. https://doi.org/10.1016/j.fpsl.2019.100345.

Zhuo, T. (2019). *New method uses food waste to feed protein-rich algae, tripling amount of food source produced: NTU. The straits times.* 01/12/2019 https://www.straitstimes.com/singapore/new-method-uses-food-waste-to-feed-protein-rich-algae-tripling-amount-of-food-source.