Chapter

Evolution of the Soil-Based Agriculture and Food System to Biologically-Based Indoor Systems

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Abstract

There is no area of human activity more basic to society than a sustainable agricultural, food and natural resource system. The 'major' question is, how will food be produced sustainably for the expected global population growth to 9.5–10 billion people by 2050? The agriculture and food system is a highly complex adaptive system, operating across the spectrum of economics, biophysics and sociopolitics. There is a need to move beyond contentious debates between many constituencies, rooted in ideological solutions, to acceptance of a broad array of different approaches. This chapter focuses on the evolution from long and traditionally soil-based systems to biologically-based indoor systems, largely independent of soil with unique characteristics. Science and technology advancements have been critical to achievements of the existing land/soil-based systems and are equally critical in development of the emerging biologically-based indoor systems of controlled environment agriculture (greenhouses and vertical farms) and plant-based food alternatives, cell-cultured foods and 3D printed foods. Thus, there is no system more in need of and more likely to benefit from a comprehensive application of convergence thinking across disciplines and stakeholders.

Keywords: Agriculture, Food, Sustainability, Systems, Digital Ag, Computing and information science, Renewable energy, Sensors, Robots, Drones, Regenerative agriculture, Circularity, Nanotechnology, Biotechnology, Plant-based food alternatives, Cell-cultured foods, 3D printed foods

1. Introduction

With the projections that global population will grow to as much as 10 billion by 2050, there has developed an increasing concern in how this population will be fed, how will food be produced and can it be done sustainably, what will constitute a healthy diet, will the environment be destroyed in the process, will natural resources and ecosystems be compromised, will the food system reduce or increase hunger and poverty, and will the system enhance or decrease equity and access to food for a healthy and productive global population? These and many more critical questions challenge all of us who are a participant in the food and agriculture system (FAS) and every one of us is involved at some level ranging from our daily consumption to innovative scientific research. Thus, one might first ask, what is meant by a food and agriculture system? A report of the National Academy of

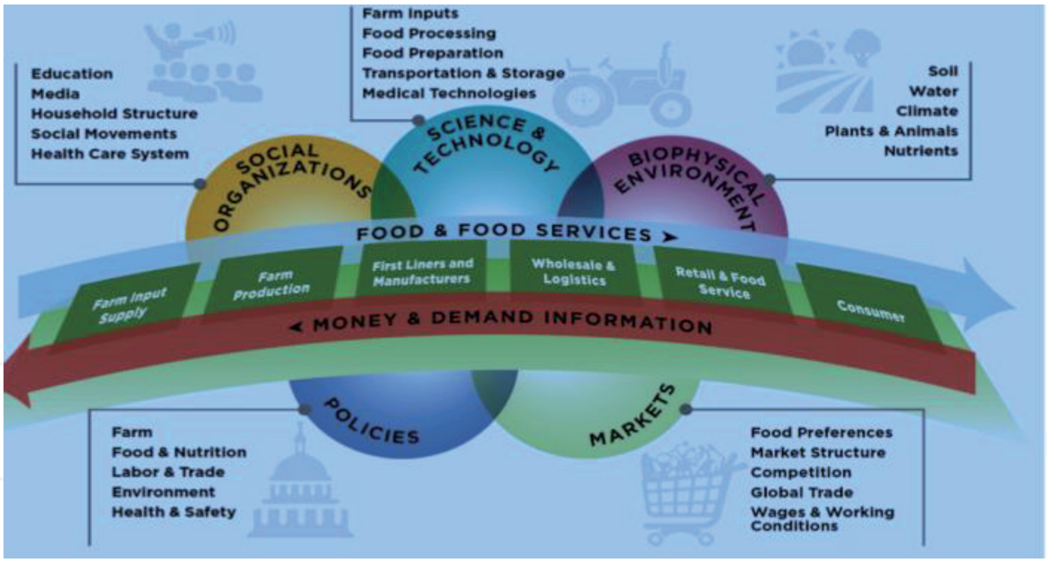

Figure 1.
Links between the food supply chain and the larger biophysical and social/institutional context [1].

Sciences, Engineering and Medicine (NASEM), characterizes the food system as a complex adaptive system that operates across a broad spectrum of economics, biophysical, and sociopolitical contexts [1]. This is captured in **Figure 1**.

The area of Food and Agriculture System (FAS) has been addressed by a number of excellent reports addressing the system from numerous perspectives. Specifically, the World Resources Foundation Report, *Creating a Sustainable Food Future* [2] presents a menu of solutions to feed nearly 10 Billion people by 2050. The report explores 22 items in broad terms that are suggested to stabilize the climate, promote economic development and reduce poverty. An Expert Panel presents a comprehensive report, *Socio-Technical Innovation Bundles for Agri-Food Systems Transformation* [3]. The Panel presents a vision within four core objectives: healthy and nutritious diets (H), equitable and inclusive value chains (E), resilience to shocks and stressors (R) and climate and environmental sustainability (S) which they characterize as HERS.

A report from EAT-Lancet Commission, *Food Planet Health: Healthy Diets from Sustainable Food Systems* [4] emphasizes a goal of transformation from current diets to healthy diets, sustainable food production and reductions in food loss and waste. Walker and Buhler [5] emphasize the role of biotechnology in catalyzing holistic agriculture innovation across a biological scale with a focus on smart machines, advanced sensors, big data, digital science, artificial intelligence, and controlled environment agriculture. A workshop sponsored by the National Academy of Science, Engineering and Medicine (NASEM) explored the future of food in a review of current and emerging knowledge about innovations for food systems [6].

2. "Toward" a sustainable food and agriculture system

Agricultural productivity has been a consistent and important focus during the 20th century and the 21st century, with good reason, to feed a growing world population. However, while providing safe and affordable food remains a driving force for the FAS, there are emerging and numerous factors that challenge our present and future FAS. Some of these are: impacts of the FAS on the environment; trust in science and technology; increasing urbanization; climate change; changing food preferences; globalization; integrated value chains; international regulations;

economic viability of rural communities; and more recently a recognition of the disruption that major events such as a pandemic can create for the FAS. Friedman [7] captures these as a time when the three largest forces on the planet (technology, globalization and climate change) are all accelerating at once, creating the greatest inflection point in history.

Since the 1990's to present, the sustainability of the FAS has become an accepted concept to capture the intersection of environment, economics and equity (or social responsibility). The concept of sustainability arising from the report, *Our Common Future,* [8] has become widely applied to many systems. In the opinion of many people, it has become over utilized and as such does not have significant meaning. Relative to the FAS, the NRC report [9], *Toward Sustainable Agricultural Systems in the 21st Century,* states, "The transformative approach to improving agricultural sustainability.... would facilitate the adoption of production approaches that capitalize on synergies, efficiencies, resilience characteristics associated with complex natural systems and their linked social, economic, and biophysical systems".

The preference of this author is to describe sustainable development as a "process of change in which the direction of investment, the orientation of technology, the allocation of resources, the development and functioning of institutions, and the advancement of human and community well-being meets present needs and aspirations without compromising the ability of future generations to meet their own needs and aspirations" (adapted and modified from [8, 10]). It suggests an imperative for action by which goals for development of the FAS can be measured. Moreover, in addition to implications for resources, it embodies attributes of the environment, economic and social responsibility now and into the future.

At an international level, the United Nation's Sustainability Development Goals [11] have been used widely to encourage development that meets sustainability objectives (**Figure 2**). At first glance it would appear that SDG 2 (zero hunger) would be the primary SDG for the FAS. But on further reflection, it is clear that because the FAS consists of a web of interactions across many complex interlinkages, todays FAS is strongly connected to the other 16 SDGs as well [3]. All of the elements of growing, harvesting, storing, processing, distributing, consuming and managing food losses and wastes are encompassed by the SDGs.

Figure 2.
The 17 sustainable development goals [11].

The recent report, 21st Century Agriculture Renaissance: Solutions from the Land, [12] offers a vision for strategies encompassing climate smart agriculture through 1) sustainable intensification of production, 2) adaptive management and 3) greenhouse gas reduction. The report highlights projects from across the globe and across various farming systems with a focus on indicating which of the SDGs goals are addressed by these respective projects.

3. An evolving food and agriculture system (FAS) to 2050

Domestication of plants and animals can be traced as far back as around 11,000–9,000 BC [13]. From its origin, a fundamental element of the FAS has been a land-based (soil-based) agricultural production system. Today we have experienced the evolution of a highly advanced FAS through emergence of the science and technology of DigitalAg, artificial intelligence, sensors everywhere, internet of things (IoT), genomics (including CRISPR), drones and robots with the one consistent factor being the use of land, the soil. However, 'new' emerging subsystems are developing, based largely on nonland-based, even soilless-based indoor facilities. It is the purpose of this chapter to briefly trace this evolution of the FAS.

First, impressive highlights of key science and technological innovations in the 'conventional' FAS are discussed. Then, science and technological innovations in an 'alternative', largely soilless and indoor system are highlighted. The author recognizes that to do this in one chapter is beyond an ability to cover many significant science and technology innovations, particularly in the 'conventional' FAS. However, the choice has been to focus on science and technologies that are perceived to have potentially a large impact going forward to 2050, and are, in a sense, 'guesses' about a future FAS. A further caveat is there is an over emphasis on the natural sciences with a largely inadequate effort to address the very important social and cognitive sciences.

3.1 Innovations in 'conventional' FAS

The use of 'conventional' is intended to represent soil-based systems. For the purposes of this chapter, science and technological innovations are focused on: (i) computing and information science (Digital Ag), (ii) nanotechnology, (iii) biotechnology, (iv) renewable energy, (v) electrification, (vi) regenerative agriculture, and (vii) circular economy.

3.1.1 Computing and information science (Digital Ag)

The FAS has increasingly embraced computer and information science at many levels from large farmers to poorest farmers in developing countries through an integration of sensors, satellites, tablets and cell phones. Research, teaching and extension (outreach) programs in Digital Ag have been developed in many land grant universities in the U.S. and universities around the world. Like sustainability, Digital Ag is defined or described somewhat differently by various proponents. A description of Digital Ag by the Cornell Institute for Digital Agriculture (CIDA) is given in **Figure 3**, including linkages to basic elements of innovation, discovery, and analytics with broad applications to areas within the FAS. A key element of CIDA is its ability to bring diverse people together from the Colleges of Agriculture and Life Science, Engineering, Business, Veterinary Medicine, and Computer and Information Science at Cornell University.

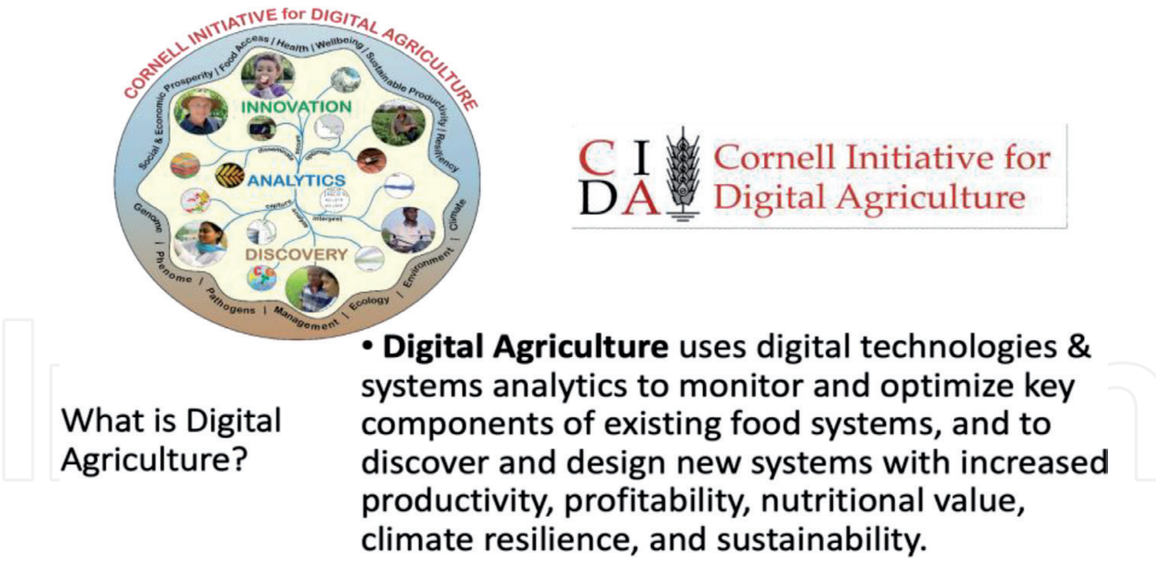

Figure 3.
The Cornell Institute for Digital Agriculture.

The capability of Digital Ag ultimately depends on an integration of critical elements for a successful system:

- Sensors (including drones, robotics, artificial intelligence) to initiate data acquisition in the field,

- Autonomous transfer of data from sensors [likely many, an Internet of Things agriculture (IoTA)] by wireless communication with digital devices (computers, tablets, and smart phones),

- Analytical devices with software capability (machine learning, artificial intelligence and handling of 'big' data) for storage, analysis, synthesis and reporting results, and

- Organizations (startups, consolidations and market developments) to apply recommendations to practice in the field.

Given that digitization is spreading through all aspects of food and agriculture one might ask, what is the difference between precision agriculture, smart agriculture and digital agriculture? There is not a unanimous definition, but for purposes of this chapter, the general descriptions offered by [14] are adapted to suggest that precision agriculture seeks to optimize conditions by means of sensory analysis and precise application technology, smart agriculture is a further development of precision agriculture to support decision making, and digital agriculture integrates concepts of both precision and smart agriculture to create value from data.

3.1.1.1 Sensors

It all begins with sensors and with the great advancements in sensor development, it is possible to study plant and animal physiology beyond the laboratory to measure, monitor and activate actions in plant, animal, and microbial production systems. The addition of the Internet of Things, Agricultural (IoTA), big data analysis and artificial intelligence is promoting a high-tech agriculture driven by data. Especially in the application of nanoscale science and technology, sensors and biosensors have been a major area of research and development. In a following section on nanotechnology, numerous examples of sensors in various applications are addressed.

3.1.1.2 Robotics

Robots have clearly moved from many industrial applications to become a significant new technology in the FAS. In labor-intensive crops and in specific identity applications, robots have assumed an important role. A few examples are: (i) identify weeds and implement weed control (e.g., mechanically remove weeds, employ microwave technology to kill weeds, and other methods); (ii) spot onset of plant diseases or pests and deliver intervention schemes (e.g., citrus greening, early potato blight, and many more); (iii) deliver fertilizer, pesticides, and herbicides at specific sites; (iv) spot controlled spray delivery in vineyards and orchards (including pollinator applications); (v) robotic 'duck' in rice fields to control weeds without pesticides; (vi) robots to pick fruit (e.g., apples, citrus, strawberries, raspberries, and more), **Figure 4** illustrates an autonomous fruit picking robot in a development stage; (vii) robot for transplanting; (viii) soil robots for soil testing and determine water-use effectiveness; (ix) in-food processing plants, robots to size, sort and package produce; and (x) autonomous robotic vehicles (including tractors, some electric) to perform field operations that could reduce soil compaction and simultaneously track data.

Robots have entered the dairy farm to milk and feed cows. Cows enter a special stall and are milked while feed is available, during milking based on production. Access to the milking stall is based on n times milking per day as a function of milk production. Cow identity is transmitted by an electronic animal tag and sensors within the teat cup provide data on temperature, milk conductivity, and milk quality. A highly desirable future biosensor would detect progesterone levels that could provide key data on reproductive status (estrus). A single robot station can handle about 40–50 cows per day which makes the system compatible with small farms as well as large farms. The milking robot has been adopted on small farms to address challenges of available human labor, freedom from the commitment of twice daily milking (minimum) permitting a more normal life, and because the cow can be milked more often, increased production has been experienced. **Figure 5** illustrates 2-robots on a small New York dairy with 100 cows. Also, a few large rotating milking parlors with robotic milking units have been installed across the world.

Figure 4.
Flying autonomous robot in development for picking fruit, (https://www.tevel-tech.com).

Figure 5.
Two robots on a New York farm of 100 cows.

The development and production of field and harvest robots is a global business. *Future Farming* [15] has produced a robot catalog with 35 field and harvest robots from sixteen countries. In this first edition, seven of the robots are manufactured in the U.S. and six from the Netherlands. It is anticipated that numbers will continue to increase significantly going forward.

3.1.1.3 Drones (unmanned aerial vehicles, UAV)

While drones (unmanned aerial vehicles) have been widely employed in military missions and for intelligence gathering, their use in agriculture is exploding. Relatively inexpensive and reasonably simple to operate, drones can be equipped with sensors, cameras and specialized hardware to perform a large array of functions in agriculture. Equipped with appropriate devices, drones are: (i) used to develop high-definition maps of fields that provide an ability to create prescriptive-defined application of sprays, fertilizer, pesticides, and herbicides, **Figure 6**; (ii) used to count the number of plants, fruit and flowers to forecast yields; (iii) employed to distribute seeds for crop planting; (iv) used when equipped with multispectral, hyperspectral and thermal cameras to measure chlorophyll, crop biomass, and plant health, as well as determine ground temperature, plant numbers,

Figure 6.
Group of drones capable of performing functions of high-definition maps of fields to create prescriptive-defined application of sprays, fertilizer, pesticides, herbicides and seeding.

soil water content, and estimate crop yields; (v) a potential way to deliver contraceptives to manage wild horse and burro population; (vi) used to monitor a plant's water stress and control irrigation for efficient water use; (vii) used, in absence, or in case of an inadequate number of normal bee pollinators, 'nanobees' (miniature drones) to supplement the pollination process; (viii) use drones in outdoor livestock systems to monitor animals for estrus behavior as well as control and manage the herd, and (xi) employed to monitor and track animals in inaccessible areas in the natural environment.

3.1.2 Nanotechnology

Nanoscale science and engineering offers the potential to significantly revolutionize the FAS. It can play an important role at each point along the FAS supply chain from production through consumption and including management of food losses and wastes [16, 17]. In broad terms, nanotechnology can be a key element in: (i) "re-engineering" of crops, animals, microbes and other living systems at the genetic and cellular level; (ii) development of efficient, "smart" and self-replicating production technologies and inputs; (iii) development of tools and systems for identification, tracking and monitoring; and (iv) manufacture of new materials and modify crops, animals and food products.

The major advancement of applications of nanotechnology in the FAS has occurred largely since 2000. A national research grants program at the USDA/NIFA (United States Department of Agriculture/National Institute of Food and Agriculture) initiated in 2002 has been an important driver of the research in the FAS over the past two decades. The areas of applications have included food quality and safety, animal health monitoring and management, plant systems, environmental systems, and assessment of societal impacts. Just a few applications are: (i) nanomaterials for crop and animal disease detection and detection of residues, trace chemicals, viruses, antibiotics and pathogens; (ii) enhance plant nutrient uptake, nutrient use efficiency, and fertilizer efficiency by controlled release of agrochemicals; (iii) seed coatings with nano-based chemicals to promote seed gemination and deliver long-term disease and pathogen resistance; (iv) DNA-based genetic materials using DNA-based nanobarcodes with a multi-probe sensor to detect pathogens (in plants, animals and environmental contaminants); (v) enhance water-use efficiency in crops by improving water retention and develop 'smart plants' to provide information to meet water needs and manage irrigation; and (vi) wide-spread advances in food packaging and food-contact materials for quality and increased shelf life (eliminate/reduce refrigeration).

Against this significant list of successful developments, the vision for the future of nanotechnology is impressive [17–21]: (i) enhanced sensitivity, selectivity, robustness, ease of use, cost-effective and longevity of nanosensors as key components of the field-distributed, intelligent sensor network for monitoring and control as part of the Internet of Agricultural Things (IoTA), **Figure 7**; (ii) use of common field crops (e.g., corn, soybean, and grains) and trees to make sustainable chemicals; (iii) design nitrogen-producing microbiome and seed coatings that promote crops to produce their own nitrogen fertilizer; (iv) tracking system for integrity of food (plant and animal) from production, transport, and storage to consumer consumption; (v) unique sensors: ingestible to monitor gut health, tooth sensor to measure food properties and chopsticks to detect food characteristics including nutrients; (vi) DNA life-like materials from agricultural biomass ranging from biosensors to biomanufacturing (replace petrochemicals) to development of value-added products including plastics that are biodegradable.

Figure 7.
Graphene sensors on plant leaf to sense water transpiration and measure plant water to control irrigation.

3.1.3 Biotechnology

The impacts of crop biotechnology has been studied over a 22-year period (1996–2018) on farm income and production [22] and on the environment [23]. Significant economic benefits at the farm level globally are estimated at $18.9 billion in 2018 and $225.1 billion (in nominal terms) for the 22-year-period. These gains are attributed at 52% to farmers in developing counties and 48% in developed countries with 72% of the gains based on yield and production increases and 28% from cost savings [22]. Returns on the investment in GM (genetically modified) crop seeds were calculated as an average of $4.41 per dollar invested in developing countries and an average of $3.24 per dollar invested in developed countries.

Assessments of environmental impact on GM crops estimate reduced global crop protection products use by 8.6% over the 22 years. Reduced GHG emissions through adoption of reduced tillage, that reduces fuel usage and improves soil carbon retention, are estimated to have an environmental impact reduction of 19% [23].

The annual report of the International Service for the Acquisition of Agri-biotech Applications (ISAAA) provides a yearly global update on adoption and distribution of biotech crops [24]. The 2019 report shows that GM crops increased to 29 countries with 190.4 billion hectares. A total of 72 countries have adopted biotech crops with 29 having planted crops and 43 additional countries importing biotech crops for food, feed, and processing.

The biological world in 2020 was marked by recognition of CRISPR (clustered regularly interspersed short palindromic repeats) with a Nobel Prize in Chemistry awarded to its inventors. Simply stated, CRISPR is a unique technology used to edit select genes by finding a specific bit of DNA inside a cell and then altering that piece of DNA. Already applied in human health, it is being used in plant science for traits that can prevent disease, create pest resistance, increase resiliency, and improve crop yields.

Animal biotechnology has contributed greatly to increasing livestock productivity through increased production, reproductive efficiency, genetic improvement, animal nutrition, and animal health [25]. Specifically recombinant bovine somatotropin (rBST) has been shown to increase feed conversion and milk yield. Major advances in animal reproduction has been experienced with biotechnology applied to genetics and breeding. The U.S. Food and Drug Administration approved in December 2020, a first-of-its-kind, intentional genomic alteration (IGA) in domestic pigs for food or human therapeutics [26].

Thus, if we are to create new crop varieties and increased yields and improved animal breeds, it is important to utilize the science of biotechnologies to advance benefits for both large and small farmers. The impressive potential of biotechnology should not be ignored and left underutilized.

3.1.4 Renewable energy

3.1.4.1 Solar energy

The challenges of meeting the needs of food, energy and water (frequently called a nexus) in the face of climate change have stimulated some innovative novel systems to co-locate agriculture and solar photovoltaics (PV), termed 'agrivoltaics'. The concept originally suggested in 1982 [27] has been further developed and analyzed by [28–31]. At present solar PV is being employed by large utility-grid systems and on rooftops but the opportunity to develop an integrated system with coupled application of PV and crop production on the same land maximizes land use without sacrificing crop land. In fact, a study of collocation in drylands [31] has shown synergistic benefits of reduced plant stress, improved yields and reduced PV panel heat stress. Development of enhanced semi-transparent PV panels would further advance collocation of PV panels and crop land. A conceptual rendering of the concept is illustrated in **Figure 8**.

Although **Figure 8** illustrates the solar PV panel elevated ('on stilts') to allow animals and equipment to move beneath the panels, another option could be ground mounted PV panels separated by an area between panels for farming [28]. At this point, the number of crops which have been evaluated under PV panels is limited. Also, the impact of PV panels on the microclimate of air temperature, wind speed and relative humidity needs significant study to assess plant response. Some studies have shown benefits for crops like tomatoes, and lettuce [30].

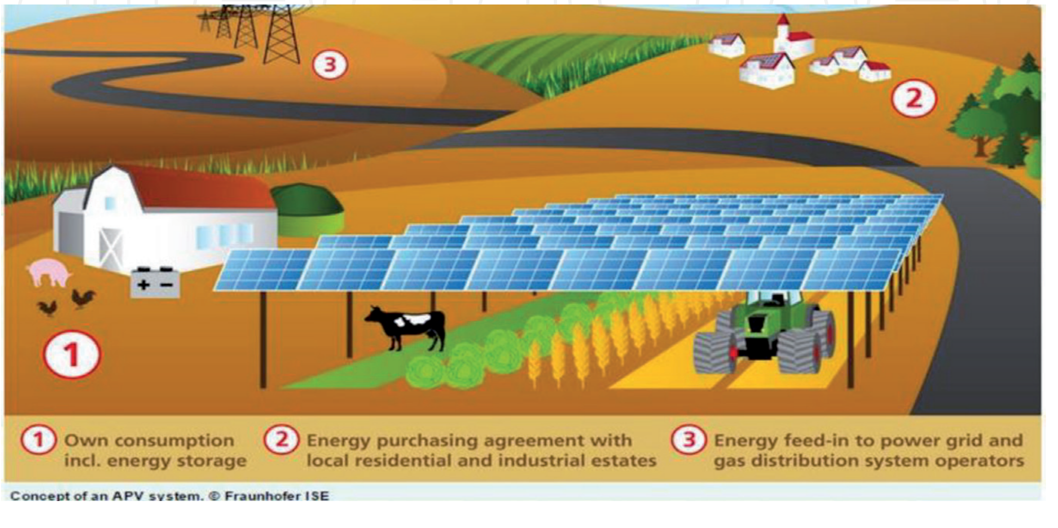

Figure 8.
A conceptual presentation of collocated solar PV and agricultural land with crops and animal production.

3.1.4.2 Wind energy

Much has changed from the early 1900's when many farmers used wind power to pump water and generate power from relatively small windmills. Today large wind turbines with generating capacity well above 1 MW are common on agricultural land, particularly in the West and Midwest, although many wind farms are found in other areas as well [32]. Like for solar PV, collocation of wind turbines on agricultural land has become common place. Farmers can lease land to wind developers, own turbines to generate power for their farm or as a farmer or group of farmers become a wind developer. Many farmers have found wind turbines on their land to be an important source of income. Typically, large turbines use a half-acre or less, including the access road, while allowing farming operations for cropping and grazing of livestock up to the base of turbines, **Figure 9**. As one farmer has been known to say, "it is a lot easier to milk a wind turbine than cows".

3.1.4.3 Bioenergy

3.1.4.3.1 Biofuels

At a time when the U.S. was dependent on imported transportation fuels, a Renewable Fuel Standard (RFS) was enacted by the Congress to create annual mandates for production of conventional biofuels and advanced biofuels. Corn ethanol became the predominant conventional biofuel and cellulosic-derived fuels as advanced biofuels. Significant controversary surrounded corn ethanol because of concerns of effects on food/feed prices, distortion of land use, increased cropland prices, and uncertainties about claims of environmental benefits. A report of the National Research Council (NRC, [33]) presented two findings: (1) the RFS may be an ineffective policy to reduce GHG emissions because the amount depends on how biofuels are produced, including changes to effects on land use, and (2) barriers to achieving the RFS due to high costs in producing cellulosic biofuels and market uncertainties. The U.S. Energy Information Administration [34], in projections to 2050, projects that the % of biofuels (ethanol, biodiesel and other biomass) may increase a bit between 10 and 13% depending on the scenario for oil prices.

Figure 9.
Large wind turbines integrated into agricultural crop land.

3.1.4.3.2 Biogas

A process using microorganisms, specifically a suite of bacteria, have been utilized to convert organic materials into biogas, primarily methane (~60–70%) and carbon dioxide (~30–40%), with small quantities of trace gases. Anaerobic digestion using methanogenic bacteria, in the absence of oxygen in airtight structures, has been used for many years, ranging from small home-owned digesters in China to advanced systems with increasingly large commercial tanks, highly instrumented in the U.S. and Europe. These large systems have been developed to manage animal manures together with food and other organic wastes by co-digestion to provide energy options of combined heat and power (CHP) and pipeline and transportation fuels) following processing and compression [35].

Anaerobic digesters number more than 250 in the U.S. while the number in Germany is now about 9,000. Germany has been particularly adept at using biogas to power bioenergy villages illustrating the potential for distributed energy generation in rural communities. It has become clear for economic success of anaerobic digesters that they operate as co-digesters by adding other organics in addition to animal manures [36]. Beyond direct products of biogas and digestate options, anaerobic digestion offers manure management opportunities for environmental benefits of reduced odors, reduced pollution and reduced GHG emissions. Opportunities for collaboration between businesses and farm digesters exist and are increasing. A recent example of this collaboration is a venture with founding members, Unilever, Starbucks and Dairy Farmers of America.

3.1.5 Electrification on the farm

The Rural Electrification Act of 1936 revolutionized rural America. Electric vehicles are revolutionizing the transportation sector. This revolution is also taking place in agriculture at an early stage with numerous equipment manufacturers launching, or working to develop, autonomous electric tractors [37]. Tractor companies, Monarch, Solectrac, Kubota, AGCO and John Deere to mention a few, are investing heavily in electric tractors and are in various stages in their development with the potential of limited availability as early as 2021. These tractors are equipped with autonomous hardware replete with many sensors and machine learning for data collection and tractor control.

At this point development of the electric tractor has been focused in the 30–40 hp. (horsepower) range (25 – 30 kW), largely due to the size and weight of batteries. An advantage of smaller equipment is potential for reduced soil compaction. **Figure 10** illustrates two experimental paths of John Deere, a battery-driven tractor and an electrically connected tractor (a long extension cord!).

First perceptions are that this high technology would be only applicable and affordable in 'industrialized' agriculture. However, the possibility of developing

Figure 10.
John Deere's battery-electric tractor and connected electric tractor.

electric-driven tractors and equipment is certainly conceivable in the developing world because smaller tractors and machines are well adapted to the small land holdings. The author envisions the co-development of solar PV for charging batteries to power electric equipment. Rapidly developing advancements in battery technologies and decreasing cost will be keys to adoption in the developing world. The unique idea of a cord-connected electric tractor, while not likely to be an option in U.S. agriculture, might well be an excellent way to connect solar PV to power electric equipment for the small farmer.

3.1.6 Regenerative agriculture

As previously noted, agriculture is coming under increasing scrutiny because of GHG emissions and negative effects on the environment. Drawing much attention recently is the practice referred to as 'regenerative agriculture". The term has no universal definition but is frequently used to describe practices to promote soil health by increasing soil organic carbon [38]. Practices commonly perceived to advance regenerative agriculture are no-till farming, cover crops, diverse crop rotations, rotating livestock grazing, and lessened use of fertilizers, pesticides and herbicides. Cropping system diversification has been shown to reduce negative environmental impacts of soil erosion and nutrient runoff, and reduced cropping inputs while maintaining crop yields [39, 40].

While there is general agreement that regenerative agriculture practices improve soil health and provide environmental benefits, some researchers [38] report that regenerative agriculture practices have limited potential to increase soil carbon sequestration. Nevertheless, some corporations have set up a carbon sequestration market (Bayer) and a carbon credit for soil carbon sequestered (Land O'Lakes) for farmers. In addition, Cargill, McDonald's, and Walmart Foundation are collaborating with the World Wildlife Foundation on regenerative practices to improve grasslands of the Northern Great Plains.

It is suggested that going forward farmers will be paid for soil carbon storage. However, this requires an ability to measure soil carbon and quantify change in the field accurately over time to assess the effects of differing practices. Thus, future research is needed to find new ways of soil carbon sequestration and develop the data through measurement of soil carbon content.

3.1.7 Circular economy in FAS

The concept of has been recently introduced in the FAS. The guiding principle is to: (1) design out waste and pollution, (2) keep products and materials in use and (3) regenerate natural systems within the FAS [41]. The Ellen Macarthur Foundation [41] articulates three ambitions for a healthy urban food system as: (1) source food regeneratively, and locally where appropriate, (2) design and market healthier food products, and (3) make the most of food. For too long the FAS has been primarily a linear system from production, postharvest, processing, distribution and consumption without regard to wastes incurred along the value chain.

Although recently introduced in the FAS [42], the fundamental concept has been applied and described by terms like 'industrial ecology' or 'industrial symbiosis' in numerous areas. It has been employed to mean that a waste from an entity (business, for example) would become an input to another entity (business), thereby circulating materials and keeping them in use within the larger system, essentially the concept of an 'ecosystem' [43]. This concept has not been adopted widely, although the concept of a 'Food Eco-Industrial Park' would be intriguing.

Specifically, technologies and systems applied along the value chain are needed to reduce food losses and wastes which are estimated to be as much as 30–50% globally and remarkedly similar across regions.

3.2 Innovations in controlled environment food and agricultural systems (CEFAS)

Emerging technological innovations, particularly over the past two decades have developed, based largely on a nonland-based or soilless-based indoor systems. These developing initiatives are captured by the term, 'controlled environment food and agricultural systems" (CEFAS) broadly, and more specifically by emerging subsystems, 'controlled biologically-based indoor food systems' (CBIFS).

CEFAS has evolved from a protected environment provided by greenhouses, originally with soil as the growth medium to advanced greenhouses with nutrient solutions to replace soil. Vertical farms have evolved further by using height (vertical) dimension to create intensification of the growing environment and greater yields per m^2 (production area). Both advanced greenhouses and vertical farms employ highly sophisticated measurements, controls and management. Sensors, computer control, artificial intelligence, machine learning and robots are common. These technologies are primarily devoted to growing fruits and vegetables and not practical for common field crops such as corn, soybeans, cereal grains and tuber crops, although recent research has studied the potential for wheat grown in vertical farms [44]. In addition, an increasingly significant area of a sustainable food future is aquaculture and specifically the development of the recirculating indoor system.

3.2.1 Recirculating aquaculture systems (RAS)

Fish, including finfish and shellfish, contribute about 17% of global animal-based protein for human consumption and particularly so in developing countries which consume more that 75% while producing greater than 80% of the global fish supply [45]. A major concern is that the annual number of fish caught in the wild, particularly in the oceans, has stagnated since the 1990s. As world consumption of fish has grown, aquaculture (fish farming) has developed, and almost half of the fish consumed comes from aquaculture. It is estimated that aquaculture production needs to double from approximately 67 million tons (MT) in (2012) to about 140 MT in 2050 [2].

Aquaculture, as described above, is based primarily on confined operations in a water environment, marine, such as 'cages' in oceans (along coasts predominately) or freshwater, outdoor ponds on land. The concept of a recirculating indoor aquaculture system (RAS) over the past several decades has emerged as an alternative system with advantages of greatly reduced land use and major reduction in water requirements compared to ponds. Simply stated the water is filtered from the growing tanks (confined environment) and recycled for reuse in the tanks, **Figure 11**. RAS have performed well relative to measures of productivity and environment parameters. A comprehensive treatment of recirculating aquaculture systems is provided by [46]. Challenges persist because of high capital costs, feed sources, concern for fish diseases, food safety, and consumer acceptance. Consumer concerns that farmed fish tend to have lower levels of omega-3 fatty acids than wild fish [47] and concerns about the highly intensive growing environment have limited acceptance.

Aquaponics can be an added element to an RAS by combining plants and fish. In an aquaponics system, fish provide waste that effectively fertilizes plants, thereby

Figure 11.
A recirculating aquaculture system.

creating a closed loop system (circular economy) [46]. Plants act essentially as a filter by taking up nitrates in the system. The benefits are little waste from the overall system and inputs are minimized.

Clearly, as noted, large projected increasing consumer interest for seafoods provide a need to advance aquaculture generally and RAS specifically. Thus, efforts to intensify aquaculture production by RAS need to be directed at approaches to mitigate negative issues of RAS.

3.2.2 Greenhouses

The concept of growing plants in environmentally controlled areas can be traced back to Roman times [48]. The concept of the greenhouse, as we have come to know it today, began in the Netherlands and then England in the 17th century. They have evolved from simple row covers to very large structures in the 1960s when materials such as polyethylene films, aluminum extrusions, special galvanized steel, and PVC tubing became available for various structural support frames.

3.2.2.1 Basic greenhouses

For purposes of this chapter the basic greenhouse is one where a plastic film (polyethylene) is supported by a light frame, often a hoop or A-frame in form. This type of greenhouse is primarily dependent on solar energy for heat in a cold environment, although some heating device may be employed in severe situations. Any ventilation is accomplished by natural ventilation with manual openings or slots to promote air flow for cooling. In times of high solar energy, shade coverings such as clothes are used. The plants are grown in soil at ground level or in raised beds. Movement of plants and materials are managed manually by humans with assistance of simple devices and equipment. Because the costs for the basic greenhouse are relatively low, they are used in small farm operations or in many urban settings.

3.2.2.2 Advanced greenhouses

The advanced greenhouse is defined here as a greenhouse with a highly controlled environment, high automation under computer control and using a soilless growing medium, hydroponic solution. The controlled environment for plant production consists of intensive assessment of the environment by numerous sensors to measure and monitor the parameters of: temperature, pH, relative humidity, dissolved O_2 in nutrient solution, electrical conductivity for dissolved salts in nutrient solution, CO_2 of inside air, and light intensity from the sun and supplemental lighting, and PAR (photosynthetically activated radiation) in μmol/m^2/s. Quality and optimum plant growth is dependent on plants getting an optimum daily quantity of PAR (mol/m^2/d). If the daily PAR is not provided by the sun, the computer will implement supplemental lighting to meet the desired value, **Figure 12**.

An advanced greenhouse consists of a complete system from germination of seeds to the finished product. Typically, the seed is planted in a fibrous material such as rockwool cube to germinate. Following germination, the cubes are inserted into a material (like Styrofoam) to float on the surface of the nutrient solution until fully mature.

Temperature will be controlled typically by mechanical fan ventilation under computer control of air flow by managing air intake openings. Where appropriate evaporative cooling may be used to provide cooling. Addition of CO_2 can be added to increase plant growth. Shading material can be used to reduce excessive solar energy and moveable insulation can be used to reduce heat loss at night respectively. Beyond the controlled thermal and growing environment, the advance greenhouse will include a significant automation for materials handling including robots [49].

3.2.2.3 Vertical farms (VFs)

Based on advances discussed for advanced greenhouses, the vertical farm uses the vertical dimension (**Figure 13**) to grow plants in stacked layers thereby increasing greatly the amount of product grown per unit area [50–53]. Like for the advanced greenhouse, the growing environment in a vertical farm is closely controlled for temperature, humidity, ventilation and the properties of the nutrient solution, including introduction of robotics. Five reasons to take vertical farms seriously are: avoid effect of weather and weather extremes, large reduction in water usage by as much as 95%, plant yields are high and the growing cycle is short, lower food losses, shorter supply chains because VFs can be located in urban areas, and products can be produced year-round [54].

Key challenges for VFs are high capital and energy costs. The issues of high energy consumption in VFs is due to full artificial lighting (LEDs) and for meeting cooling and humidification loads. More efficient LEDS and using LEDS tailored to the light spectrum for the specific crop, rather than the full spectrum, may save

Figure 12.
An advanced controlled environment greenhouse.

Figure 13.
A vertical farm.

electricity. Possibly the residual heat could be used in a surrounding case where a need for heat is needed. Clearly, because of large capital costs and energy requirements VFs will be a 'niche' system until these are resolved. In comparison with advanced greenhouses, where solar energy is utilized and where greenhouses can also be located in urban environments (rooftops and vacant lots for example), VFs would seem to offer uncertain benefits.

Efforts to conduct a Life Cycle Assessment of VFs and, in addition, approaches for an integration of VFs into cities are critical to assess the future of VFs. Numerous VFs have been developed and a substantial number, as well, are in the planning stages in the U.S. and Asia. Some of these are conceptualized to include solar energy directly, and inclusion of aquaculture and even livestock production [55].

3.3 Innovations in 'alternative', biologically-based indoor food systems (CBIFS)

Foods, like all materials, are an assemblage of molecules arranged in a specific structure and one is witnessing significant new biological/biochemistry efforts to create foods from plant or animal cells from the 'bottom up'. Three technologies (CBIFS) are characterized in this overview as: (1) plant-based alternative foods, (2) cell-cultured foods, and 3D printed foods. Because they use biochemical building blocks from proteins, carbohydrates, fats, and oils from plants and animals, CBIFS is a 'new' agriculture.

While much of the hype has been directed to burgers [56], there has been substantial advancement of other alternative foods, such as, for eggs, fish, shrimp, milk, yogurt, chicken nuggets, and chicken tenders to mention a few. The objective of CBIFS is to develop food products that mimic traditional foods with significant benefits. The benefits can be: (i) an environment unaffected by weather/extreme weather; (ii) year-round production; (iii) shortened growing cycles and higher yields; (iv) reduction in land, energy, and water use, (v) lower food loss and waste; (vi) shorter supply chains, local access compatible with urban settings; (vii) reduction or elimination of pesticides and antibiotics; (viii) reduction of GHG emissions; (ix) reduction in water pollution; (x) potential for enhanced micronutrients, and (xi) eliminate animal welfare concerns (growing conditions and slaughter).

However, there are potential uncertainties (questions), such as: (i) high capital cost; (ii) timeline to market; (iii) in some cases, high energy consumption; (iv) consumer acceptance; (v) concern about food quality and safety, particularly nutritional content and presence of growth hormones; (vi) price to consumers,

(vii) potential contamination; (viii) impact and possible detrimental effect for small farmers; (ix) proprietary nature of processes; (x) unproven technology, and (xi) whether the CBIFS benefits large-scale economies to the detriment of markets for small farmers [56–58].

Sustainability is critical to any future food system and is a driving force for CIBFS. In broad terms, CIBFS seeks to develop foods that impose less environmental impact, enhance human health, and reduce ethical implications of traditional animal-agriculture production, particularly for meat. Global meat consumption is estimated to increase 3% per year to 2040 [59, 60]. However, several groups [60, 61] forecast a major protein disruption in the conventional animal-agriculture system where engineered foods at the molecular level will lead to a reduction of as much as 50% or more from conventional meat and dairy by 2040.

In this section, a brief overview is presented for three types of CIBFS: plant-based alternative foods, cell-cultured foods and 3D printed foods. Through research and development each of these subsystems has a potential to enhance sustainability, availability, reliability, consumer acceptance, and quality and safety of food production.

It should be noted that food cost to the consumer is a critical issue for success of any new product. Over the past 5–10 years, numerous entrepreneurs, start-ups and food companies have created alternative foods that are already in the marketplace. In many cases, the price to consumers, at present, is higher than equivalent traditional foods, but the difference has decreased over time. As these emerging alternative products are improved, it is likely that cost to the consumer will be reduced to be comparable or even less. The food system is a high complex, adaptive system and like in other emerging technologies, there will be major changes with business failures and new players going forward.

3.3.1 Plant-based alternative foods

The development of plant-based alternative foods has become a very hot area, particularly for plant-based meat alternatives [58, 62–64]. Development of plant-based meat alternatives have attracted the greatest public attention. Environmental, human health, and concerns for animal welfare are prime factors. Among more than 50 manufacturers currently, (*Beyond Meat, Light Life and Impossible Foods*), are leading developers of plant-based burgers that are widely available in grocery stores, restaurants, and online. While burgers are a major food product, other products such as ground beef sausage, bacon and hotdogs are available.

Globally the food and agricultural system is estimated to generate as much as 34% of total GHG emissions with 71% from agriculture and related land use and land use change [65]. The opportunity for plant-based alternatives to substantially reduce environmental impacts was determined in a comparative study (Life Cycle Assessment-LCA) of the *Beyond Burger* and a U.S. beef burger (quarter pounder) by the Center for Sustainable Systems at the University of Michigan [66]. The selected parameters were GHG emissions, cumulative energy use, water use, and land use. The comparison was made to an LCA study by the National Cattleman's Beef Asssociation [67]. For the *Beyond Burger* system the results showed 90% less GHG emissions, with 46% less energy, 99% less water and 93% less land use. *Impossible Foods* also commissioned a study which found that their burger uses 96% less land, 87% less water and 86% less fossil fuel than a quarter pound beef burger. Independent LCA studies would be beneficial, given the rapidly changing ingredients being used to create plant-based meat alternatives.

Plant-based protein sources (legumes and cereal grains) are an important choice for both the vegetarian and traditional meat consumer. However, challenges remain for developers of plant-based proteins to deliver a healthy, nutritionally safe, tasty flavor, texture and appearance (color) comparable to traditional products. Because the development of plant-based meats involves complex processing of many ingredients, there have been concerns expresses about health benefits. One report [68] reviewed formulation and nutrient content of some common commercial products (burgers, hams and chicken nuggets) which contained as many as 20–30 ingredients. Comparisons yield a mixed story because plant-based meats provide about the same calories as traditional meat with more sodium, more potassium (helps eliminate sodium), no cholesterol, more iron, more B vitamins, more calcium and more saturated fat. Also, there have been reported concerns [69] about whether high-temperature cooking (grilling, frying, etc.) of protein foods could generate toxins and carcinogens. Thus, there is a need to assess whether plant-based meat protein would be any less safe or safer than traditional meat.

Consumer acceptance of plant-based meats and food products is key to the ultimate impact of these products. Substantial improvements have been made during the decade with plant-based burgers such that many people find them indistinguishable from a traditional burger. Nevertheless, the author suggests the need for future research and study in: (i) independent LCS studies to quantify environmental benefits; (ii) further evidence on health benefits, nutrition, and safety; (iii) development of new plant proteins sources; (iv) reduction in number of non-protein ingredients; and (v) reduction in cost to consumer.

3.3.2 Cell-cultured foods

Cell-cultured meat, also known as cultivated meat, has advanced at a rapid pace over the past 20 years. The concept, although relatively simple, uses animal cells nurtured within a bioreactor to produce food that is designed to mimic meat products [70]. Compared to plant-based protein where protein is extracted from plants, cell-based meat is created from cells extracted from animals and grown in a culture. Specifically, a small piece of fresh muscle, obtained by biopsy, from a living animal is disrupted by a combination of mechanical and enzymatic methods to produce stem cells [71].

Using culturing methods, the adult stem cell (called satellite cells), in the presence of relatively high serum concentrations, divide leading to multiplying populations. Tissue engineering methods are then used to differentiate these expanded cells into muscle and fat tissue, which lead to generation of a cultured meat product closely resembling conventional meat [72]. **Figure 14** illustrates, in broad terms, the process based on the starting point of obtaining adult muscle stem cells from an animals or pluripotent stem cells from an embryo [73]. However, a recent study suggests that it may be possible to grow cultured meat with much less dependence on animals by using a soy-based scaffold for support of muscle cells and form a meat-like 3D-cell structure [74].

Today, there is no cultured meat available for consumers to purchase at retail or food service outlets in the U.S., unlike plant-based meat, but there are 20 or more start-ups in the cultured meat space [60]. However, the Singapore Food Agency approved in December 2020 a cultured chicken product by Eat Just [75]. With an investment more than $100 million in global funding by billionaires and venture capitalists, there are significant efforts to develop the area [55].

It is very difficult to reproduce the diversity of meats from the numerous existing animal species, breeds and cuts so there is a great need to optimize cell culture technology [76]. A LCA [77] and a (TEA) techno-economic assessment [78] have modeled future large-scale cell-cultured meat production facilities and have shown reduced overall environmental impacts and the potential to be cost-competitive

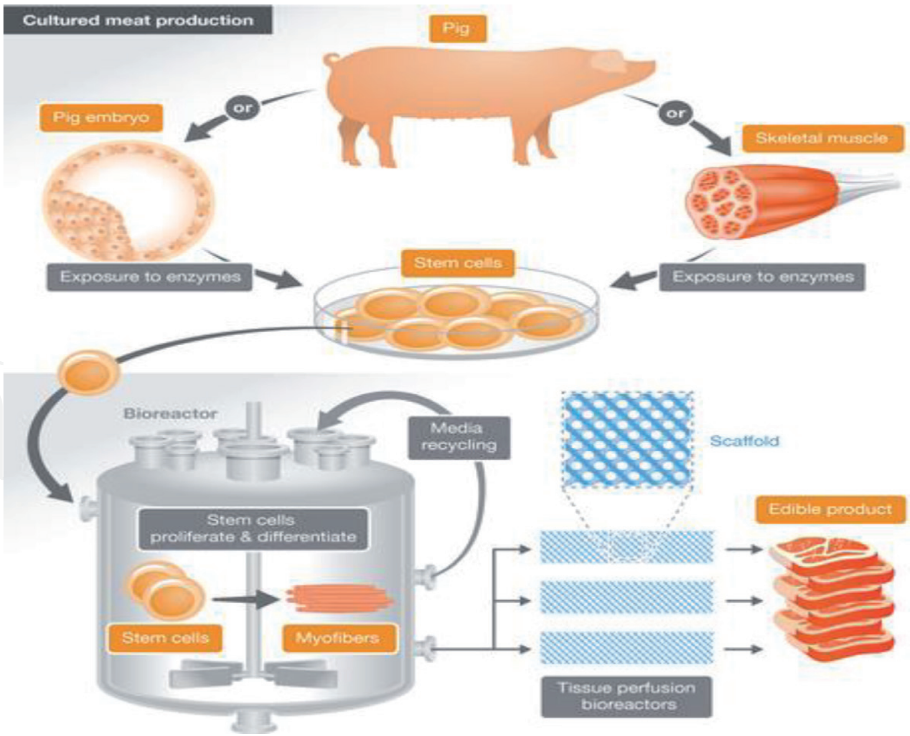

Figure 14.
The development process for cell-cultured meat [73].

with conventional meat by 2030. These are the first repots using data collected from active companies (more than 15) in the chain. The LCA shows cell-cultured meat is about 3.5 times more efficient (feed conversion ratio) than poultry which is the most efficient system of conventional meat production. The LCA in its comparisons with traditional meat includes the use of renewable energy in which case the reduction in GHG emissions shows a reduction of 17–92%, less land use of 63–95% and 51–78% less use of water depending on the respective conventional animal system.

However, studies by [76, 79] suggest that comparison is not that simple. They conclude that the relative comparisons with conventional meat depend on the type of systems for energy generation (i.e., decarbonized and renewable) and the specific production animal system. Thus, there is a need for independent and transparent LCA studies of cultured meat production.

A major challenge for cultured meat production is meeting consumer demands for flavor, texture, color, nutritional composition and cost [80, 81]. Conventional animal meat is high in protein with amino acids, vitamins and minerals. As development of cultured meat has advanced, the similarity to conventional meat has improved greatly, such that many people cannot distinguish a difference between the two [55]. An advantage that cultured meat can have is an ability to add texturizing ingredients, colorants, flavorings and nutrients to address sensorial and nutritional properties [80]. Challenges facing cell-cultured meat systems include: (i) replace animal serum with plant materials; (ii) reduce costs by material substitutions and advances in scalability; (iii) assessment of health effects, short and long term; (iv) conduct detailed, independent and transparent LCAs to quantify environment impacts; (v) eliminate growth hormone factors; (vi) develop cell lines that are more accessible; vii) safety assessment, particularly with respect to potential contaminants that might enter in the process; (viii) ability to replicate the diversity of conventional meats; (ix) address the issues of potential regulation, as well as labeling, and (x) develop a name or nomenclature for marketing (presently there is much variation and uncertainty about a common name).

3.3.3 3D printed foods

The combination of robotics and software has entered the realm of food manufacturing in the form of 3D printing [81–84]. 3D printing technology is a novel approach which can create complex geometries, tailored textures, and nutritional contents. The 3D technology can provide a 'customized food' to meet special dietary needs as well as mass customization. NovaMeat, a Spanish company, and Redefine Meat, an Israeli company, have utilized 3D technology to produce beef steaks and other meats that resemble animal meat.

In the 3D printing process, food ingredients are placed in cartridges, and the product is created layer by layer by a controlled robotic process, similar to 3D printing of non-food items. The technology has been employed to use tissue engineering to create meat and other food alternatives. Also, the 3D technology has been employed at the home scale to create 'designer 'foods. Depending on the specific food, ingredients can range from processed components (sauces, dough, etc.) to more elemental ingredients such as sugars, proteins, fats, and carbohydrates [82]. Some foods may require further processing, such as some form of cooking or storage. A significant challenge is linking material properties and structure to the printing process variables to get a desired 3D printed product. The parameters of control are those relating to the printer and those controlling the food-relevant parameters.

In Switzerland, Jungbunzlauer AG [85] is providing 'recipe cards' to guide consumers to use bio-based ingredients to create one's own dairy and meat alternatives. Recipe cards are available online to create foods such as non-dairy ice cream, cream cheese and yogurt as well as plant-based burgers and bratwurst. The respective recipe card provides a detailed list of ingredients, suppliers, quantities, together with directions to create the specific food product and with nutrition information as well. Thus, it seems not to be a great stretch that this information could lead to 3D printing of designer and specialized food products.

The 3D printing process compresses the value chain to a highly local system of inputs (ingredients), a single controlled process (the 3D printer) and a single output (the food product).

4. Conclusions

Meeting the demand for food of the growing world population will require both conventional land-based agriculture systems and controlled environment agriculture and food systems, including emerging controlled biology-based indoor food systems (CBIFS).

Already during the 21st century the impact of innovations in 'conventional' agriculture and food systems has been impressive:

- Digital Ag, driven by computing and information science, has progressed rapidly to offer technically advanced solutions to support an efficient FAS with decreases in food loss and waste with greater productivity, prosperity, and sustainability, with more to come,

- Sensors, robots and drones are, and will become even more ubiquitous moving forward,

- Nanoscale science and engineering, and biotechnologies (particularly CRISP) will continue to drive innovations in many areas of the FAS,

- Renewable energies of solar, wind and bioenergy are increasingly integrated into the FAS through co-location of sources on the land, as well as providing sustainable energy for rural communities, domestically and internationally,

- Electricity will be an increasing driving force in FAS for motive power of agricultural machines, including tractors and autonomous systems,

- Emphasis on the soil health is likely to increase substantially as a part of the initiatives in regenerative agriculture practices if it proves profitable and successful in sequestering significant carbon, and

- Circularity in the FAS is likely to be a major initiative in an effort to design out waste and pollution, keep materials in play and to maintain natural systems.

In acknowledging the fact that traditional FAS uses substantial land and creates considerable GHG emissions, an emerging area of food production has developed. Controlled Biologically-based Indoor Food Systems (CBIFS) can greatly reduce land area for agriculture production by largely soilless methods and produce foods with less environmental impact, enhance human health and avoid ethical concerns about traditional methods, particularly for meat. CBIFS described herein: recirculating aquaculture, advanced greenhouses, vertical farms, plant-based alternative foods, cell-cultured foods and 3D printing of foods are in various stages of development but are poised to grow in the future. Principal keys to growth are costs to the consumer and consumer acceptance. Nevertheless, numerous products are in the marketplace and already enjoy modest growth.

CBIFS use basic biochemical building blocks of proteins, amino acids, sugars, fats, carbohydrates, and oils from plants and animals. Thus, controlled environment agriculture and food systems, including CBIFS, should be viewed as complementary to conventional agriculture and typical supply chains. Further development of CBIFS foods that are as healthy, nutritious, safe and appealing as conventional foods will significantly contribute to the sustainability, resilience and circularity of food and agriculture systems.

Finally, there is a need to transcend the debate between numerous constituencies, rooted in ideological attitudes, to invoke and encourage an array of different approaches to meet the challenge of a food and agriculture system that is robust, safe, and sustainable in meeting the 17 Sustainable Development Goals for a sustainable planet.

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