

A REVIEW OF FOOD SYSTEM SUSTAINABILITY: PRACTICAL APPROACHES,
CHALLENGES, AND TECHNOLOGIES

A Thesis

Presented to the Faculty of the Graduate School
of Cornell University

in Partial Fulfillment of the Requirements for the Degree of
Master of Food Science

by

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December 2022

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ABSTRACT

Due to globalization, the food value chain has expanded significantly, introducing unique challenges. These include: the surplus of food in developed countries, the lack of sufficient food in other countries, intense resource utilization to produce commercial products, and the burden of waste management. The goal of this thesis is to review the present work addressing these topics. Food sustainability, a concept including concepts related to the affordability, environmental impact, and the social needs surrounding food products, has been a major goal across fields. In this thesis I will review some of the diverse contributions of these different efforts, including food processing, waste management, packaging and food alternatives, and I will discuss some of the limitations and challenges each of these methods.

BIOGRAPHICAL SKETCH

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ACKNOWLEDGMENTS

The author would like to acknowledge Dr. Abby Snyder for her guidance and support. Dr. Snyder is a patient and kind mentor to guide me along the way from developing the thesis to formatting and writing a review with new ideas and useful suggestions. Additionally, the author would like to thank ShiYu Cai for their help for giving advice on the outline and constructing the whole backbone of the paper.

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Introduction

Food sustainability could be a complex, broad, and vague word since the standard for sustainability is changing over time. The concept of sustainability itself can be divided into three parts: economy, society, and ecology (Helms et al. 2004). Ecology asks how the resources are being utilized and recycled; economic questions whether the product will be consumed and produced feasibly; society covers humans and their needs. Several different perspectives fall into those basic categories and form several challenges food industry must address. Does utilizing innovative food processing and alternatives reduce food waste and benefit the environment; will the alternative satisfy consumers' demands, and can food security and food sustainability both be achieved. More questions pull in all three spectrums together, complicating the development of solutions. It has also shown itself as a long-term balance between ecological, economic, and social processes at the whole level of society. (Aiking et al. 2004).

There has not been much historical interest in this challenge, or even on sustainability more generally. Historic concerns focused more on under-production, health and food safety problems, and hunger and malnutrition due to a short supply chain (Lang et al. 2012). This result indicates people still view food as a simple and isolated system, excluding it from a bigger entity or a system that exerts impacts on economy and the whole society.

Globalization has rapidly changed the face of food and agriculture due to larger networks of food distribution channels. This has raised awareness about the issues facing food sustainability and increased the participation of governments and social groups on the topic. In 1990, United State Congress addressed sustainable agriculture that could provide for people's needs for food and fibers. They further defined sustainable development as "sustainable

development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Morawicki et al. 2018). Other policies could even be seen in 1980 to establish the concept of food sustainability in all nations. People take corrective actions and paths, but the debate on managing earth's resources has continued for decades. With increasing globalization, governments started to shift their focus from smallholders to a world-wide large globalized market (Arthur et al. 2022). Countries opened their borders; better transportation and communication technologies accelerated the development of food systems (Betoret et al. 2020). Global sourcing for distribution of fresh fruit increased, and the production system began to build standards for livestock production. More exports and imports are relied upon among the world's population, increasing people's labor contracts and opening up more opportunities (Phillips 2015). However, changes bring challenges as well; the food system has grown its network rapidly, connecting more supply chains, wider external system, including agricultural, ecological systems (Alroe et al. 2016), sustainability assessment of food systems are showing some conflicting benefits and goals with other demands and systems. One of the obvious successes is the increasing of food productivity, but that has brought about the uprising food waste. According to United Nations, by 2030, people will need 50 percent more food, 30 percent more water, and 45 percent more energy (Yuan et al. 2020).

Increased food productivity reduces hunger and malnutrition and the growing population food demand, but excessive food waste works against those efforts. In total, 90 million tons of food are wasted in the EU annually (Cicatiello et al. 2016). The total estimated food waste and loss is about 20-40 percent of all food produced (Premanandh et al. 2011). Furthermore, half of the food is still edible when it is discarded. This large amount of food waste leads to many other detrimental results, such as lost labor, capital, and the resources used to produce food products

(VagSholm et al. 2020). More than one-third of the food has been wasted before it arrives at the market even before reaching their consumers. Consequently, all the effort put into the product will be discarded, further squandering human resources and other energetic inputs.

This, in turns, contributes to the increase in other waste streams. When people throw away products, the packaging and food waste are usually thrown together, and especially plastic wastes will be nearly impossible to recycle, causing more irreversible damage to the environment. Some food products have multilayer or high-barrier packaging to prevent food spoilage. For instance, results show that the packaging alone will cause about 3.35 kg of CO₂ per kg processed (Dilkes-Hoffman et al. 2018). In addition, food wastes mostly come as rotten food when they are transported to the dumpster. Burning the food will further impact the environment (Kim et al. 2010). The resulting methane and CO₂ are contributing to global climate change. Environmental governance are calling for the natural services, like REDD (Reducing Emissions from Deforestation and Forest Degradation), and controlling the farming to minimize the cost of the carbon, but those efforts are not effective as imagined; farmers required compensation due to less agricultural activity, more farmers leaving the land further affected the productivity of the food system, since food system is such a multidimensional network, intervention by governments never lead to a win-win situation (McMichael et al. 2011).

More food demands and a protein-heavy diet also mean increasing agricultural activities. Fertilizers will directly emit nitrous oxides, which also leads to greenhouse problems. Research shows that ammonia is released as well as nitrogen oxides during the fertilizer application, leaving acidification and eutrophication in soils. Livestock creating methane is also a source of greenhouse emissions, contributing 10 percent of the greenhouse gas emission (Scherhauser et al.

2018). With more farmers and soil being exploited to grow food, forestation has also decreased, decreasing biodiversity.

Food security has also never been completely solved, even as food waste represents an enormous loss of product, almost a paradox as Clara Cicatiello et al. (2016) has stated food security is defined by four pillars mentioned during the World Summit on Food security: food availability, food access, food use, and food stability (Bilali et al. 2019). The ready availability of food gives a sense of food security, as opposed to fear of hunger or malnutritional. But there is still an imbalance existing among different parts of the world. People in developed countries no longer have malnutrition problems, and even most families leave a large amount of food wasted. However, low-income countries, and the lack of modern technology deepens the imbalance between developed countries and developing ones. The demand of animal products is not being fulfilled, though there are benefits in healthy plant-based diets. (Garnett et al. 2013)

Consumers do not have a clear concept of the word “sustainability” itself and do not know where the issues come from. They see that as "green and good," creating communication gaps between the consumers and the industries. Consumers are also anxious about having clean labels, with a wanting for simpler process, healthier foods, but simultaneously lacking the command of the vocabulary used in food processing and information panels. Researchers are tasked with filling this gap. Various economic models can be useful in showing the environmental impact of products, are ideally an easy-to-communicate tool for scientists and even the public. These models can incorporate information regarding nutrients, health, even social and economic dimensions to identify the upsides and downsides of human behavior on food and how it affects food sustainability. (Green et al. 2020).

Many methods have been put into practice to attempt to address food sustainability problems. For example, food recycling is an effective way to mitigate the environmental impacts caused by food disposal. For example, Ming Hung Wong et al. (2016) show that adding food waste to fish feeds may make the fish a higher quality and safer to consume, an appealing possibility as an avenue for utilizing waste streams. People are trying to achieve sustainability in food systems in various angles, looking into almost every aspects of the whole life cycle of a food product, including food processing, energy use, food waste management, package recycling and new technologies, and even raising awareness of the consumers, improving designs of the packaging for education and appeals, trying to pull the strings and factors all together to form a more dense and closed loop environment that causes less adverse impact to the planet and consumers and build a more sustainable food network. None of them are perfect, with each of the methods facing their own challenges, since food systems have many regulations, some theories need excessive experiments and examination, and a practical adjustment to prove they are not only theories on paper.

This thesis will discuss cases, methodology, and how people approach food sustainability challenges and assess their effectiveness. Generally, I will focus on: (1) food waste, (2) food packaging, (3) food processing, and (4) novel food (largely protein) alternative sources.

Food packaging

Environmental impact of plastic food packaging

The environmental impact food packaging has brought is emerging after other food waste and food safety problems. Food packaging has flown under the radar for a long time, but it has always been essential for serving its functions: a protection preventing the product getting damaged and spoiled from different pathogens, a promotion for being more competitive against other products, but also a waste reduction since some of the package design is increasing the shelf life. (Verghese et al. 2015) No food can go on the shelves without a package to face the consumers, it made them to understand the food concept, and could be said food packaging is a significant anchor connecting consumers with the food products and the whole food system. For a long time, plastic packaging is being used for different areas, most of packaging are a one-time-use product, getting thrown away with the food waste. Some of them got buried in mountain but increasing amounts of them end up in the oceans to dispose the plastic packaging (Akerman et al. 2021). There have been 4.7-12.8 megatons of mismanaged plastic being dumped into the ocean, polluting the marine creature environment annually. Incineration of plastics are also causing great CO₂ emission, 5 to 10 tons of CO₂ along with other pollutants (polycyclic aromatic hydrocarbons, carbon monoxide, furans) are released by 1 ton of plastic over its life cycle (Ina Vollmer et al. 2020). However, plastic as a light, affordable, versatile material is still prevalent in the food systems. Polyethylene (PE), low density polyethylene, polyethylene

terephthalate (PET) are all very common seen types according to the studies. During processing, plastic packaging has a high 90.5 percent among all the types according to the research results (Joe Yates et al. 2021). Moreover, polymers with the additives like antioxidants, plasticizers, toughening agents, which are all giving more burdens to the environment. Governments or Unions are addressing the food packaging problems, encouraging industries, authorities and consumers to make a transition away from using plastics, but finding a good substitution material seems like great challenge. People are currently finding different ways to seek a material that achieve both efficiency (a long shelf life) like plastic but also a sustainability, and this section will look into some of those technologies, concepts and their application and impacts on the food markets and the environment.

Life Cycle Analysis

One of the biggest problems of plastic is its afterwards treatment. Data shows plastic packaging account for 26 percent of the total plastics, and only 14 percent of these plastics will eventually be being recycled. The Concept of New Plastic Economy has the goal of creative after-use of the plastic economy, decreasing the leakage of the food additives and plastics into the soil and ocean (Ximena Shimidt Rivera et al. 2018). During the development of the plastic packaging solutions, 3 categories, circular, environmental and packaging has been established and considered when we are drafting the NPE concept. Life Cycle Analysis (LCA) is being conducted to estimate different plastic materials by measuring climate change (gas emission), primary energy demand (water, land and electricity), depletion of fossil fuels and metals. It is worth to note the whole timeline should be studied during the analysis (Sara Toniolo 2013), starting from the production of the container, the recyclability and the end-of life will be

included in the assessment. Using LCA methods, it will be easier to compare different plastic materials to look for a best formulation that can cause the least damage to the environment.

Mechanical and Chemical Recycling

Another important concept is to build a closed loop, adopting a more recyclable container or whole packaging internet. Shutting the carbon loop means to have the plastic wastes being collected, eventually recovered and captured in a carbon form, being reused back into the packaging material, usually, feedstocks and monomers. This is no meant to be a process without energy loss, since recycling over and over will eventually get into an inevitable situation that the yields and quality is too low to be used again (Carl Schirmeister 2022). However, improving the recyclability of the product will effectively close the loop temporarily, achieving sustainability to some extent. Mechanical recycling is a way to separate the plastics and shred the plastic into small pieces, turning into PET pellets to be recycled. In other words, plastics will go through extrusion machine that exerts heat and mechanical forces to break down the chain length of the polymers, ending up a degradation of strength and flexibility of the plastic. (Michael Shaver 2020), so more treatments, such as stabilizers, which are necessary to prolong the polymer chain's shelf life and alleviate light exposure, are required if people still want those recycled products to re-enter the food market. Chemical recycling is also trying to give plastic new lives; full depolymerization of PET to the purified monomer by solvolysis to cleave ether, ester and acid amide bonds to filter out any additives, avoiding recycling low quality plastics. Other methods such as catalytic pyrolysis which is combining catalysts and temperature to force plastic polymer chain to move to the pores and bind to the macromolecules; through chain scission,

depolymerization and deoxygenation, polymers ended up converting into liquid carbon hydrocarbon, use in waxes or transportation oil (Jie Jiang 2022).

Nanotechnologies for better-quality packaging

People are also looking this challenge in a different perspective; a better-quality packaging will guarantee longer shelf life of the product, resulting less food waste. Some new technologies are developing, mostly by improving the recyclable food packaging or utilizing nano materials. Whey protein isolate was used to formulate the whey-based coatings and used in the PET films. Experiments are conducted to study more of its thermomechanical properties, comparing coated and uncoated samples and barrier properties to see the oxygen permeability of the films. Given results by Markus Schmid et. al (2012) show stiffness of the product, and a higher barrier property, potentially both due to the high-density protein crosslinked network. Whey protein isolate is not the only material that compensate into films for food protection; nanocellulose as a biodegradable nontoxic material also puts itself on the table to compete with traditional plastic packaging. Protein, in general as a natural constituent in animal tissues, is also being studied by people to develop a protective and reliable film as a packaging material. Proteins can provide the packaging structure through hydrogen bonds, hydrophobic interaction, and ionic bonds. To achieve a good protein network by forming a cross-linkage by a different protein, blending agents such as polysaccharides, chitosan, and starch could be used to get a better texture of the whole network. (Milani et al. 2020) Nanocellulose, as a biodegradable, nontoxic material, could also be used to replace traditional plastic packaging. Nanocellulose has been extracted from various sources of cellulose, such as cotton, wheat rice, through the process of bleaching, acid hydrolysis, and oxidation, followed by flexible choices such as high-pressure

homogenization (Khalil et al.) As Ahankara et al. (2021) stated, cellulose types are divided into three types: cellulose nanocrystals, cellulose nanofibrils, and bacterial nanocellulose. While all have different properties, all of them can be recycled and processed without too much downgrade. Due to the ability to form hydrogen bonds, the network of the nanocellulose is tougher than normal biopolymers. It creates an impermeable barrier against gases, increasing the sustainability of the food product. Worth noting things that have more cellulose nanocrystals indicate a greater film crystallinity. It also offers more protection and superior rigidity, tensile and flexural properties, and cellulose nanofibrils have a protective coating and are edible at the same time, especially on fresh fruits, to prolong their shelf-life. Moreover, cellulose is the most abundant natural biopolymer, so it holds enormous potential to be a suitable substitute for plastic.

Limitations of new technologies

Plastic has a low tolerance towards heat, which is a downside to its use. However, it is still widely used. This is because other materials still have their disadvantages, such as using great energy consumption, not being appropriate for industrial scale, or difficulty in decreasing pretreatment steps (Khali et al. 2016). In addition, although most new packaging alternatives or nanoparticles added in packaging provide similar properties such as coating, antimicrobial activity, and moisture barrier, the reduced size and increased surface area per unit volume will cause potential toxicity. Silver nanoparticles, as an antimicrobial agent, will migrate from containers to food and then into the human body (McClement et al. 2017), causing potential adverse effects in the liver, and gut microbiota, according to cell culture models. Zinc oxide nanoparticles are used for a similar purpose but more for a light barrier against UV. They may

also aggregate over time and exhibit more significant toxicity. There are many more examples, and some of those particles will not cause damage unless they have exceeded the average level.

Food processing

Traditional food processing

Food processing is a core aspect for achieving food sustainability. The question of how to make food products with a higher quality and the desire of consumers to have a healthier food diet drives the industry towards a more effective, safe, and efficient direction of food processing.

Salting is a very historical preservative method used to improve water absorption and control microbial growth. It reduces the water activity by influencing the water-holding capacity to make anion binding between a salt molecule and meat proteins, resulting in protein molecules above the isoelectric point pH having a negative charge. The repulsing chloride ions enlarge the water absorption network, extending the product shelf-life. (Albarracin et al. 2011) However, salted products may have net negative effects on health. Though in moderation, some diets can incorporate high-sodium foods. Taking Japanese diets as an example, pickled vegetables have 1.5-7.6 percent salt, and salted fish contain a high 4.6-4.8 percent salt content. In a pool of 91,225 respondents' analysis, the Japanese Health Center (2010) concluded that the median sodium intake ranged from 3,084 mg per day to 6,844 mg, which can increase the risk of negative health outcomes.

Another historical and common food preservation strategy is thermal processing. Thermal processing has been used since the early stage of food history. It inactivates pathogens by temperature manipulation and prolongs some product shelf-life. Many canned foods use this

method. During batch retort operations, energy and steam flow are energy intensive operations. In the experiment conducted by R.Simpson et al. (2006), the total energy consumption obtained at a higher temperature simultaneously will take more energy, especially from the steam mass flow. In other technologies, thermal processing has the same problem. Fluid milk requires the application of thermal treatments such as heating and cooling, which will cause massive energy consumption, having a demand of 15 percent of total energy use in the dairy industry, which totals approximately 10 MJ/kg powder (Yildirim et al., 2017).

Besides energy consumption, people also are assessing the impact on food quality via traditional thermal processing. In the paper written by B.Ling et al. (2015), the food quality changes under thermal processing have been evaluated by modeling. Through the use of food quality kinetics, the order of reactions and the relationship between time, temperature, and the quality changes are determined. The indirect heating (small volume samples under isothermal conditions with a hermetic seal) method has been used. Similar models could also be used to measure texture, bioactive compounds, and color change over time. By combining the kinetic models, it could be seen that an increase from a 20 degrees Celsius increase to 121 degrees Celsius will have 3.77 times increase in quality loss while killing the microorganisms at 83.2 times increase rate. Those numbers imply the trade-off that potentially exists between food quality and microbial inactivation.

Consumers are more concerned about energy, health, and food quality, or even clean-label foods, the food industry than ever before. The practice of non-thermal processing has grown more popular in the past decades. Data showed that high-pressure processing technology has considerably increased sets of equipment from less than 50 to over 300 from 2000 to 2015, along with more than 10 million sales worldwide (Huang et al. 2017). It is not surprising to see

different kinds of non-thermal processing bloom. Many of them have advantages and contributions to food sustainability, but some challenges and other aspects must be improved for more widespread use.

High pressure processing

High-pressure processing utilizes high pressure on the product to prolong shelf-life. It kills the pathogen and gives clean labels to the product, in diverse product categories, including meat, fruit, seafood, juice products, Ready-to-Eat foods, and even infant formula (Nabi et al. 2021). The basic principle is slowing down enzymatic reactions and not affecting color and flavor by maintaining the covalent bonds that form colors. The pressure vessel is the essence of the whole technique; usually appearing as a cylinder, the vessels have specific thicknesses for different working pressures. During the process, pressure is exerted on the vessel, either through direct compression (using the vessel ends closure as a piston to build and release pressure) or indirect compression (more in the food industry, has a high-pressure pump compress a fluid from pressure tank into the pressure vessel). (Elamin et al. 2015)

With the help of LCA (life cycle analysis) of cost and environment and the impact of HPP on the environment and economy has been studied as well. Cost components for HPP should consider purchasing, handling, operating (including energy, water consumption, manpower, safety, maintenance, packaging, and sanitation), and the residual value after reaching the lifetime. Take juice products as an example. We use the formula of $\text{cost} = \text{initial investment} + \text{operating cost} + \text{maintenance cost} - \text{residual value}$. The water consumption only caused 17.87 percent of the full costs, costing up to 50.94 percent if using thermal processing under a 20-year

life cycle assumption. However, the HPP method's overall cost will be way expensive in all aspects (Federica Cacace et al., 2020).

More expensive than thermal processing, HPP has more greenhouse gas emissions. In the study by F.Sampedro et al.(2014), the environmental impact is analyzed based on the greenhouse gas levels in terms of kg of CO₂, and looking at all the steps causing energy to see how much the CO₂ kg emission is per year. Although thermal processing has tremendous steam consumption, the overall CO₂ emission amount is deficient, eight times less than the HPP and the electric pulse field, another non-thermal processing. Other researchers categorized the impacts in more detail, including ecotoxicity, toxicity, land use, ozone formation, and much more. The number does not show the HPP as a considerable advantage over other thermal processing, especially on radiation. The toxicity towards freshwater and marine ecosystems is close to the impact of the thermal processing methods. Nevertheless, it does have a significant improvement in food quality and overall nutrient quality. Some good examples can be starches, by releasing less amylose, having higher moisture content, and maintaining a fresher texture than the ones from thermal processing. (Chakka et al. 2021)

Pulsed Electric Field

As mentioned earlier, pulsed electric field (PEF) is another non-thermal processing but slightly less popular than HPP. During PEF treatment, the product will be treated under an intense electrical field in a short time window. The following pores generated will break down the mechanical membrane and inactivate cells. The PEF leaks the small ionic entities, causing osmotic pressure and imbalance between cell cytoplasmic and cell medium; this pressure keeps increasing and will lead to cell lysis (Soltanzadeh et al.2020). Besides inactivating cells, it can

also be implemented as a pretreatment method or electrically stimulating cells. It has less water and energy, significantly reducing the drying process time by opening the cell membranes. Rai Naveed Arshad et al. (2021) also pointed out an interesting finding: PEF lowers the production of the Hydroxyl Methyl Furfural (a potentially harmful carcinogen compound to humans) compared to the thermal processing, having 5.25 mg/L compared to 5.9 mg/L for date juice products. The shelf-life extension is also very promising. Milk product under a five pulses treatment (2.3 s pulse width and 35 kV/cm peak electric field intensity) combined with ten seconds at 65 Degrees Celsius had a 24-day-longer shelf life (Chughtai et al. 2021). The inactivation combined with light heating (different temperatures depending on the pathogen) seems to be somewhat effective against many pathogens, including *E.coli*, *Bacillus cereus* and its spore form, *Listeria monocytogenes*, and more (Buckow et al., 2014). The limitation of PEF lies in its novelty and needs to be a wholly known mechanism. Energy usage is still debatable due to some conflicting voices on environmental sustainability, so this method needs more analysis or studies to make a more comprehensive conclusion.

Cold Plasma

Other non-thermal processing methods, like cold plasma, a microbial decontamination method, and its plasma-treated water, are emerging technologies. Initial work has shown that it is effective on solid-like surface food products. However, stress hardening of the microbial target during the processing, making the pathogen more resistant, is a consideration. Moreover, insufficient regulation and experiments greatly restrain the technology implementation (Bourke et al., 2018).

Conclusion and future of food processing methods

In conclusion, thermal processing and non-thermal processing are important areas for sustainability improvements within the food industry. Non-thermal processing methods are generally newer and often expensive, and some are energy-consuming and have limited usage. Thermal processing, nonetheless, is a significant use of energy and water consumption in the food industry and affect product quality. Some efforts have been made to combine approaches, there are also combinations of the two methods. For example, ultrasound waves with light heating could prevent off-flavors and even inactivate vegetative spores in meat products. In the future, to achieve better quality food and be more eco-friendly do more research and work more on different combinations of methods are still needed.

Food alternatives

Overview of the environmental impact of producing meat products

Food consumption significantly contributes to environmental impact, affecting overall sustainability. Food production starts from the ingredient and extends through product development, processing, distribution, sales and then, finally, consumption. Meat productions are one of the leading commodities impacting sustainability and the environment. Besides livestock production, meat production, slaughterhouse, broiler production, and transportation feed are relatively energy intensive. Some well-known examples could be electricity by-products, such as direct and indirect nitrous oxide emissions and methane (Kalhor et al 2016). The demand for global meat consumption has grown from 63 grams in 1961 to 115 grams daily for one person (Stubbs et al. 2018). Consumers' perception of meat products is based on quality, nutritional adequacy and healthiness, potential health risks such as high sodium or high-fat content, and other problems protecting against fraud (Araújo et al. 2022).

Nevertheless, in most cases, consumers do not often consider that their choices affect sustainability in the larger picture. For example, research has indicated that the consumers' perceptions of the environmental impact of protein-rich products are only slightly related. That said, consumers have awareness and an interest in sustainability, but one that may not necessarily turn into purchasing behaviors as they need to thoroughly estimate the extent of food choices and environmental impacts (Siegrist et al., 2019). Therefore, more and more companies and researchers are looking for a new possibility to replace meat products or find other protein products to achieve the same or similar nutrients, flavor, and texture as meat products. Meat substitutes and newly developed proteins have become popular trends and directions. This

section will mainly introduce some of the meat substitutes, their advantage in achieving sustainability, and the challenges they will face as a commercialized product.

Meat analogue definition and categories

Meat analogues or meat substitutes are defined as a kind of food product that mimics meat's sensorial qualities and chemical characteristics (Kumar et al., 2017). It can be divided into plant-based, cell-based, and fermentation-based (Lei Sha et al., 2020). Plant-based proteins as meat analogues have a long history and different types, including lipids (edible vegetable oil), soybeans, cereals, legumes, and more. They can be used separately but also could be used in combination for better taste and structure. Among all these categories, soybean-based protein is the most widely used one while also being readily available worldwide (Singh et al., 2021). Soy protein can also lower blood cholesterol (LDL) and trimethylamine-N-oxide, which is potentially correlated to cardiovascular disease. In addition, soybeans can produce ammonia by bacterial symbionts in their roots, making them not use nitrogen fertilizer. This will reduce the environmental impact because for general crops requiring nitrogen fertilizers, half of the nitrogen will get lost, entering the surface and groundwater (Messina et al., 2022).

Plant-based protein and cell-culture protein

According to the definition of crop sustainability, crops must be able to grow on acreage that has low water expenditure, and can maintain high yields. Alternatively, the source should be accessible, affordable, and culturally acceptable while positively contributing to the environment (FAO). Stephanie Grahl et al. (2018) mentioned that spirulina contains up to 63 percent protein. Compared to the average 35-40 percent of protein, it also has a high antioxidant activity due to

the containing phycoerythrin. Phycoerythrin could also use as an alternative for artificial coloring in food industries. As an extracted microalga, spirulina also has good digestibility while containing essential amino acids and minerals, such as iron, zinc, and copper. It also has vitamins B, C, and E. Containing 1.6 to 3.2 ug of vitamin B, which can be a good vitamin supplement in daily intake recommendations (Ramírez-Rodriguez et al., 2021). The challenge of spirulina cultivation is the high cost of the chemical-based culture medium, like sodium bicarbonate and sodium nitrate, which provides a carbon and nitrogen source, respectively. So, researchers have attempted to use wastewater. Wastewater having a high nitrogen and phosphorus content makes it a suitable replacement for the chemical culture medium. According to Hooi Ren Lim et al. (2021), bacteria in wastewater can give carbon dioxide to promote spirulina growth. At the same time, it can take in oxygen produced by spirulina, having a closed circle as a result. Swine waste generated from the pig-domesticating industry could also be considered a cultivation medium for spirulina. This method is a viable option for recycling the swine wastewater, but too high or too low algae concentration, in the beginning, will cause different problems. The former will have low photosynthesis and later will make the algae unable to adapt or die early (Cheunbarn et al., 2010).

Single-cell Protein

Single-cell protein (SCP) is dried cells of microorganisms or total protein extracted from the biomass. SCP has a high protein, low fat, and high protein: carbohydrate ratio and contains other vitamins and essential amino acids. There are several ways to produce SCP, such as using high-energy resources (gas oil, neutral gas), renewable plant resources (starch, sugar, and cellulose), and wastes (such as sulfite waste liquor, whey, milk, and fruit waste) (Bratosin et al.

2021). As Chewapat et al. (2016) experimented, undiluted wastewater was filtered to separate the large particles and then sterilized at 121 degrees Celsius for 30 minutes. After analyzing the water quality (chemical oxygen demand, total Kjeldahl nitrogen, total phosphorus, and total solids) using the Kjeldahl method and stannous chloride method, the strain will be cultivated in the pre-treated wastewater under a neutral (6.8) pH with 1 percent of additional carbon sources (malic acid, glucose, and sucrose) to serve as carbon and energy sources for bacteria. The resulting cells of *Rhodospseudomonas* contained 60.1 crude protein percent and included all essential amino acids. Other ways, like extraction of pectin and phenolic compounds from almond hulls, are thought to be able to produce exopolysaccharides like pullulan, which is a linear polymer and could be used in SCP production (Najari et al., 2022).

Application limit and challenges

However, those methods and ideas still face many challenges from various aspects. The market shares of alternative proteins remain low, and multiple studies show that alternative proteins have a low acceptance compared to traditional meat products. A massive 67 percent of 533 respondents answered that they would choose to purchase beef when available, and only 27.2 percent will choose to purchase plant-based protein products (Slade, 2018). Admittedly, many techniques still need to be fully proven to be practical on a commercial scale, and one of the most important reasons consumers fear new technology and concept. There are concerns for the environment and health, but consumers still are more likely to value taste at the top of their list. Social norms, the influence on the acceptance of alternative proteins exerted by consumers' surroundings, are also crucial in shaping the opinion and attitude against those protein products (Onwezen et al. 2021).

Moreover, plant-based protein itself should not only appeal to the consumer with its health benefits but also its sensorial attributes. Meat alternatives generally need to mimic the flavor of meat and its aroma, and flavor loss will happen easily during thermal and high-pressure processing; companies need to use thiamine or other reducing sugars and amino acids to replicate the meat's aroma. The coloring will also be needed since proteins like soy and gluten give a yellow-brown hue that is not attractive or like meat products (Ahmad et al., 2022). The processing is more expensive than traditional meat products, and consumers, in general, still need to believe in its sustainability and potential. Not to mention the processing, like wastewater treatment, needs a lot of preparation work, such as diluting the wastewater beforehand. The direction of meat/protein alternatives is worth further study in the future. The three big challenges:

1. The practical production and sale of different non-animal-based proteins needs to be proven and experimented
2. The consumers and their knowledge of meat alternatives and non-animal-based protein
3. The improvement in texture and appearance, or other sensorial attributes close to traditional meat

Food Waste Management

Overview of food waste and environmental impacts

After arriving at consumers' tables, food products are inevitably getting wasted by many families for different reasons, and food wastage has become a significant concern worldwide. According to FAO, food loss and waste refer to a decrease in food's qualitative or nutritional value (edible parts) throughout the supply chain that was intended for human consumption (Liu et al., 2016). FAO has assumed that one-third of food produced is wasted globally, and developed countries are wasting larger amounts of food. An amount of 95-115 kg of food is being wasted per capita in Europe and North America each year (FAO, 2011). As Harish Jeswani et al. (2021) stated, primary production waste is farmers over-producing or losing agricultural products during the initial phase of the food-producing chain. Those farmers are generally concerned about decreased production due to poor weather conditions and pest infestation. They overplant, causing excessive food production from the initial and post-harvest stages since food is not meeting desired quality and may get discarded and eventually wasted. Total waste will cause 3.3 Gt of carbon dioxide without even counting the greenhouse gas emission from land usage and other resource waste such as water and energy wastage (Munesue et al., 2015). Food waste, as an essential part of the whole food system, is undoubtedly linked to sustainability, including overusing fertilizers because of overplanting, competition in using water and the degradation of water quality, and the relationship between the irrigation system and the groundwater depletion (Zach Conrad et al., 2018). This part will talk about several ways to deal with food waste and the challenges involved throughout the process.

Incineration

Incineration is one of the most used technologies; many countries, such as Singapore, China, and Malaysia frequently utilize it. The process of burning food waste into ashes under high temperatures with fuels under 800-1000 Degrees Celsius will eventually lead to volume reduction, and the ashes will be landfilled. Incineration ultimately kills the pathogens and will achieve a 90 percent volume reduction (Yingqun Ma et al., 2019). Felix Mayer et al. (2021) conducted the environmental life cycle analysis for incineration. It happened in a waste incinerator, downstream ash disposal, and the co-combustion from the lignite power plant. The whole cycle starts from waste collection to residues that cannot be used or dealt with further, and environmental impacts are calculated via the ReCiPe method. The 2017 ReCiPe is a method that embraces the impact and includes the following factors published by Goedkoop et al. (2008), starting from the raw land usage as parameters combining midpoint indicators including ozone depletion, radiation, climate change, marine water, fuel consumption, mineral consumption and endpoint indicator which is damage to calculate the impact on human bodies, ecosystem impact and the resource cost. The 2017 ReCiPe method considers more damaged pathways, such as an increase in respiratory disease, various types of cancer, and other diseases (Huijbregts et al., 2017) in the ReCiPe updated method. From the calculated results, incineration creates the most exported net heat and electricity. It also has the highest added energy compared with anaerobic digestion and hydrothermal carbonization. It also does not have feed prepared from food residues since it turns into ashes and will not be available for contributing any nutritional value, unlike recycling liquid feed to pigs or other animals. As Ogino et al. (2007) stated, incineration requires more significant water consumption yet lower electricity than other methods.

Anaerobic digestion

Anaerobic digestion is another way to resolve food waste problems. Instead of burning all the food waste, it is a technology that turns into renewable energy in four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Pramanik et al., 2019). According to Xu et al. (2018), microbes convert biomass and wastes into biogas containing 60-70 percent methane and 30-40 percent carbon dioxide). The overall mechanism allows stabilizing organic wastes and transfer of lignocellulosic materials to easily degradable food wastes as well as producing renewable energy and offering other nutrients. Those biogases could be used in different applications, such as heat and electricity generation in combined heat and power systems (Labatut et al., 2018). Slorach et al. (2019) have proposed an environmental sustainability calculation of food waste in the UK. Assuming the anaerobic digestion plant has a mesophilic reactor and a 25-year lifespan, biogas production, electricity, heat consumption, and retention time are considered in the calculation. The methane production from anaerobic digestion ranges from 1 to 3 percent of the amount of biogas produced and has 40 percent of nitrogen fertilizer displaced and 100 percent of potassium and phosphate fertilizer displaced, which could all be used as effective mineral fertilizers. However, the whole process does depend on many aspects. Pramanik et al. (2019) stated that temperature during the process highly affects methane production. Lower temperatures will reduce methane production due to potential cell energy fatigue and intracellular substance leakage. Higher temperature does offer better growth of the methanogenic bacteria and reduce the retention time, but thermophilic conditions also require more heat energy; at the same time, a lower retention time (average time that the liquid spends in the digester) does not always indicate a good thing since it will have less time to have optimal

degradation process for the substrate. The pH is an essential parameter as well, as microorganisms are very sensitive to pH since they have a different range in which to grow. The ideal growth pH for hydrolysis, acetogenesis, and methanogenesis is 6.0, 6.0-7.0, and 6.5-7.5, respectively, while the pH for the enzymatic bacteria for acid-forming bacteria and methane-forming bacteria is only 5.0, and 6.2 respectively (Leung et al., 2016). To have a stable and properly functioning process, the product needs to have at least a 1.4:1 molar ratio between HCO₃/Volatile fatty acid, and a volatile fatty acid concentration in the range of 5800-6900 mg/L will inhibit the methane production completely (Shi et al. 2018).

Hydrothermal Carbonization

Other ways like hydrothermal carbonization, a thermal conversion process making wet feedstocks convert into a value-added liquid or solid and gas products without drying beforehand. It requires a lower temperature than incineration (180-250 degrees Celsius) and lowers energy input (Idowu et al., 2017). The afterward transition, especially nitrogen, could be used as solid fuels. Hydrothermal carbonization will convert waste to energy in only hours, the solid hydrochars will be easily transferred, and water could be reused. In hydrothermal carbonization, carbohydrate, protein and lipid will go through the same process and produce the identical end product, which is hydrochar. All three go through hydrolysis and produce glucose and fructose (carbohydrate), amino acid (protein) and fatty acid (lipid), respectively. Glucose degrades into propenoic acid, and dehydrate to nitrogen free polymers, finally into hydrochar through polymerization. Fructose and amino acid has the Maillard reaction and produces furan and amino organic acid, respectively. Both converts into ketones and aldehyde during dehydration and condensation and finally produces hydrochar. Fatty acids via amidation produces fatty acid amide and polymerized into hydrochar.

However, without more data and the high cost of a reliable model makes hydrothermal carbonization a less practical method for industrial applications. Current data and literature cannot build up large-scale modeling, and the models only work with accurate equilibrium and kinetics data. In the future, more modeling and data should be acquired to guide practical decisions (Ischia et al., 2021).

Conclusion

Food sustainability connects many diverse issues in food production, and this review addresses only some aspects. Achieving food sustainability is still very long since new technologies have not been fully commercially realized. The barrier between companies, researchers, and consumers are still hard to overcome, and educating consumers to prevent their bias requires patience and extensive work. As 2050 approaches, 10 billion people need to be fed, according to the United Nations (Vågsholm et al., 2020). That increase in population truly requires us to approach food sustainability and food decrease waste from food processing, packaging, and wastage of leftovers as soon as possible. This paper introduces diverse solutions that people use to solve or manage the food system's problems, but none alone perfect. Food sustainability is a long-term dilemma that cuts across stakeholders.

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