Sustainable Food Technology

REVIEW

View Article Online
View Journal | View Issue

Check for updates

Cite this: *Sustainable Food Technol.*, 2024, **2**, 1365

Received 10th April 2024
Accepted 16th July 2024

DOI: 10.1039/d4fb00108g

rsc.li/susfoodtech

Food systems restoration

Dietrich Knorr *[a] and Mary Ann Augustin [b]

The current global food system is unsustainable. The depletion of natural resources and increased environmental emissions, climate change, biodiversity loss and increasing population contribute to food system unsustainability and food insecurity. Conventional intensive agriculture and industrial food production practices need to be examined, with a view to transitioning to more sustainable alternative agricultural production. Factors such as farm energy use and their effects on the biophysical environment and biodiversity, trade-offs between productivity and environment and agricultural policy contribute to agricultural production choices and sustainability. Alternative agricultural practices are discussed with a focus on farming systems which protect natural resources and biodiversity. These include alternative land and marine food production systems and the use of various cellular agriculture and culture-based methods for producing food. Selected emerging sustainable food systems are highlighted. Key actions for restoration of land and aquatic food production systems include rebuilding of soil and aquatic ecosystems, wider application of alternative sustainable agricultural and processing practices, and integration of innovative technology into traditional and emerging agricultural systems. These actions need to be supported by policy which encourages the co-creation of sustainable alternative agricultural systems by multiple stakeholders.

Sustainability spotlight

The restoration of food production systems is required due to the declining sustainability of food systems and their inability to provide food and nutritional security to all people. Food production systems that are more sustainable, preserve biodiversity, contribute to soil health, and that conserve the environment need to be developed. The importance of restorative actions to improve the sustainability of current agricultural production systems and the potential sustainable alternative future production systems are discussed. Although there are challenges to the adoption of sustainable practices in food production systems, it is imperative that all stakeholders work together to facilitate the restoration of food systems that operate within our planetary boundaries.

1. Introduction

The current epoch, the Holocene which began 11 700 years ago, may be replaced by a new one based on the impact of humans on the planet over the past few decades. The mid-20th century has been proposed as the approximate date of the start of the new epoch, the anthropocene.[1] This is in the context of the term anthropocene being understood as the "age of irreversible human impacts on the planet". However, geologists consider that the anthropocene will not be an official epoch in Earth's geological time.[2] Despite the lack of consensus, the mid-20th century was the beginning of irreversible changes to the Earth system where there were major perturbations to C, N and P cycles, and the Earth's biosphere and biota.[3] These changes to the planet have resulted in significant challenges to feed the growing population sustainably with the planet's diminishing natural resources, while not compromising nutrition and planetary health.[4] It is important to maintain the resilience and stability of the Earth system to safeguard the well-being of all humans.[5]

Feeding people requires an adequate provision of calories and nutrients to consumers. Food availability and food supplies have changed over time with advances in food production and infrastructure, and climate change. Sustainability, which includes responsible use of natural resources, sustainable production and consumption, and sustainable value chains, is inextricably entwined to our future and that of generations to come.[6] The global food system is no longer sustainable.[7] The four key aspects of food system sustainability are environmental, social, economic dimensions, and food security.[8] There has been a call for a global revolution to be able to feed the world in 2050.[9] Feeding the world now and into the future requires understanding the challenges and providing solutions for achieving food security whilst preserving ecosystems.[10,11] The production, processing, preparation and consumption, distribution and trade of food are all part of the food system and activities within each part of the system can impact sustainability.[12]

[a]*Food Biotechnology and Food Process Engineering, Technische Universität Berlin, Königin Luise Str. 22, D-14195, Berlin, Germany. E-mail: dietrich.knorr@tu-berlin.de*
[b]*University of Adelaide, School of Agriculture, Food and Wine, Waite Campus, Urrbrae, SA 5064, Australia*

Agri-food systems are responsible for much of the land and environmental degradation, emissions, depletion of natural resources and biodiversity loss. The Green Revolution that began in the late 1960s led to significant increases in food production due to adoption of genetic strategies to improve crop varieties to obtain increased yields[13] but the impact of the green revolution had mixed impacts on the environment.[14] Restorative actions are needed for current food production systems to improve their resilience and stability in the face of climate change and depleting non-renewable resources. Alternative and emerging agricultural production practices are also needed to make the food production systems more sustainable.

This review focusses on the restoration of food production systems and examines the potential of selected alternative systems for producing food that are not presently mainstream. It provides a brief overview of selected current agricultural production systems which promote sustainable practices. This is followed by an examination of some of the major factors affecting sustainable agricultural production including energy use, the biophysical environment, soil fertility, biodiversity and government policies. Restorative actions to improve the sustainability of agricultural production systems are discussed. Examples of transitions to future sustainable alternative production systems for (i) land-based food production, (ii) soil-free food production, and (iii) re-imagined and re-emerging food production practices are considered. Key actions for restoration of land and aquatic food production systems including rebuilding of soil and aquatic ecosystems, wider application of alternative sustainable agricultural and processing practices, integration of innovative and technology into traditional and emerging agricultural systems are provided.

2. Current food production systems that prioritize sustainability

In this section, selected food production systems that include sustainable practices are discussed. The focus is on their movement to more sustainable food production systems.

Agroecology is a pathway to sustainable food systems.[15] It encompasses ecological, technological, economic, sociocultural and political dimensions of food from production to consumption and the formation of multistakeholder partnerships to facilitate co-creation of sustainable solutions for all.[16] This includes reducing agro-chemical inputs, substituting for more sustainable inputs, re-designing farming practices at farm-scale, re-establishing producer-consumer relationships and supporting global shifts towards ecological restoration.[17] A community managed natural farming project in India (Andhra Pradesh Community-managed Natural Farming, APCNF) program based on agro-ecological transformation of farming practices of 6 million farmers, over 6 million hectares and 50 million consumers, showed that APCNF farms had higher crop diversity, 11% yield increase of prime crops (paddy rice, maize, millet, finger millet, red gram) in APCNF villages, 49% net increase in income (lower input cost, *e.g.*, fertilizers, pesticides) and 21% higher labor intensity.[18,19] A further important aspect is to consider the nutrient profiles of the produce from different farming systems. So far, studies in humans comparing health effects of foods from different production systems are rare,[20] making such large-scale studies even more relevant. A recent cluster-randomized controlled evaluation of agricultural households in the APCNF program, aimed at assessing if the government-implemented agroecology program delivers nutritional, developmental and health co-benefits, is being conducted.[21] Agroecological symbioses for sustainable food system networks, interlinking the primary production of food and its processing with the guiding principle to base production and processing on renewable energy has been proposed.[22]

Agricultural production is conducted both on small and large farms, with most of the world's farms being small (<2 ha in size). A meta-analysis of the relationship between farm size and production, profitability, biodiversity and greenhouse gas emissions showed that on average, smaller farms had greater crop and non-crop diversity.[23] While some studies suggested the size of farm was not related to resource efficiency, greenhouse gas emissions or profit,[23] others found that in China, increasing farm size had benefits for the environment and profits.[24]

Intensive farming (which maximises high yields) with higher levels of inputs (pesticides, fertilizers) with less land use and labour compared to extensive agriculture are currently used for producing food. Sound science and innovation can improve the environmental performance of intensive agricultural systems and make them more sustainable.[25] Sustainable intensification ("a process or system where agricultural yields are increased without adverse environmental impact and without the conversion of additional non-agricultural land") has potential to enhance various renewable assets (natural, social and human) and has to be integrated into a wider range of initiatives.[26] For accelerating uptake of sustainable intensification initiatives, multiple goals for sustainable food systems which interface with areas such as biodiversity and land use, animal welfare, human nutrition, rural economies and sustainable development, need to be considered in the development policies and governance frameworks.[27] Other technologies such as gene-editing for crop improvement enables the rapid introduction of sequence specific modifications into cells and organisms for generating crops with desirable traits (*e.g.*, pest resistance, drought tolerance, improved nutritional traits).[28] Also, there is the use of precision and digital agriculture which employs high-tech equipment to reduce agricultural inputs and lower greenhouse gas emissions.[29,30]

Various agricultural systems aimed at improving the sustainability including organic culture, conservative manufacture, permaculture, agroforestry and regenerative agriculture have been discussed in recent reviews.[31,32] An international author group[33] states "sustainable agrifood systems are critical to averting climate-driven social and ecological disasters overcoming the growth paradigm and redefining the interactions of humanity and nature in the twenty-first century". The authors further state "we no longer have the luxury of ignoring viable, successful options when it comes to agrifood system sustainability…".

3. Factors affecting sustainable agricultural production systems

Efficient and sustainable agricultural production is essential for ensuring that the world has sufficient food. Sustainable agriculture production is underpinned by energy efficiency, soil conservation and enhancement, water management, biodiversity preservation and social equity and fair trade.[34–36] Land use and crop yields are the primary drivers of increased crop production.[37] The biophysical environment (*e.g.*, climate conditions – temperature, humidity, day length; soil health, soil type and nutrient requirements; agrobiodiversity) has a significant influence on crop production.[38] In this section, some of the major factors (energy use, the biophysical environment, soil fertility, biodiversity, and government policies) which influence sustainable agricultural production practices are discussed.

3.1 Energy use

A recent estimate is that 15–30% of humanity's energy consumption is used for food production (including machinery, fertilizers, pesticides, irrigation water, harvesting, transportation, storage, marketing and food preparation).[39] A historical perspective highlights the impacts of US food production on energy resources between 1945 and 1970,[40] demonstrating the reversal of input of human labor to machinery and resources (*e.g.*, fertilizers, electricity, transportation, drying) as well as the related increase in products yields (Table 1).

3.2 Biophysical constraints

Climate change and increasing CO_2 concentrations in the atmosphere are major risks to the sustainability of the food system, along with population growth and changing food consumption patterns.[42] Five major constraints that impact on food production are (i) slowing of increases in agricultural production due to climate change, (ii) loss of fertile soils, (iii) limited ground water supplies, (iv) dangerous levels of toxic substances, and (v) decline of pollinators.[9] The biophysical constraints affecting the ability of food production systems and suggested mitigation actions to achieve food security are provided in Table 2.

Table 2 Biophysical challenges for food production systems[a]

Biophysical constraints and actions for improvement
Challenges
• Climate disruption → slowing increase in agricultural production
• Loss of pollinators and increasing CO_2 → lower nutritional quality and yields of crops
• Soil erosion by wind and water, salinization and depletion of nutrients → decrease in soil fertility
• Over-pumping and aquifer contamination → reduced groundwater supplies for irrigation
• Excessive use of pesticides and fertilizers → increased levels of toxic substances
• Habitat destructions, poisons in environment, climate disruption → decline of pollinators
• Ocean acidification → decrease in wild fish catch due also to overfishing
• Land-use change → loss of biodiversity
Suggested actions
• Reduce excessive use of pesticides, fertilizers, antibiotics, and growth hormones
• Regulate water use and improve water-use efficiency
• Increase research into long-term sustainability of production systems
• Increase energy efficiency and use of renewable energy
• Protect biodiversity and ecosystem services on land and at sea (*e.g.*, preserve natural areas)

[a] Source: ref. 9.

3.3 Biodiversity

Expansion of agricultural land and change in land-use is one of the greatest threats to biodiversity and *vice versa* biodiversity can affect food production.[43] A related proposal for preserving ecosystems titled "30 by 30" aims to set aside 30% of representative samples of global land and sea area by 2030.[44] While there have been many proposals to increase food production whilst protecting biodiversity, the loss of biodiversity is difficult to maintain without slowing population growth.[45] The global biodiversity framework (target 3) calls for conservation of at least 30 per cent of terrestrial, inland water, and of coastal and marine areas.[46] The Farm to Fork Strategy and Biodiversity Strategy of the European Commission have suggested setting ambitious goals for mid-to long-term targets for the agricultural sector, which may be achieved by extensive farming but results in productivity losses.[47] Biodiversity can be protected by farming of a high diversity of crops with "integrated management of land, water and living resources that promotes conservation".[48] Although maximizing biodiversity conservation and agricultural production appear to be mutually exclusive, a conceptual framework that considers the effects of various aspects of land

Table 1 Average energy inputs in corn production 1945 to 1970 (all numbers per hectare)[a]

Energy input (per hectare basis)	1945	1950	1954	1959	1964	1970
Labor (h ha^{-1})	59.0	44.5	41.0	34.6	27.2	22.2
Machinery (kcal $\times 10^3$)	445	618	741	865	1038	1038
Dry to 13% moisture (kcal $\times 10^3$)	25	74	148	247	296	296
Electricity (kcal $\times 10^3$)	79	133	245	346	502	766
Transport (kcal $\times 10^3$)	49	74	111	148	173	173
Corn yields (tons per ha)	22.9	25.6	27.6	36.3	45.8	54.5

[a] Sources: ref. 40 and 41.

Table 3 European union common agriculture policy – budgets and objectives[a]

Objectives	% (of total budget)	Expenditure, (million €)
Viable farmer income	60.6	38 078
Increase competitiveness and improve farmer's position in supply chain	11.4	7192
Climate change action	8.8	5552
Biodiversity and landscape	8.5	5360
Vibrant rural areas – attract young farmers and facilitate business	5.8	441
Management of natural resources	2.3	1462
Promote employment, growth, social inclusion, and rural development	5.8	3621
Improve societal demands to food and health (including quality employment, animal welfare, school food schemes)	1.8	1100

[a] Division of CAP budgets and objectives linked to new CAP objectives for 2018; source: ref. 59.

use (composition, configuration, intensity) on both agricultural production and biodiversity can identify options for balancing the beneficial ways to converse biodiversity and optimize crop productivity has been developed.[49]

3.4 Soil fertility

Soil is the foundation of traditional agriculture. Over 90% of our food is grown in soil, a virtually irreplaceable non-renewable natural resource and its preservation is required for food security as soil is essential for food, fuel and fiber production.[50] In 2015, there was 33% of soil that was moderately or highly degraded.[51] Every year, an estimated 12 million hectares of soil are lost to soil degradation leading to a potential loss of 20 million tons of grain per year.[50]

One of the longest running series of experiments on soil fertility, crop production and plant nutrition, the UK Rothamsted experiments started in 1843.[52,53] The experiments demonstrate sustainability and increases in crop yields when soil fertility is managed and optimized. All soil-based systems rely on soil fertility for productivity. Soil fertility and biodiversity in biodynamic, organic and conventional farming systems in central Europe were compared in a 21 year study.[54] There was lower crop yield (20%) in organic systems, although there was reduced fertilizer and input by 34 to 53%, and pesticide input by 97%. The authors suggested that organic systems depend less on external inputs due to enhanced soil fertility and higher biodiversity.[54] Regenerative agriculture, merging farming and natural resource conservation in the Northern US Plains showed that pests were 10-fold more abundant in insecticide-treated corn fields than on insecticide-free regenerative farms.[55]

Soil microbiomes are crucial for soil health but also for plant health. Roots are immersed in soil microbiomes and provide plants with important nutrients, protect them from disease and pathogens and help plants to adapt to environmental changes. Additionally, plant and human microbiomes are linked to each other (sharing similar bacteria phyla) and microbes from produce (fruits, salads, vegetables) can join the human gut microbiome and thus can affect gut microbiomes and human health.[56] There is a crucial need for a better understanding of the parallel effects of agricultural management (conventional, organic cropland) and climate conditions on soil–microbe–plant interactions.[57] A recent collection "soils in food systems" encompassing advances in soil management, soil microbiology and biogeochemistry from the Nature Portfolio has been compiled, with an intent to guide future policy issues.[58]

3.5 Agricultural policy

Policy interventions and governance are being designed to influence and regulate the agricultural sector and include strategies and measures that aim to promote sustainable agricultural practices. The EU Common Agricultural Policy (CAP) initially had a focus on supporting farm production and income but is examining whether they can address key sustainability issues and meet societal demands for higher environmental performance.[59] Key parts of the CAP budgets and objectives have been summarized in Table 3.

The CAP objectives post-2020 are to (i) foster smart, resilient and diversified agricultural sector ensuring food security, (ii) bolster environmental care and climate actions, and (ii) strengthen socio-economic fabric of rural areas.[59] Recently there have been farmers protesting against EU regulations and seeking a proposal for more flexibility for farmers to comply with environmental conditionalities.[60] Agricultural subsidies provided by governments influence food production choices. Transitioning to healthy and sustainable food production systems will be aided by reforming agricultural subsidies schemes that are based on health and climate change.[61]

4. Restoration of agricultural production systems

There needs to be a holistic approach to the restoration of global food systems. Over the course of human history, agricultural systems that have emerged have featured some trade-off between productivity and environmental load.[62] This included three major soil erosion linked agricultural transitions: expansion of river-based population and up-forested slopes around 2000 BCE, the invention of the sharp plough/deep tillage from 1600–1900 and crop expansion into tropical biomes after WWII. Recent rates of erosion on agricultural land are approximately 35×10^9 tons per year.[62]

Agricultural systems restoration will require attention to ecosystems and adoption of technologies that improve conservation of resources (including energy), and embracing alternative agricultural production methods, with acceptance that there will be trade-offs and disruption of traditional food production practices. To achieve sustainable agrifood systems, redesigning of existing systems is needed according to the principles of sufficiency, regeneration, distribution, commons and care as opposed to the current ones of efficiency (economic principles), extraction (social-ecological principles), accumulation (allocative principles), private ownership (institutional principles) and control (relational principles).[33] The authors[33] also stress the importance and impacts of diversified small farms, as well as the role of home and urban gardening, as still underestimated components of sustainable agrifood systems. The sustainability principles for future global agrifood systems[33] are briefly summarized as follows: (i) sufficiency: producing sufficient food for all whilst promoting welfare and stewardship practices for food producers, (ii) regeneration: scheduling production of food at timings that are compatible with the creative and recuperative process of ecosystems and people, (iii) distribution: avoiding concentration and over-accumulation practices and taking steps to correct historic injustices (*e.g.*, usurpation of indigenous land), (iv) commons: changing the perception of food from a commodity to commons and promoting food democracy practices, and (v) care: replacing the ideal of control in agrifood system sustainability, guiding inter-and intra-species relationships, establishing food sovereignty, and recognizing agricultural knowledge and spirituality.

Restoration requires that actions to be taken to (i) protect what we have, (ii) engage in large-scale science to generate the best possible evidence base, (iii) identify what seems to work, consider how it can be scaled (up/down), share it and study in restoration projects, (iv) mine the existing evidence base, (v) anchor decisions in a sober evaluation of benefits, risks and uncertainties, (vi) strengthen partnerships between practitioners and scientist to create a community of practice, and (vii) seize the opportunity to engage the public.[63]

4.1 Energy use

Currently, most of the energy for agricultural production and processing currently comes from using non-renewable sources (*e.g.*, fossil fuels) but with transition to renewable sources of energy (*e.g.*, solar, hydro-power, biogas, wind power) in agriculture, the effects on agricultural production on climate

Table 4 Key renewable energy sources: principles, advantages, and disadvantages

Renewable energy sources		
Principles	Advantages	Disadvantages
Agrivoltaics/agrophotovoltaics/solar energy[64,65]		
• Clean solar energy transition *via* mounted photo-voltaic systems	• Reducing evaporation from soil	• Partial shading, water runoff may lead to soil erosion
	• Crop protection from excessive heat	• Slow drying process
	• Reducing global warming	• Food quality & safety implications
	• Low cost	
	• Filtering of harmful radiation	
Water energy/hydropower[66,67]		
• Use of water velocity for energy generation (*e.g.*, mills, pumps, dykes)	• No fuel costs	• Potential threat to wildlife
	• Can be placed in existing water ways	• Environmental impacts
	• Continuous and consistent availability	• Land change which affects livelihoods in area
	• Long history of use	• Decrease ecosystem productivity
Wind energy[64]		
• Electricity generation by wind velocity (>7–9 m s^{-1})	• Clean resource, free from greenhouse gases	• Alteration of visual aesthetics
• Storage in accumulator batteries	• Low price energy source	• Noise generation
	• No fuel costs	• Threat to wildlife (*e.g.*, birds)
	• Can be placed in agricultural areas	• Fluctuating source
	• Few moving parts	• High turbine costs
	• Proven ancient technology	
Bioenergy (biomass/biofuel/biogas)[67,68]		
• Biomass to produce energy (*e.g.*, with use of combinations of chemical, thermal,biological, and mechanical methods)	• Abundant sources	• High energy and water requirements for production
	• Re-use of residual bioresource	• Environmental impacts
	• Clean energy	• Competition between food and biofuel production (*e.g.*, oil palm)
	• Greenhouse gas reduction	• Biodiversity loss
	• Energy security	

change can be mitigated.[64] The choice of which energy source to use requires and understanding of the trade-off between their applicability, advantages and disadvantages. The principles, advantages and disadvantages of selected key renewable energy sources are given in Table 4.

4.2 Ecological restoration

Ecological restoration is an emerging discipline. There is a need to commit to a "decade of restoration" and to take actions to restore the ecosystem.[63] Biodiversity offers a largely untapped resource to support our planet.[69] Interdisciplinary collaboration and inclusive bottom-up processes will be critical for leveraging past, present and future biodiversity data in a way that aligns with the equity goals of global biodiversity policy.[70] An agenda for actions to reverse biodiversity loss has been set by The Kunming-Montreal Global Biodiversity Framework (GBF) of the UN Convention on Biological Diversity. It includes maintaining and restoring biodiversity and sets out a framework for collating data, analysis, and synthesis of ecosystem data.[71] Additionally, multiple, coordinated goals and holistic actions have been considered for global food biodiversity and sustainability including food, water, health, and climate security for the most vulnerable people and more resilient "natural" and "managed" ecosystems.[72] In addition, co-development of agrobiodiversity-based markets with citizen-consumers for reversing the decline in agrobiodiversity should be encouraged.[73]

To cope with the ongoing degradation of the planet's ecological state and associated health risks, fundamental reformation of food production has been required[74] *via* creation of new integrative approaches including open system science with strong emphasis on relationships with surrounding systems when solving problems and making use of computational technologies to dynamically deliver timely and effective control within limited observation conditions. This includes biodiversity mainstreaming, and empowering low-input smallholders to generate bottom-up synergy among most stakeholders.[74] Biodiversity is also seen as a key to addressing the challenges of increasing world population food shortages (hunger) and excess (obesity), with at least 7039 existing edible plant species in contrast to the handful of food crops providing the majority of calories to humans.[6,69]

4.3 Soil and land restoration

Land is a major resource for agricultural production. Soil is a limited resource and sustainable soil management is required for their restoration in order to improve their capacity to sustain plant, animal, microbial productivity, and balance hydrological, carbon, nutrient and the ecosystem functions.[75] A decline in soil fertility results in loss of agricultural production and significant economic losses for farmers.[76] A shift to more restoration and maintenance of soil fertility, stability and enhanced resilience in the face of global change is needed.[77] The impacts of agrochemicals (herbicides, fungicides, insecticides, biopesticides, microbial based products) on soil microbiota diversity as well as soil enhancement and sustainability practices have been presented extensively.[78] The traditional methods for restoring soil fertility are by using humus material. Due to the insufficiency of humus amounts required for recultivation, alternative substrates such as sludge from wastewater plants are being considered.[79] Capitalizing on plant–microbe interactions and the underground world in and around plant roots presents opportunities for improved soils. There are a vast number of protozoa, fungi, archae, bacteria, nematodes, algae, and viruses which help the plants to shield from a wide variety of threats such as heat, cold, flooding, drought, osmotic stress, pathogens, insects, heavy metal toxicity and nutrient limitations.[80] Such complex symbiotic relationships are essential for sustainable agricultural systems and once again stress the need for controlled regeneration of healthy soils.[81,82]

Grassland biomes are large open areas of grass. Grasslands create and stabilize fertile soil, store carbon, and generate oxygen, building materials and food.[83] Grassland, constituting almost 40% of the terrestrial biosphere, provide a habitat for a great variety of animals and plants and contribute to the livelihood of more than 1 billion people.[84] Grasslands store approximately one third of the global terrestrial carbon stock and act as an important carbon sink. Related plant diversity increases soil organic carbon storage and promotes microbial necro mass contribution to soil organic storage.[85] Relating to the ongoing decline in grass biomass,[84] it was stated "We urge conservation initiatives to safeguard against the conversion of old-growth grasslands for tree planting or tillage agriculture, to maintain our ancient biodiverse grass lands with appropriate disturbance regimes, and to emphasize the long-term restoration of grasslands in efforts to restore Earth's biodiversity".

In addition to agricultural crops, animals raised on land are an important source of food for many populations. Although there are challenges to sustainable livestock rearing, these can be mitigated by good feed and nutritional management in various types of animal production systems to obtain positive (or neutral) socioeconomic and environmental outcomes.[86] A new Grassland Animal response model (GLAM) which relates livestock-cohort grass and feed requirements to farm-grassland system areas has been developed.[87] The authors suggest that there is potential for sparing good quality land by applying GLAM to improve grass and cattle management, with up to 18% grassland in Ireland spared without compromising total protein production.[87]

4.4 Restoration of aquatic systems

As for aquatic food systems, food from the sea represents only 17% of the current production of edible meat with Castello *et al.* (2020) estimating that edible food from the sea could increase by 21–44 million tons by 2050 (36–74% increase compared to current yields) with most pronounced increases estimated for mariculture. Looking at the environmental performance of fish and other aquatic foods, with pelagic fishes generating lower greenhouse gas emissions than all fed aquaculture (flatfish and crustaceans highest) and farmed salmon with the least land and water use,[88] attractive concepts for future environmental restoration activities have been developed. Shifting to such low-stressor aquatic foods providing high nutritional values (*e.g.*, iron, zinc, vit. B_{12}, polyunsaturated fatty acids) can become a viable alternative to terrestrial animal food sources. Replacing fish meal and fish oil which are currently used in most aquaculture facilities with feed generated from insects would further increase resilience of farmed fish production.[89]

Six global principles for restorative aquaculture activities have been proposed. These include (i) developing farms at sites where environmental benefits are generated, (ii) farming species which provide the desired environmental benefits, taking into consideration their differing natural functions and growth, (iii) using the appropriate farming equipment (*e.g.*, that reduce risks of entanglement of plastics and have positive effects on fauna), (iv) adapt farming management practices (*e.g.*, timing of construction, farm configuration, seeding, harvesting), that improve environmental benefits, (v) conduct aquaculture at an appropriate scale and intensity to ecosystems, and (vi) recognize the social, economic, and environmental benefits.[90]

Also, the value of seagrass ecosystems for providing food and supporting livelihoods should be promoted. Seagrasses are a unique group of submarine flowering plants that belong to the monocotyledon order Alismatales.[91] Seagrass meadows store and sequester carbon, provide coastal protection and water filtration. Seagrass have nitrogen fixing bacteria in their roots, allowing them to colonize nitrogen poor environments and their associations with clams (and their bacterial symbionts), and have aided the ability of seagrass to inhabit otherwise toxic marine soils.[91] Eelgrass seeds have been used by the native Seri people of the Gulf of California to create a gruel as food supply.[92] Seagrasses offer opportunities to combat the biodiversity crisis and provide nature-based solutions to mitigate climate change and sustainable development.[91] The restoration of seagrass meadows, which support marine species, produces oxygen, store carbon and stabilizes the coastline, is important for marine conservation and aquatic environments.[93]

5. Alternative land and soil-based food production systems

While restorative actions to improve current mainstream agricultural production systems will help improve sustainability, this by itself is insufficient to achieve food systems sustainability. This section considers alternative agricultural production systems, which may be introduced in addition to restorative actions on current production systems. The transitions required to make selected (i) land- and soil-based, (ii) soil-free, and (iii) re-emerging food production systems more sustainable are covered (Fig. 1). Selected land and soil-based food production that merit consideration in the development of sustainable alternative production systems include (i) traditional food systems (alpine farming, indigenous farming and wild food) and (ii) promising future systems (leaf protein, agrivoltaics).

5.1. Traditional food systems

Alpine farming, indigenous farming and wild food foraging have been practiced by human civilizations for many generations. Traditional farming practices (crop rotation, intercropping, organic composting, terracing, agroforestry, integrated crop-animal farming, slash-and-burn farming, seed saving and preservation, natural pest control) are age-old practices based on indigenous knowledge that have been passed down through generations. They promote sustainability,

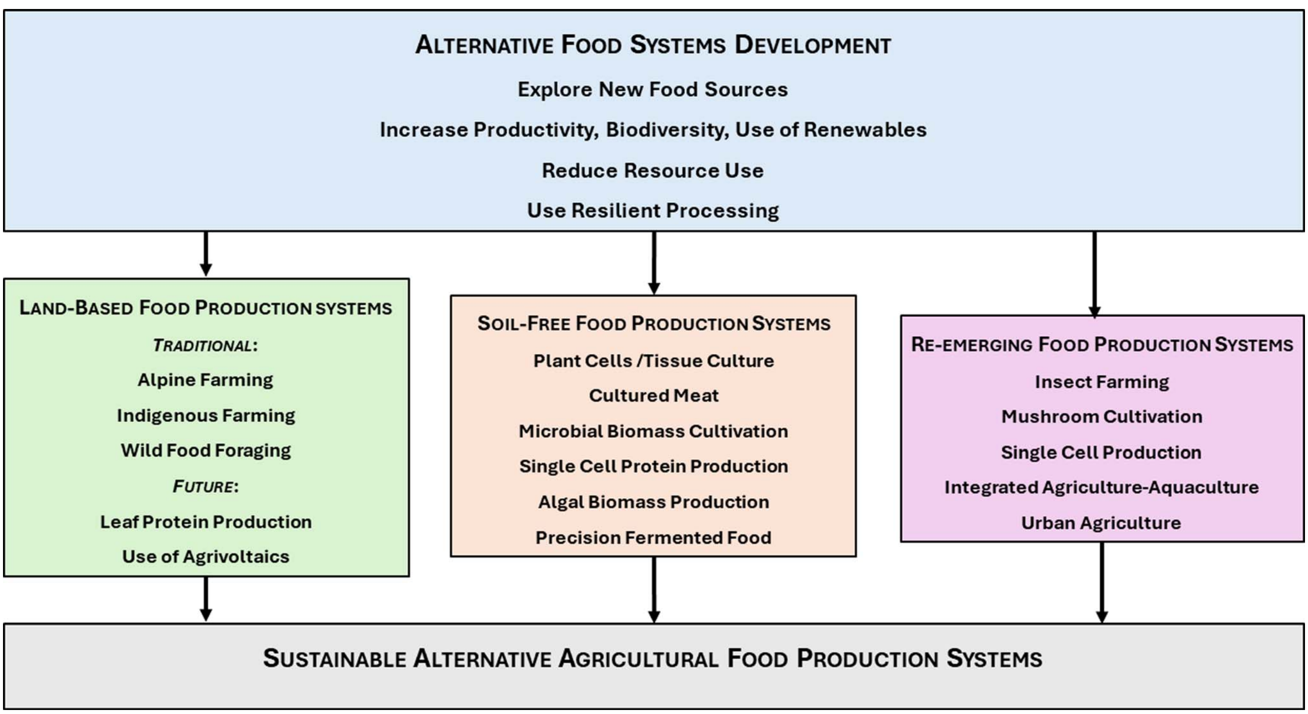

Fig. 1 Transitions to sustainable alternative food systems.

preserve biodiversity, contribute to soil health, and conserve the environment.

5.1.1 Alpine farming. Alpine farming is commonly described as the movement of humans with their livestock between permanent settlements in the mountain valleys in the winter and temporary settlements in the subalpine/alpine belt for pasturing in summer. Such natural pastures above the tree line, where the soil is not fertile enough for crop production can provide a farm with a third of the food needed and are traditionally combined with milk processing.[94] Livestock in the Alps usually includes cows, goats, and sheep for milk and cheese production, and more recently pigs (feeding on whey) for meat production.[95] Such traditional breeding systems provide ecosystem services including conservation of genetic resources, water flow regulation, pollination, climate regulation, landscape maintenance, ecotourism (increasing due to global warming) and cultural heritage.[95]

5.1.2 Indigenous farming. Indigenous communities have been practicing sustainable farming practices through the ages. Their farming practices are usually productive, adaptative and based on ecological principles. Native American farming practices are based on deep respect for nature, with a rich heritage of ecological wisdom and community resilience. Empowering native Americans to develop their agriculture practices has led to increased numbers of farms (from 7211 in 1982 to 15 494 after twenty years).[96] Native American practices (dry farming to conserve water, seed preservation to maintain genetic diversity, controlled burning to renew solid nutrients and help reduce pest infestation, community farming).[97] A study in Hawaii highlighted the food-producing potential of indigenous agriculture, and showed that the traditional agroecosystems of Hawaii could have similar production levels to consumption today.[98] Indigenous farming, food and fire burning practices could regenerate Australia.[99] There is much to be learnt from indigenous practices to inform sustainable agricultural practices. Indigenous farming practices may be integrated into modern farming approaches for more sustainable food systems. The Globally Important Agricultural Heritage Systems initiative (GIAHS), has a role in encouraging integration of inherited new elements with traditional knowledge.[100]

5.1.3 Wild food foraging. Wild plants provide food security to many rural communities and are important for meeting the nutritional needs of these populations. It is estimated that around one million people use wild foods in their diets. Forests provide food for some 300 million people and wild game is routinely used even in urban households.[101] According to the authors these wild species contribute to biodiversity and efforts to conserve it and to preserve traditional food systems and farming practices need to be combined.[101] The inclusion of wild edible plants as an integral part of human diets is an untapped potential to ensure wider access to micronutrients for sustainable food systems.[102]

Wild mushrooms are an example of wild foods. Wild mushrooms (mycetes) are a diverse group of fungi that grow in the wild (forests, grassland, urban environment). Ancient Greeks believed that mushrooms provided strength for warriors in battle, Romans saw them as "food of the gods" and Chinese culture treasured them as "elixir of life".[103] They provide important nutrients (selenium, potassium, riboflavin, niacin, proteins, fiber and plant-based vitamin D) and are low in calories, carbohydrates, fat and sodium.[103] Estimates for total numbers of mushrooms on Earth vary, and of the expected 140 000, only about 10% (about 14 000 known) are known.[103–105] There have been 480 species of wild edible mushrooms identified in Africa, with average consumption (northern Mozambique) reaching estimated 72–160 kg per household per year, and up to 60.4% of crude protein (dry weight basis) for the *Lepista nudi* species.[106] In rice-based ecosystems in Asia (Cambodia, China, Laos and Vietnam) many foods are directly caught or collected by rural people in poor households. These wild foods include 145 species of fish, 11 species of crustaceans, 15 species of molluscs, 13 species of reptiles, 11 species of amphibians, 11 species of insects and 37 species of plants.[107] These wild foods are valuable for the communities and have important ecosystem roles but have often been overlooked in official statistics.[107]

Non-domesticated wild foods thrive in harsh environments as they have adapted to various stresses over time. Their resilience and genetic diversity may be exploited for an alternative to the major staple crops that are facing challenges due to yield reduction and nutritional quality as the climate changes.[108] However, there are hurdles to the popularization of wild foods and contrasting views on whether this should be pursued, as success or failure depends on many factors (*e.g.*, natural stocks, biological profile ecosystem properties, management, market demand, maturity of value chains, land tenure, policies) which are yet to be examined.[109] However, the contribution of local knowledge and indigenous knowledge will help in developing conservation and management practices for wild foods and facilitate their sustainable use.[110]

5.2 Alternative future food production systems

In this section a promising source of underutilized biomass (green leaves) for sustainable plant protein production with potential to contribute to alleviating the world shortage of protein is examined. Leaf protein was chosen as an example as it is one of the most widely available sources of plant-based protein which is currently an unexplored source of plant protein.[111] Leaf protein expertise has existed since the 1960s and it timely that this area should be re-examined. There are already a few new start-ups in the area of production of leaf protein who have seen the commercial opportunity for leaf protein.

Also considered is the application of agrivoltaics. This is a new food production system with potential for improving the sustainability of agricultural production systems (reduced water use, improved crop protection and better animal welfare).[112] Agrivoltaic technology is a most promising and fastest advancing technology, especially for developing countries with a lot of sun. It is flexible, easy to install, and cheap.

5.2.1 Leaf protein production systems. Green leaf biomass is one of the largest underutilized sources of nutrients worldwide. Sources can include cultivated plants (forage crops, duckweed, alfalfa), discarded leaves and grass biomass.[113] The history of leaf proteins, starting with the first related publication in 1773, has been summarized,[114,115] including processing aspects and future perspectives. The importance as a food source and consumer acceptability of leaf proteins has been discussed almost 50 years ago.[116] Leaves are an effective protein source, which can be used for restoration of depleted soils. Plant leaves which have high protein content (>20% on a dry basis) include leaves from spinach (30%), sauropus (29.8%), moringa oleifera (29.4%), sugar beet (1924%), chaya (24%), cauliflower (21.7%), soybean (20–25%), green tea leaves (21–31%), alfalfa (20–25.75%), and cassava (11.8–38%). Many plant proteins have low solubility which is a limitation in food applications but green leaves are a good source of the enzyme RuBisCO which has many desirable functional and nutritional properties.[117] The yield of protein extracted with the same extraction procedure varied between different leaves, due to the differences in the amounts of insoluble and bound protein, and cell wall thickness as well as the age of the plant.[111,117]

The emergence of new processing technologies (*e.g.*, pulsed electric field) allows effective protein recovery with low chlorophyll content. There can be multiple harvests per year and mixtures of grasses can lead to tailored nutrient composition.[118] The remaining grass/leaf residue after protein recovery may be used as feed. Recent developments in protein and nutrient extraction from grass and clover, leading to improved protein and mineral yields by application of pulsed electric fields and pressing of the biomass, stress the potential of leaf proteins for food application.[118]

Most leaf proteins are an excellent source of indispensable amino acids but contain some undesirable components (*e.g.*, anti-nutritional factors, tannins). Protein from green leaves have potential in food applications (*e.g.*, egg white replacer, plant-based meat, dairy alternatives, snack foods, nutritional meal replacement).[119]

5.2.2 Agrivoltaics. "Agrivoltaics" is a method to combine agricultural and electricity production on the same unit of land which significantly increases land-use efficiency. It boosts the resilience of renewable and food production security.[120] Originally, photovoltaic systems (crystalline silicon modules, thin film modules) were ground mounted ("solar sharing"), and more recent developments include vertical, tilted, tubular, concentrating modules with mirrors or semi-transparent luminescent collectors.[65] The installed capacity for photovoltaic modules worldwide increased from 5 MWp in 2012 to 14 GWp in 2021, with applications in grassland farming, arable farming and horticulture.[65] Increased land productivity with an average increase in alfalfa biomass generation of 10% has been shown in a two year experimental setup.[121] However, at present agrivoltaics are primarily in the experimental stage and there is a need for further optimization of crop and variety selection, water and nutrient management and crop protection to find the most promising crops for application of agrivoltaics.[112]

6. Alternative production systems: cellular agriculture and culture-based methods

Strategies to reduce the environmental and global warming effects of food production have recently included the introduction of foods without traditional agricultural production (*e.g.*, soil-free pathways through use of chemical and biological processes for producing edible molecules).[122] The concept of cellular agriculture, the controlled and sustainable manufacture of agricultural products with cells and tissues without plant or animal involvement has been summarized in relation to opportunities and challenges, including its historic development.[123] There is increasing interest in the application of synthetic biology and various forms of fermentation for future food production.[124,125]

An early quest for synthetic foods as agriculture independent food sources to feed the growing world population has been made by Haldane in 1923 who insisted that sugar could be made from sawdust and yeast would one day replace meat.[126] Fifty years later there was a call for the initiation of an interdisciplinary program for the development of "synthetic food".[127] Up to recent times, chemical and biological processes have received less attention compared to traditional land-based agriculture despite their potential to combat the adverse environmental impact of agriculture. Davis *et al.* (2024) show that the idea of "food without agriculture" is not new and refer to the Ziegler or Fischer–Tropsch processes which were used to convert syngas and ethylene to paraffins, fatty acids and fat; and by processes such as the Strecker to amino acids and subsequently to proteins; or by electrochemical catalysis and processes to transform methanol to carbohydrates.[122] Biological pathways to fats, proteins and carbohydrates are feasible. A chemical–biochemical hybrid pathway for starch synthesis from carbon dioxide and hydrogen in a cell free system at an approximately 8.5-fold higher conversion rate than for starch synthesis in maize has been reported.[128] Synthetic biology has also been used to improve traditional food production using machine learning, pathway design, expression fine tuning, protein engineering, synthetic scaffold, CRISPR system, genetic circuits, and modular engineering.[129]

The terms microbial biomass/protein refers to microbial biomass as source of food or feed. Fluxes from agriculture (CO_2, CH_4, H_2, H_2O, nutrients)[59] can be utilized for microbial biomass production with conventional microbial protein producers (bacteria, yeast, algae) as well as emerging ones such as hydrogen oxidizing bacteria, methanotrophs, fungi and specific microalgae such as cyanobacteria.[130] The environmental impact of animal biomass (beef, pork, chicken, egg) ranges from 15 400–3300 ($m^3\ kg^{-1}$) for water footprint, 99.5–3.5 (kg CO_2-eq. per kg) carbon footprint, and 326.2–6.3 ($m^2\ kg^{-1}$) land use. For commercial microbial biomass the values are 500–104 ($m^3\ kg^{-1}$), 5.5–0 (kg CO_2-eq. per kg) and 2–0.034 ($m^2\ kg^{-1}$).[131] Microorganisms are divided into autotrophic (using CO_2 as carbon sources and light or chemical energy for CO_2 assimilation) and heterotrophic (using other carbon containing substrates as carbon source such as acetic acid, methane, methanol, formic acid).[132] Since current global food production is ultimately constrained by the conversion rate of atmospheric CO_2 into edible biomass, microbial conversion is most essential, *e.g.*, CO_2 + light (cyanobacteria, microalgae), CO_2 + H_2 (non-photosynthetic bacteria, methanogenic archaea), or CO_2 + electricity (non-photosynthetic bacteria, methanogenetic archaea).[132]

Cellular agriculture is an alternative to traditional soil-based agriculture and is typically carried out in bioreactors. Plant cells, animal cells, and microorganisms may be cultivated for the production of foods that have similar properties to food from traditional crop and animal agriculture.[133] Single cell protein is one of the earliest examples of cellular agriculture.[134] An area of cellular agriculture that is rapidly emerging is that of precision cellular agriculture, where cellular hosts (*e.g.*, yeasts) are used to express specific components (*e.g.*, fats, proteins, carbohydrates, food additives) that are harvested for food use.[124,135] The application of cell cultures and genetic engineering reduces the need for arable land and enables desirable traits to be engineered into food products,[136] and presents a sustainable alternative to traditional soil-based agriculture. Achievements, applications, and safety considerations of the engineering potential of synthetic biology (*e.g.*, genome editing, assembling methods, metabolic engineering) have been reviewed.[137] Safety considerations and risks which need to be carefully evaluated include ecological impact (potential to disrupt natural balance), gene flow (escape of GMOs, impact on biodiversity), unintended effects (unintended changes in GMOs traits), allergenicity (introduction of new proteins or compounds into GMOs), toxicity (altered genetic pathways in GMOs producing toxic compounds), resistance development (pest or diseases targeted by GMOs could evolve resistance), ethical concerns (limits of human intervention in the natural world), human health concerns (concerns relating to unforeseen health effects resulting from GMOs), loss of traditional varieties (loss of genetic diversity within agricultural systems) and long term environmental impact (concern about cumulative impact over time).[137]

A hybrid inorganic–biological artificial photosynthesis system for energy-efficient food production uses a two-step CO_2 electrolysis system to produce acetate for direct use for the generation of a mushroom producing fungus and a photosynthetic algae in the dark.[138] According to the authors coupling this approach to existing photovoltaic systems could increase solar-to-food energy conversion efficiency by about fourfold over biological biosynthesis.[138] A photovoltaic driven microbial protein production system using a model with photovoltaic electricity generation, direct capture of CO_2, electrosynthesis of an electron donor and/or carbon source for microbial growth (hydrogen, formate, methanol), with subsequent microbial cultivation and biomass and protein production has been described.[139] Microbial protein production per unit of land was shown to reach an over 10-fold higher protein yield and at least twice the caloric yield compared with any staple crop.[139] An envisioned dark food chain relying on chemoautotrophy with primary production based upon assimilation of CH_4 and CO_2 by methane and hydrogen oxidizing bacteria has been proposed.[140] Engineered microorganisms producing hydrogen gas through water electrolysis as energy source, then reducing CO_2 into C1 and C2 building blocks (methane, methanol, formic acid, acetic acid) being used as electron donor and/or carbon source for microbial protein production has also been presented.[141]

6.1 Plant cell and tissue cultures

The concept of cellular totipotency – that living cells are independent individuals capable of developing when separated from the organisms if provided with conditions existing in the organisms was formulated by Schleiden in 1838 and by Schwann in 1839. In 1902, Haberlandt put these principles in actual practice leading to the opening of the field of plant tissue culture during 1914–1939.[142] Biotechnologically produced cellular products are currently emerging to replace and add to the portfolio of agriculturally derived commodities, and plant cell cultures used for food could supplement current food production.[143] Cultivated arctic bramble (*Rubus arcticus*) and birch (*Betula pendula*) were produced using lactose rich dairy side streams a carbon source and coconut water as natural growth enhancer without compromising the nutritional composition or sensory properties of the cultivated products.[143] The nutritional value of two cell cultured products, Rowan (*Sorbus aucuparia* L.) and Arctic bramble (*Rubus arcticus* L.) were good in terms of their contents of protein (18–22%) and dietary fiber (28–29%) (on a dry matter basis).[144] An extract from red cultured cells has potential for applications as a nutraceutical food additive.[145] Although plant cells and tissue cultures are an alternative production method, their commercialization require regulatory approval and further testing of cultured cells and extracts need to be carried out for them to have an important place in the food sector.[146] An interesting development has been the successful application of low level pulsed electric fields (1.6 kV cm^{-1}, 10 pulses) for stimulating secondary metabolite biosynthesis in a suspension culture of *Vitis vinifera* L. cv. Gamay Fréaux.[147] The authors suggest that pulsed electric field could be a novel abiotic elicitor for secondary metabolite production in cultured cells.[147] Such production systems could be valuable food generating systems *via* using food processing waste streams.

6.2 Cultured meat

Cell-based meats are obtained by culturing muscle cells *in vitro*, without involving animals. The cells are grown in culture media and are attached to a scaffold to facilitate replication.[148] Recently an approach based on co-cultivation has been suggested with potential for reducing growth factor supplementation and accelerating fabrication process, whilst making cultured meat more similar to meat from animals.[149] There are still technical and economic challenges for wider scale adoption of economically produced cultured meat with desirable properties.

Cultured meat uses less land and water and produces less greenhouse gas emissions than conventional livestock agriculture. An early comparison of cultured meat production with conventional meat production systems in Europe showed that cultured meat used 82–96% less water, 99% less land and had 78–96% lower greenhouse gas emissions, depending on the meat product compared.[150] However, producing muscle may be costly and inefficient in resource use (*e.g.*, for production of growth medium and for running the bioreactor) and also the production of a complete muscle tissue and the mimicking of the marbling effect in meat is expected to be difficult.[151] The acceptance of cultured meat products and their ability to replace conventional meat will require addressing market-entry and consumer acceptance hurdles.[152]

6.3 Microbial biomass production

Historical large-scale examples for the production of microbial biomass exist (*e.g.*, 1500 m^3 bioreactor producing microbial feed (Pruteen) from methanol).[132] Hyde *et al.* summarized 50 ways to exploit fungi industrially, including modern industrial mushroom production, use of fungi to enhance food value (soy sauce, miso, tempeh, Quorn, rennet), generation of food coloring from filamentous fungi, food flavorings, microbially fermented teas, alcoholic beverages, functional foods and nutraceuticals, and probiotic fungi as food related examples.[153] Mycoprotein, derived from filamentous fungi, has been presented as a good meat alternative because of its additional health benefits over conventional meat, such as prebiotic and antioxidant function, and as regulators for blood cholesterol and blood glucose level.[154] There are an estimated 6 billion ton of carbon in marine biomass with about 5% of it being fungal which have a role in multiple biogeochemical cycles including those involving carbohydrates, amino acids and lipids.[155] Due to fungi's metabolic flexibility they may be invaluable allies in digesting plastic refuse (*e.g.*, food packaging materials).[155] A call to include all macrofungi in the post-2020 global biodiversity targets and to halt biodiversity losses has recently been made.[156]

6.4 Algal biomass production

Algae (macroalgae and microalgae) are good nutritional and food sources that have been part of the human diet since antiquity. Historically, mass cultivations of photosynthetic algae have been carried out for food production, as food sources for countries in need of additional food supply, for regeneration of waste into food, for conversion of CO_2 into O_2 in life support systems (*e.g.*, space explorations), and for sewage and waste treatment with recovery of algal cells for animal feed.[157] The ability of algae to sequester CO_2 lends to its sustainability by helping to reduce the carbon footprint of its production.[158] Seaweeds absorb carbon dioxide, provide natural carbon sequestering, absorb pollutants and extract inorganic nutrients (*e.g.*, nitrogen, phosphorus) directly from the marine environment to produce biomass.[159] Microalgae are also considered as tolerant to biotic and abiotic stress and a number of existing commercial microalgal based products and several prospective uses have been summarized recently.[160]

Common edible algae, compliant with EU Novel Food regulations are macroalgae, mainly seaweed (green, brown, red), microalgae (green, red) and blue-green algae (cyanobacteria). Various algal species (*e.g. Schizochytrium*, *Chlorella vulgaris*, *Euglena gracilis*) have achieved USA GRAS status by FDA and compared to terrestrial plants, even low biomass production can generate high levels of essential nutrients.[158,160] There is increasing global demand for macroalgal and microalgal foods. Of the approximately 30 million tons of seaweed biomass used by humans in 2018, 97% was farmed in a relatively small number of countries. Most of the global seaweed production is processed for direct human consumption of hydrocolloids (*i.e.*, carrageenan, alginate, agar). Three groups dominate for human consumption (kombu, wakame, nori).

Algae produce highly digestible proteins, lipids, carbohydrates, and are rich in essential fatty acids, vitamins, and minerals.[158] Protective effects of algae on glucose and lipid homeostasis as well as anti -inflammatory properties have been shown.[161] There is a need to understand how the nutritional composition of various algal species in different geographical regions and seasons affect their food and nutritional value, and to improve harvesting, storage and food processing operations to enable the potential of algal food to be fully exploited.[160,161] With respect to the consumption of algal ingredients, further research is needed to understand the long-term human health effects of consuming algal protein, protein concentrates and isolates on human health.

Substituting human diets with seaweeds at a rate of 10% annually is predicted to spare up to 110 million hectares of land.[162] Recently this low carbon source of proteins has been demonstrated to be able to provide an equivalent of up to 45% of the world's food following an abrupt sunlight reduction scenario such as after a nuclear war or asteroid impact in around 9–14 months, using only a small fraction of the ocean.[163]

6.5 Precision fermented food systems

Synthetic biology is grounded in the convergence of biological science and engineering. The rapid development of synthetic biology has enabled the tailoring of cells and their cultivation in bioreactors to produce a range of compounds, has advanced the field of precision fermentation, which have applications across many industries.[164–166] Products using precision fermentation include soy leghemoglobin produced by engineered *Pichia pastoris* to produce plant-based "burgers that bleed",[167] recombinant egg and milk proteins,[168] animal-free bioengineered milk, sweeteners, soy sauce, rice wine, fats, oligosaccharides, and lycopene.[124,129]

7. Alternative production systems: re-emerging food production systems

The pressure on the sustainability of the food system has re-ignited interests in methods of food production such as insect farming[169] and rice-fish farming.[170] With the rise in the urban population, there has also been increasing relevance of urban and peri-urban agriculture.[171] The modernization and re-imagining of these previously used practices have been made more attractive and relevant to today's needs with the application of innovative approaches and improvements enabled by technological advancement.

7.1 Insect farming

The consumption of insects by humans (entomophagy) has been practiced since early hominids and widely eaten in Africa, South America and Asia but is not well accepted in Western cultures.[172,173] Edible insects include those that belong to the orders of blattodea (cockroaches and termites), coleoptera (beetles), diptera (flies), hemiptera (cicadas, stink bugs), hymenoptera (bees, wasps, ants), lepidoptera (butterflies, moths), odonata (dragonflies), and orthoptera (crickets, grasshoppers, locusts). A compilation of approximately 200 edible insect species[174] revealed that insects are an excellent source of proteins (containing all essential amino acids) in concentrations (*e.g.*, crickets, yellow mealworm) comparable to salmon, chicken, beef or pork, and fat (mono- and poly-unsaturated), carbohydrates and fiber higher than the above reference nutrient values.[175,176] They also possess bioactive properties including antioxidant, antimicrobial, anti-inflammatory, immunomodulatory, antihypertensive, and anti-obesogenic effects.[176]

Some of the advantages of farming insects compared to livestock include the use of less land and water, lower greenhouse gas emissions, high feed conversion ratios, ability to convert low-value organic products into food and the possibilities of using some insects (*e.g.*, black soldier fly *Hermetia illucens* L., yellow mealworm *Tenebrio molitor* L.) particularly for aquafeed.[177] A comparison of resource requirement needed to produce 1 kg protein from livestock and from insects shows for feed 7.7 kg *versus* 1.7 kg; greenhouse gas emission 2835 g CO_2, 114 g CH_4 *versus* 1539 g CO_2, 5 g CH_4, ammonia emissions 170.0 mg *versus* 5.4 mg; water requirement 15 400 L *versus* 15.5 L; land requirements 200 m^2 *versus* 15 m^2.[175] Several insect species can transform low value organic side streams (*e.g.*, manure, catering waste, expired foods) into high-value products, thus contributing to waste recovery and conversion.[178] The safety of insect products depends heavily on the substrate on which insects are fed. Pesticides and mycotoxins can be degraded in insect guts but heavy metals may accumulate.[179]

With the increase in insects farmed for insect protein, it is expected that there will be increased availability of chitin (β(1-4)-*N*-acetyl-D-glucosamine) and chitosan (water soluble, deacetylated chitin), which have broad applications in food and other industries.[180] The availability of chitin and chitosan, also found in marine invertebrates[181] and fungi,[182] can help in some of the activities for the restoration of the food systems.

7.2 Mushroom cultivation

Traditional cultivation of mushrooms involved transfer of mushroom mycelium onto logs of food. Nowadays, mushroom cultivation uses lignocellulose waste, thereby enabling recycling of agricultural wastes.[183] Mushroom production systems use locally available substrates (*e.g.*, paddy, wheat and soybean straw; cotton and coffee wastes, sugar cane bagasse, saw dust). Additionally advancements in technology which enable quick composting methods and changes from log to bag cultivation have reduced cropping time for various types of mushroom (*e.g.* button, oyster and shitake mushrooms).[184] Gene editing techniques may be applied for breeding of mushrooms, and this holds potential for creating new mushroom strains with improved substrate conversion and environmental adaptability.[185,186] Recent mushroom cultivation operations include indoor settings or in submerged cultures.[104,187]

7.3 Single cell protein production

The term single cell proteins (SCP) refers to microorganisms such as microalgae, actinomycetes, bacteria, yeasts, molds and higher fungi grown in large-scale culture systems for use as protein source in human foods or animal feeds.[188] The first large-scale production was with yeast. *Candida utilis* was cultivated on sulfite waste liquor from pulp and paper manufacture during WWI and WWII. Industrial scale production was reached in the 1970s[157] but it was not economically competitive with other protein source (*e.g.*, soy). Yeast protein biomass is considered an attractive alternative to traditional protein sources but its high contents of nucleic acid can cause health problems such as gout, kidney stones.[189] This necessitates reducing nucleic acid contents.[190] *Saccharomyces cerevisiae* biomass can also serve as a source of next-generation food preservatives.[191] In addition, *Saccharomyces cerevisiae* has recently been enabled to use light as its energy source.[192]

Protein production by conventional agriculture-based food supply chains has become a major issue in terms of global and environmental pollution such as greenhouse gas emission, land use and water footprint. Microbial sources are effective substitutes for more expensive protein sources such as fish and soybean products. The current need to no longer disintegrate but to upgrade low-value organic and inorganic side streams is becoming a key driver for microbial bioconversions to valuable nutrient sources.[193] Food processing side streams as well as food and agricultural wastes are considered as the most suitable plant-based substrates for the production of these single cell proteins.[194] Bacterial single cell production from different substrates was reported to reach up to 56.2%, fungal SCP reached up to 44% and yeasts 56%. Additional nutrients provided by single cell protein production include lipids, carbohydrates, β-carotene, biotin, folic acid, niacin, pantothenic acid, riboflavin, thiamine, and vitamins B_{12}, C and E.[194] Generation of edible microbial proteins produced by methanotrophic or hydrogen-oxidizing chemosynthetic bacteria which rely on methane or hydrogen and CO_2 instead of sugar as energy sources is currently under development[195] and work on fungal proteins (mycoproteins) and evidence of its health benefits is also re-emerging.[196,197] An interesting development is the co-cultivation of methane and hydrogen oxidizing bacteria (*Methyloparacoccus murrelli* LMG 27482 with *Cupriavidus necator* LMG 1201) for production of microbial mass.[198] Co-cultivation resulted in 3.8 times higher protein concentration and 6.1 times higher essential amino acid content compared to pure cultures, leveraging safe and sustainable gaseous substrates.[198]

7.4 Integrated agriculture-aquaculture systems

There has been co-cultivation of fish with crops practiced by traditional farmers. Traditional symbiotics rice-fish farming was reported in China about 2000 years ago and could be made more sustainable with further development.[199] Fish can be cultivated with livestock, crops or a combination of the three in a production system. The outputs from one sub-system can be an input into the other sub-system.[200,201] Integrated agriculture systems which cultivate aquatic foods (*e.g.* fish/crustaceans) and crops (*e.g.* rice, vegetables, fruits) are more environmentally sustainable and support a natural ecological balance.[202] Co-culture technologies with proper configuration of fields for rice and fish is necessary for achieving sustainable of rice-fish culture systems.[203]

7.5 Urban agriculture

Urban food production, as an alternative agricultural production system, should receive more attention. Urbanization, which started out as a rare way of life in human history is now a key phenomenon structuring human lives, economics, politics, societies and Earth-system dynamics.[204] In early cities urban growth and agricultural intensification were intertwined or low density forms of urbanisms with food production as part of agro-urban landscapes or peri-urban agriculture systems (including urban gardens, agroforestry, wetland raised foods) existed, depending on climate zones or regions.[204] Urban agriculture has been defined as “the growing, processing and distribution of food or livestock within and around urban centers with the goal of generating income”, or “the production of food and non-food plants, as well as husbandry, in urban and peri-urban areas”.[205] Reported benefits of urban agriculture include local ecosystem services (increased biodiversity, combating food insecurity, beautification, habitat for pollinators, recycling of organic waste, increased rainwater drainage) and climate change mitigation (potential reduction in greenhouse gases, carbon sequestering by vegetation and crops, protection of green spaces, potentially reduced energy and resources inputs).[205,206]

Hydroponics use a nutrient-rich water solution for the growth of crops. In aeroponics, plant are held in a soilless container where the roots are hanging in air and nutrient rich-water is sprayed onto the roots.[207] It is possible to have indoor vertical farms that employ cultivation techniques where plants are grown in soil-free culture medium with nutrient-rich solutions by suspension in a medium (*e.g.* rockwool, perlite) and provided with nutrients.[208] There are possibilities with the use of alternative soilless systems made from renewable and environmentally friendly organic material as growing media (*e.g.*, composted organic waste, coir, soft-wood pine bark). These systems can prevent excessive spread of soil pathogens and improve efficiency of water and fertilizer use whilst allowing for optimal plant growth and productivity.[209,210]

The recent status of urban agriculture consists of vertical farming, hydroponics, aeroponics (vertical farming using nutrient mists spayed on plant roots), aquaponics (vertical farms combining aquaculture and hydroponics) and digeponics (hydroponics combined with anaerobic digester for organic matter).[206] Vertical farming has a long history of use which dates back to ancient times. The Hanging Gardens of Babylon and the floating gardens of the Aztecs are old concepts which have been revolutionized with development in vertical farming systems. The Sky Urban Vertical Farming System is an example of low carbon hydraulic farming system, which maximizes the use of space and reduces water use by employing a rotating tower system, with growing troughs built to accommodate soil and hydroponics as the growing medium, and is another example of a sustainable solution to urban agriculture. It can also be used as a hybrid farming system that combines aquaculture with vertical farming.[211]

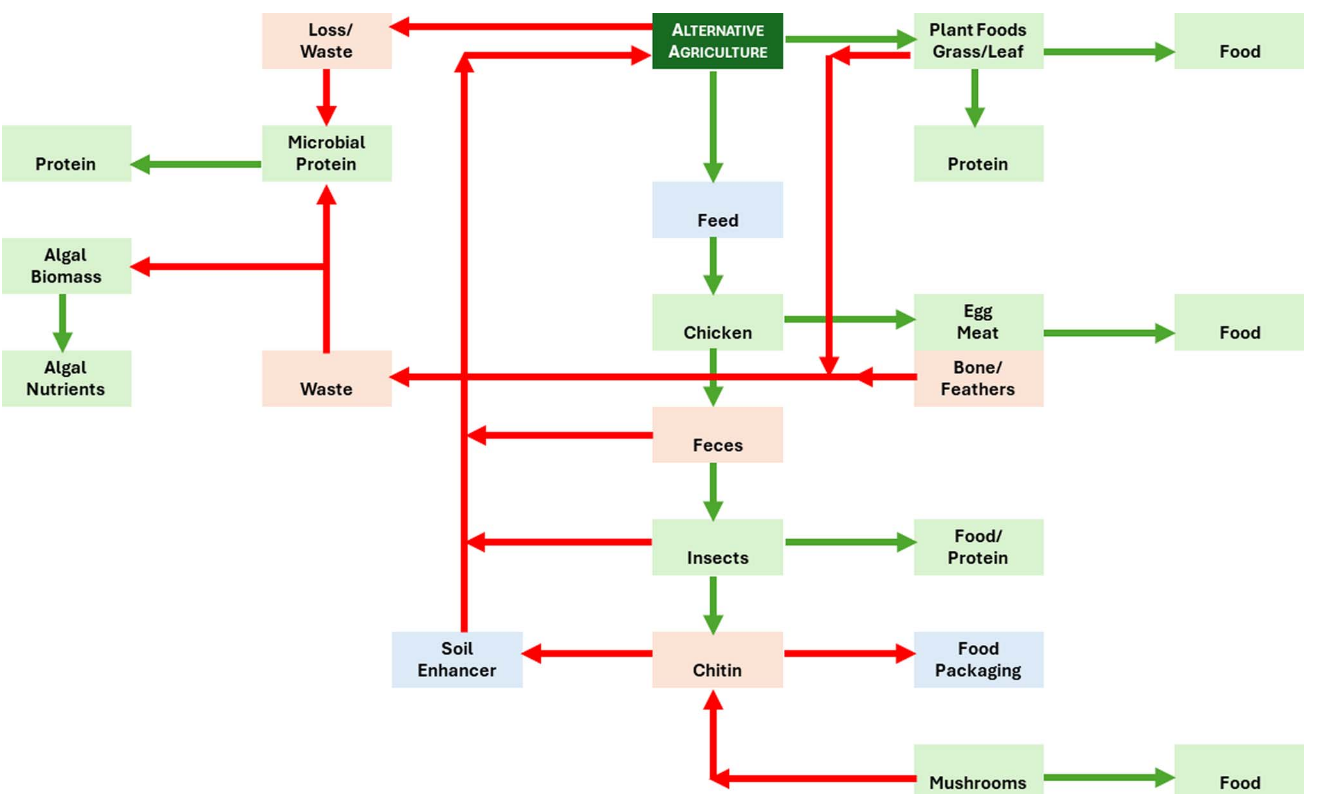

Fig. 2 Simplified example of cyclical food production.

Urban food (*e.g.*, urban gardens, urban agriculture) is a key lever for change with transformative outcomes such as changed diets; greened urban spaces; improved food quality, self-sufficiency, social resilience, ecological resilience; and (re) connection to nature.[171,212] Although urban agriculture has many benefits, greenhouse emissions are six times higher in urban agriculture than conventional agriculture.[213] Urban agriculture can become more climate friendly by growing crops that are generally grown in green-houses or air-freighted and using waste as inputs.[213] The development of green "sponge cities" is an example where the ancient wisdom of peasantry in field making, irrigating, fertilizing, growing, and harvesting, have been revived and integrated to build alternative ecological infrastructures to replace conventional gray infrastructures of cities.[214] This improves the connection between human beings and nature and transforms urban environments into productive and sustainable landscapes, particularly around water management.[214]

8. Re-imagined synergistic alternative agricultural practices to improve circularity

Alternative agricultural practices can be combined in a synergistic way with existing and emerging production systems to optimize use of natural resources. Fig. 2 gives a simplified example of an envisioned cyclic food production process which incorporates the use of alternative agricultural processes for restoring food production systems. It integrates elements of land-based (plants, grass, chicken), aqua-based (algae), soil-free systems (insects, mushroom) production systems and use of waste streams as inputs into food systems.

9. Key actions for food systems restoration

A paradigm shift from economically driven (poor environmental and public health, mining natural resources) to one-health driven food systems (improved environmental and public health, management of natural resources) has promoted a move away from cheap food at any cost to food within one-health framework.[215]

There needs to be more input in climate change issues, biodiversity, landscape/habitat preservation and societal demands on food and health including safe, nutritious, and sustainable food and animal welfare. There is also a need for a coherent system that combines regulations, incentives and sanctions following the "polluter pays, provider gets" principle.[59] To halt and reverse biodiversity losses, the European Commission has proposed the Nature Restoration Law which could become a cornerstone to restore biodiversity and ecosystem services.[216] It focusses on the protection and restoration of habitats and the authors see additional potential to operate on an ecosystem level, including enhancing landscape structure and rewetting peatlands which increase drought resilience, and restoring pollinator populations with direct positive impact on agricultural production. Other actions include reconnecting rivers with their floodplains, increasing green urban spaces, increasing forest diversity, and restoring marine ecosystems to improve resilience, people's health and diversity of ecosystems. Examples for key features of the proposed law[216] include that marine ecosystems reach good condition (30% by 2030; 60% by 2040 and 90% by 2050). For agricultural ecosystems, the goals are for the "Common Farmland Bird Index" to increase by 10% in 2030; 20% by 2040 and 30% in 2050, and restoration of organic soils in agricultural use constituting drained peatlands (30% by 2030; 40% by 2040 and 50% by 2050). For example, peatland covering only 3% of earth's land area holds the equivalent of half the carbon that is in the atmosphere as CO_2 (ref. 217) and the clearest threat to peatland is agricultural conversion or drainage.

A review on the building of a resilient, sustainable, and healthier food supply has been published.[10] Possible solutions suggested were: (i) improving food production through modern biotechnology (*e.g.*, CRISPR-based genome editing technologies), (ii) improving food sustainability using circular agriculture (*e.g.*, cultured meat, nutrient dense microbes), (iii) reducing waste through biotechnology (*e.g.*, innovative biotechnology approaches), (iv) enhancing agricultural efficiency using nanotechnologies (*e.g.* nano-fertilizers and -pesticides), (v) digital building block (big data, artificial intelligence, machine learning) to optimize the ability to produce and distribute foods and have better information regarding food properties, (vi) advanced robotics and autonomous machines (*e.g.*, tractors and combine harvesters, sensor technology), (vii) increased sustainability

Table 5 Key actions for food rural and urban production restoration[a]

Actions
General rural
Integration of benefits of all existing and potential food production systems
Increase production efficiency
Increase biodiversity
Explore new food sources
Apply reduced energy use systems
Re-cycle waste and up-cycle by-products
Connect sustainable agriculture with resilient food processing and consumption
General from science policy
Remove incentives making food production and consumption harmful to biodiversity
Accounting for true value and true cost of production by sector
Reduce food waste and loss across supply chains
Strengthen sustainability standards and certification
Promote the use of life cycle assessment
Promote sustainable and varied diets
Improve transparent reporting/definitions for describing sustainable foods
Mainstream biodiversity considerations (cross-cutting)
Strengthen governance of sustainable food production and consumption (cross-cutting)
Include climate change mitigation potential when developing dietary guidelines

[a] Sources: ref. 171 and 218–221.

Table 6 Alternative food production systems: (i) key principles, (ii) potential benefits & applications, and (iii) challenges & needs

Alternative food systems		
Principles	Benefits & applications	Challenges & needs
Traditional food production systems[223–226]		
• One with nature • Adaptation to change • Ecological knowledge for management • Self-sufficiency • Collective rights over communal resources	• Resilience • Preserve biodiversity • Conserve natural resources • Low energy dependence on external sources	• Undervalued indigenous knowledge • Loss of indigenous knowledge • Lack of documentation • Lack of market access • Lack of supportive government policies
Leaf and grass proteins[113,115,118,227]		
• Fresh leaves crushed or permeabilized/grasses pressed • Separation of solid and liquid by centrifugation • Protein extraction from liquid fraction	• Multiple annual harvests • Unique nutritional and functional profiles • Potential for source-dependent tailor-made nutrient profiles • Good source of vitamins and micronutrients • Low-cost processing • Grassland restoration • Good potential for development and start ups	• Selection of high nutrient leaf/grass sources • Selection of extraction process • Sensory properties • Color (chlorophyll) removal • Anti-nutritional components • Consumer acceptance • Processing to remove anti-nutritional compounds and pigments • Food safety assessments • Food regulation compliance
Plant cell and tissue cultures[123,143,144,146]		
• Surface sterilized leaf discs placed on solid medium for callus formation • Transfer to liquid medium • Scale up to bioreactor processing	• New generations of plant-based foods • Food processing side streams useable as nutrients sources • Good nutritional value • Acceptable sensory properties • Alternative to constrained traditional soil-based processes • Alternative to existing processes for pharmaceuticals, food ingredients production • Potential for start-ups	• Contamination • Consistency of cell culture lines • Replacement needs for plant growth regulators • Sterile process development & scale up • Food regulation compliance
Single cell proteins and microbial biomass[72,132,154,188–190,195]		
• Growth of photosynthetic and non-photosynthetic microorganism (yeast, fungi, bacteria, algae) • Grown on carbon and energy sources • Fermentation and drying	• Substitutes for traditional food protein • Climate, location, and season independence • Limited land space and water requirements • Good macro- and micro-nutrient sources • High product yields • Existing large scale production expertise • Environmental benefits • Past industrial production	• Strain selection, stability, and high nutrient generation • High nucleic acids content/nucleic acid reduction • Consumer acceptance • Safety assessments and food safety compliance • Economics (energy and access to cheap nutrient resources) • Life-cycle analysis data generation • Environmental impact studies • Use of waste streams as substrates • Food regulation compliance
Cultured meat[148,151,152,228]		
• Growth of muscle cells in culture media in bioreactor • Use of scaffolds for cell growth	• Reduce animal use • Less water and land use	• Higher energy requirements

Table 6 (*Contd.*)

Alternative food systems		
Principles	Benefits & applications	Challenges & needs
		• Price and competition from other plant-based substitutes
• Harvesting	• Less greenhouse gas emissions	• Difficulties in reproducing muscle texture and meat structure
• Cell processing	• Reduced nitrogen pollution	• Life-cycle analysis data generation
	• No killing of animals	• Consumer acceptance
Mushroom cultivation[104,153,229]		
• Inoculation of fungal mycelium in solid organic medium (*e.g.*, compost, sawdust, soil, straw, hulls)	• Valuable source of proteins (essential amino acids like animal protein, plant source for vitamin D2)	• Underutilized resource
• Fermentation at pH 4–8, 20–40 °C, 60–90% RH or in submerged culture fermentation to fleshy fruiting bodies	• Unique tastes and textures	• Highly perishable
	• Therapeutic properties	• Accumulation of heavy metals and radioactive isotopes
	• Large diversity	• Appropriate storage and preservation systems
	• Small to large scale production	• Safety assessment and quality assurance
		• Greenhouse cultivation systems
		• Standardized cultivation procedures
Dark food chain[140,141]		
• Chemoautotrophic conversion of CH_4 and CO_2 to biomass by methane- and hydrogen-oxidizing bacteria	• Protein alternatives	• Lack of knowledge about existing dark food chains
	• Reduce cropland need	• Selection of suitable microorganisms and process conditions
	• Delivery of chemical energy	• High nucleic acids content/nucleic acid reduction
	• Low water requirements	• Identification of low-cost substrates
	• Beneficial use of greenhouse gases (proposed based on marine and cave dark chains examples, industrial hydrogenotrophs, methylotrophs and acetotrophs based concepts and processes)	• Process optimization • Safety and consumer acceptance • Low energy bioreactor design • Food safety assessments
Cellular agriculture/Precision agriculture/Culture based foods[122–124,137,230]		
• Biological processes producing food without agriculture	• Controlled and sustainable food production	• Strain selection and stability
• Cultivation in bioreactor	• Limited space and land needs	• Process sterility/Contamination risks
• Harvesting	• Weather-, season- and location-independence	• Food safety maintenance
• Processing to obtain product of interest	• Potential for optimized productivity	• Toxicity & allergy issues
	• Controllable processes	• Extraction and purification
	• Niche operations for crops and food ingredients and start-ups	• Scale-up • Safety assessment
		• Long tern environmental studies
		• Labelling
		• Regulatory issues
		• Consumer acceptance
		• Economic barriers

through innovative farming methods (*e.g.*, climate controlled greenhouses, hydroponic and aeroponic facilities, supply chain shortening), and (vii) improved sustainability through alternative proteins (*e.g.*, plants, microbes, insects, tissue culture based).[10] Table 5 summarizes additional key actions proposed for food production restoration for rural and urban settings.

The United National Food Systems Summit (UNFSS) in 2021 highlighted the interconnections of food systems with Sustainable Development Goals (SDGs). Knowledge, science, evidence, and technology are all essential for transforming food systems. A UN Food Systems Coordination Hub following the 2021 Summit brings together knowledge and expertise on food systems. Areas for actions identified were (i) nourishment for all people within planetary boundaries, (ii) boosting of nature-based solutions and production, (iii) advancing equitable livelihoods, decent work and empowered communities, (iv) building resilience to vulnerabilities, shocks and stresses, and (v) ways of implementing transitions to transformation of food systems.[222]

10. Challenges to adoption of alternative food production systems

While it is recognized that alternative food production systems can preserve biodiversity, landscapes, and improve the sustainability of food systems, they have not been widely adopted. Bringing produce from an unconventional source has its challenges understanding the principles that underpin alternative food systems, the potential benefits and applicability of the produce from these systems, as well as the challenges and hurdles that need to be overcome are important for developing policies and actions to facilitate their adoption. Table 6 summarizes the key principles, benefits & applications, and challenges & needs for alternative food production systems.

11. Conclusion

Investment in resilient food systems is especially critical in vulnerable and fragile regions of the world. This requires a halting of agricultural land expansion, investing in food security and putting resilient landscapes at the heart of transformation.[231] Within this context, the resilience of indigenous peoples to environmental change[232] is noteworthy and evidence supporting the benefits of learning from their knowledge is mounting.[233] Accelerators to enable food systems innovation include (1) building trust among actors (developing shared visions and values), (2) transforming mindsets (promoting acceptance of different ways of producing/handling foods), and (3) enabling social license and stakeholder dialogue (ensuring responsible innovation).[234] Finally, we agree with the proposed fundamental concepts that have to be considered to enhance food systems resilience. These are (1) robustness (based on the capacity of the food system actors to adapt their activities to resist disruption to desired food system outcomes), (2) recovery (based on the ability of food system actors to adapt their activities so as to be able to return to pre-existing food system outcomes following disruption), and (3) reorientation (based on the ability of food system actors to adapt their activities based on accepting alternative food systems outcomes as a strategy before or after disruption).[235] We believe that such an appropriate balance is only achievable if consumers become a more active and well-educated group regarding values and importance of foods, and if appropriate resource-efficient food processing, distribution and preparation activities[236] are applied.

Data availability

No primary research results, software or code have been included and no new data were generated or analyzed as part of this review.

Author contributions

Dietrich Knorr: conceptualization, writing and reviewing; Mary Ann Augustin: writing and reviewing. All authors have read and approved the final manuscript.

Conflicts of interest

The authors declare no competing interests.

References

1 C. Ly, Has human activity put earth into a new epoch, *New Sci.*, 2023, **246**(3471), 15, DOI: **10.1016/S0262-4079(23)02363-1**.
2 D. Adam, Ditching 'Anthropocene': why ecologists say the term still matters, *Nature*, 2024, DOI: **10.1038/d41586-024-00786-2**.
3 J. Zalasiewicz, C. N. Waters, C. P. Summerhayes, A. P. Wolfe, A. D. Barnosky, A. Cearreta, *et al.*, The Working Group on the Anthropocene: Summary of evidence and interim recommendations, *Anthropocene*, 2017, **19**, 55–60, DOI: **10.1016/j.ancene.2017.09.001**.
4 M. B. Cole, M. A. Augustin, M. J. Robertson and J. M. Manners, The science of food security, *npj Sci. Food*, 2018, **2**(1), 14, DOI: **10.1038/s41538-018-0021-9**.
5 J. Rockström, J. Gupta, D. S. Qin, J. Lade, J. F. Abrams, L. S. Andersen, *et al.*, Safe and just Earth system boundaries, *Nature*, 2023, **619**(7968), 102–111, DOI: **10.1038/s41586-023-06083-8**.
6 D. Knorr and M. A. Augustin, Food systems at a watershed: Unlocking the benefits of technology and ecosystem symbioses, *Crit. Rev. Food Sci. Nutr.*, 2023, **63**(22), 5680–5697, DOI: **10.1080/10408398.2021.2023092**.
7 A. Meybeck and V. Gitz, Sustainable diets within sustainable food systems, *Proc. Nutr. Soc.*, 2017, **76**(1), 1–11, DOI: **10.1017/S0029665116000653**.
8 C. Béné, J. Fanzo, S. D. Prager, H. A. Achicanoy, B. R. Mapes, P. Alvarez Toro, *et al.*, Global drivers of food system (un) sustainability: A multi-country correlation analysis, *PLoS One*, 2020, **15**(4), e0231071, DOI: **10.1371/journal.pone.0231071**.
9 P. R. Ehrlich and J. Harte, To feed the world in 2050 will require a global revolution, *Proc. Natl. Acad. Sci. U.S.A.*, 2015, **112**(48), 14743–14744, DOI: **10.1073/pnas.1519841112**.
10 D. J. McClements, R. Barrangou, C. Hill, J. L. Kokini, M. A. Lila, A. S. Meyer, *et al.*, Building a Resilient, Sustainable, and Healthier Food Supply Through Innovation and Technology, *Annu. Rev. Food Sci. Technol.*, 2021, **12**, 1–28, DOI: **10.1146/annurev-food-092220-030824**.
11 P. Lillford and A. M. Hermansson, Global missions and the critical needs of food science and technology, *Trends Food Sci. Technol.*, 2021, **111**, 800–811, DOI: **10.1016/j.tifs.2020.04.009**.
12 D. Knorr and M. A. Augustin, From value chains to food webs: the quest for lasting food systems, *Trends Food Sci.*

Technol., 2021, **110**, 812–821, DOI: 10.1016/j.tifs.2021.02.037.

13 G. S. Khush, Green revolution: the way forward, *Nat. Rev. Genet.*, 2001, **2**(10), 815–822, DOI: 10.1038/35093585.

14 P. L. Pingali, Green Revolution: Impacts, limits, and the path ahead, *Proc. Natl. Acad. Sci. U.S.A.*, 2012, **109**(31), 12302–12308, DOI: 10.1073/pnas.0912953109.

15 A. Wezel, H. Brives, M. Casagrande, C. Clément, A. Dufour and P. Vandenbroucke, Agroecology territories: places for sustainable agricultural and food systems and biodiversity conservation, *Agroecol. Sustain. Food Syst.*, 2016, **40**(2), 132–144, DOI: 10.1080/21683565.2015.1115799.

16 HLPE Report 14, Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition, The High Level Panel of Experts (HLPE) on Food Security and Nutrition, 2019, FAO, Rome, https://www.fao.org/3/ca5602en/ca5602en.pdf.

17 A. Miles, M. S. DeLonge and L. Carlisle, Triggering a positive research and policy feedback cycle to support a transition to agroecology and sustainable food systems, *Agroecol. Sustain. Food Syst.*, 2017, **41**(7), 855–879, DOI: 10.1080/21683565.2017.1331179.

18 H. Sandhu, A. Müller, P. Sukhdev, K. Merrigan, A. Tenkouano, P. Kumar, *et al.*, The future of agriculture and food: Evaluating the holistic costs and benefits, *Anthropocene Review*, 2019, **6**(3), 270–278, DOI: 10.1177/2053019619872808.

19 S. Duddigan, L. J. Shaw, T. Sizmur, D. Gogu, Z. Hussain, K. Jirra, *et al.*, Natural farming improves crop yield in SE India when compared to conventional or organic systems by enhancing soil quality, *Agron. Sustainable Dev.*, 2023, **43**(2), 31, DOI: 10.1007/s13593-023-00884-x.

20 D. Knorr, Organic agriculture and foods: advancing process-product integrations, *Crit. Rev. Food Sci. Nutr.*, 2023, **28**, 1–13, DOI: 10.1080/10408398.2023.2200829.

21 L. M. Jaacks, L. Bliznashka, P. Craig, M. Eddleston, A. Gathorne-Hardy, R. Kumar, *et al.*, Co-Benefits of Largescale Organic farming On huManhealth (BLOOM): Protocol for a cluster randomised controlled evaluation of the Andhra Pradesh Community-managed Natural Farming programme in India, *PLoS One*, 2023, **18**(3), e0281677, DOI: 10.1371/journal.pone.0281677.

22 J. Helenius, S. E. Hagolani-Albov and K. Koppelmäki, Co-creating Agroecological Symbioses (AES) for Sustainable Food System Networks, *Front. Sustain. Food Syst.*, 2020, **4**, 588715, DOI: 10.3389/fsufs.2020.588715.

23 V. Ricciardi, Z. Mehrabi, H. Wittman, D. James and N. Ramankutty, Higher yields and more biodiversity on smaller farms, *Nat. Sustain.*, 2021, **4**(7), 651–657, DOI: 10.1038/s41893-021-00699-2.

24 C. Ren, S. Liu, H. van Grinsven, S. Reis, S. Jin, H. Liu, *et al.*, The impact of farm size on agricultural sustainability, *J. Cleaner Prod.*, 2019, **220**, 357–367, DOI: 10.1016/j.jclepro.2019.02.151.

25 J. Gaffney, J. Bing, P. F. Byrne, K. G. Cassman, I. Ciampitti and D. Delmer, Science-based intensive agriculture: Sustainability, food security, and the role of technology, *Glob. Food Secur*, 2019, **23**, 236–244, DOI: 10.1016/j.gfs.2019.08.003.

26 J. Pretty and Z. P. Bharucha, Sustainable intensification in agricultural systems, *Ann. Bot.*, 2014, **114**(8), 1571–1596, DOI: 10.1093/aob/mcu205.

27 T. Garnett, M. C. Appleby, A. Balmford, I. J. Bateman, T. G. Benton, P. Bloomer, *et al.*, Sustainable Intensification in Agriculture: Premises and Policies, *Science*, 2013, **341**(6141), 33–34, DOI: 10.1126/science.1234485.

28 S. Fiaz, S. Ahmar, S. Saeed, A. Riaz, F. Mora-Poblete and K. H. Jung, Evolution and Application of Genome Editing Techniques for Achieving Food and Nutritional Security, *Int. J. Mol. Sci.*, 2021, **22**(11), 5585, DOI: 10.3390/ijms22115585.

29 A. Balafoutis, B. Beck, S. Fountas, J. Vangeyte, T. V. Wal, I. Soto, *et al.*, Precision Agriculture Technologies Positively Contributing to GHG Emissions Mitigation, Farm Productivity and Economics, *Sustainability*, 2017, **9**(8), 1339, DOI: 10.3390/su9081339.

30 B. Basso and J. Antle, Digital agriculture to design sustainable agricultural systems, *Nat. Sustain.*, 2020, **3**(4), 254–256, DOI: 10.1038/s41893-020-0510-0.

31 V. Š. Kremsa, 5 - Sustainable management of agricultural resources (agricultural crops and animals), in *Sustainable Resource Management*, ed. C. M. Hussain and J. F. Velasco-Muñoz, Elsevier, 2021, pp. 99–145, DOI: 10.1016/B978-0-12-824342-8.00010-9.

32 S. H. Muhie, Novel approaches and practices to sustainable agriculture, *J. Agric. Food Res.*, 2022, **10**, 100446, DOI: 10.1016/j.jafr.2022.100446.

33 S. R. McGreevy, C. D. D. Rupprecht, D. Niles, A. Wiek, M. Carolan, G. Kallis, *et al.*, Sustainable agrifood systems for a post-growth world, *Nat. Sustain.*, 2022, **5**(12), 1011–1017, DOI: 10.1038/s41893-022-00933-5.

34 H. Hamadani, S. M. Rashid, J. D. Parrah, A. A. Khan, K. A. Dar and A. A. Ganie, *et al.*, Traditional Farming Practices and Its Consequences, in *Microbiota and Biofertilizers, Vol 2: Ecofriendly Tools for Reclamation of Degraded Soil Environs*, ed. G. H. Dar, R. A. Bhat, M. A. Mehmood and K. R. Hakeem, Springer International Publishing, Cham, 2021, pp. 119–128. DOI: 10.1007/978-3-030-61010-4_6.

35 Scale Climate Action, *Traditional Farming : Ancient Techniques for Modern Agriculture*, 2023, https://scaleclimateaction.org/news/traditional-farming-ancient-techniques-for-modern-agriculture/, accessed 18 March 2024.

36 Scale Climate Action, *Principles of Sustainable Agriculture: Promoting Ecological Balance and Food Security*, 2023, https://scaleclimateaction.org/agriculture/sustainable-agriculture/principles-of-sustainable-agriculture-promoting-ecological-balance-and-food-security/, accessed 18 March 2024.

37 H. Ritchie, L. Rosa and M. Roser, *Agricultural Production in Our World in Data*, 2023, https://ourworldindata.org/agricultural-production, accessed 17 March 2024.

38 C. Musvoto, K. Nortje, A. Nahman and W. Stafford, The Biophysical and Environmental Context, in *Green Economy Implementation in the Agriculture Sector: Moving from Theory to Practice*, ed. C. Musvoto, K. Nortje, A. Nahman and W. Stafford, Springer International Publishing, Cham., 2018, pp. 41–59. DOI: 10.1007/978-3-030-01809-2_3.
39 J. R. Schramski, C. B. Woodson and J. H. Brown, Energy use and the sustainability of intensifying food production, *Nat. Sustain.*, 2020, **3**(4), 257–259, DOI: 10.1038/s41893-020-0503-z.
40 D. Pimentel, L. E. Hurd, A. C. Bellotti, M. J. Forster, I. N. Oka, O. D. Sholes, *et al.*, Food production and the energy crisis, *Science*, 1973, **182**(4111), 443–449, DOI: 10.1126/science.182.4111.443.
41 W. A. Johnson, V. Stoltzfus and P. Craumer, Energy Conservation in Amish Agriculture, *Science*, 1977, **198**(4315), 373–378, DOI: 10.1126/science.198.4315.373.
42 E. Vogel and R. Meyer, Chapter 3 - Climate Change, Climate Extremes, and Global Food Production—Adaptation in the Agricultural Sector, in *Resilience*, ed. Z. Zommers and K. Alverson, Elsevier, 2018, pp. 31–49, DOI: DOI: 10.1016/B978-0-12-811891-7.00003-7.
43 A. M. D. Ortiz, C. L. Outhwaite, C. Dalin and T. Newbold, A review of the interactions between biodiversity, agriculture, climate change, and international trade: research and policy priorities, *One Earth*, 2021, **4**(1), 88–101, DOI: 10.1016/j.oneear.2020.12.008.
44 G. Lawton, *New Sci.*, 2022, **254**(3382), 48–51.
45 E. Crist, C. Mora and R. Engelman, The interaction of human population, food production, and biodiversity protection, *Science*, 2017, **356**(6335), 260–264, DOI: 10.1126/science.aal2011.
46 WWF, IUCN and WCPA, *A Guide to Inclusive, Equitable and Effective Implementation of Target 3 of the Kunming-Montreal Global Biodiversity Framework, Version 1*, ed. N. D. B. A. Mitchell, S. Stolton, J. Campese and H. L. Timmins, 2023, https://www.iucn.org/sites/default/files/2023-09/30x30-target-framework.pdf.
47 L. Latruffe, A. Niedermayr, Y. Desjeux, K. H. Dakpo, K. Ayouba, L. Schaller, *et al.*, Identifying and assessing intensive and extensive technologies in European dairy farming, *Eur. Rev. Agric. Econ.*, 2023, **50**(4), 1482–1519, DOI: 10.1093/erae/jbad023.
48 FAO, How to manage biodiversity for food and agriculture, FAO, Rome, https://www.fao.org/agriculture/crops/thematic-sitemap/theme/spi/scpi-home/managing-ecosystems/biodiversity-and-ecosystem-services/bio-how/en/, accessed 18 March 2024.
49 R. Seppelt, M. Beckmann, S. Ceauşu, A. F. Cord, K. Gerstner, J. Gurevitch, *et al.*, Harmonizing Biodiversity Conservation and Productivity in the Context of Increasing Demands on Landscapes, *BioScience*, 2016, **66**(10), 890–896, DOI: 10.1093/biosci/biw004.
50 R. J. Rickson, L. K. Deeks, A. Graves, J. A. H. Harris, M. G. Kibblewhite and R. Sakrabani, *I*nput constraints to food production: the impact of soil degradation, *Food Secur.*, 2015, **7**(2), 351–364, DOI: 10.1007/s12571-015-0437-x.
51 FAO, *Soil is a non-renewable resource*, FAO, Rome, 2015, https://www.fao.org/3/au889e/au889e.pdf, accessed 29 May 2024.
52 S. A. M. Perryman, N. I. D. Castells-Brooke, M. J. Glendining, K. W. T. Goulding, M. J. Hawkesford, A. J. Macdonald, *et al.*, The electronic Rothamsted Archive (e-RA), an online resource for data from the Rothamsted long-term experiments, *Sci. Data*, 2018, **5**, 180072, DOI: 10.1038/sdata.2018.72.
53 A. E. Johnston and P. R. Poulton, The importance of long-term experiments in agriculture: their management to ensure continued crop production and soil fertility; the Rothamsted experience, *Eur. J. Soil Sci.*, 2018, **69**(1), 113–125, DOI: 10.1111/ejss.12521.
54 P. Mäder, A. Fliessbach, D. Dubois, L. Gunst, P. Fried and U. Niggli, Soil fertility and biodiversity in organic farming, *Science*, 2002, **296**(5573), 1694–1697, DOI: 10.1126/science.1071148.
55 C. E. LaCanne and J. G. Lundgren, Regenerative agriculture: merging farming and natural resource conservation profitably, *PeerJ*, 2018, **6**, e4428, DOI: 10.7717/peerj.4428.
56 H. Hirt, Healthy soils for healthy plants for healthy humans, *EMBO Rep.*, 2020, **21**(8), e51069, DOI: 10.15252/embr.202051069.
57 H. Azarbad, Conventional vs. Organic Agriculture-Which One Promotes Better Yields and Microbial Resilience in Rapidly Changing Climates?, *Front. Microbiol.*, 2022, **13**, 903500, DOI: 10.3389/fmicb.2022.903500.
58 Y. Guo and L. Zinke, *Soils in Food Systems*, Nature Portifolio, 2023, https://www.nature.com/collections/cdcajciajc, accessed 29 May 2024.
59 G. Pe'er, Y. Zinngrebe, F. Moreira, C. Sirami, S. Schindler, R. Müller, *et al.*, A greener path for the EU Common Agricultural Policy, *Science*, 2019, **365**(6452), 49–451, DOI: 10.1126/science.aax3146.
60 Euronews, *EU to revise Agricultural Policy in response to farmers protests*, 2024, https://www.euronews.com/2024/03/16/eu-to-revise-agricultural-policy-in-response-to-farmers-protests, accessed 18 March 2024.
61 M. Springmann and F. Freund, Options for reforming agricultural subsidies from health, climate, and economic perspectives, *Nat. Commun.*, 2022, **13**(1), 82, DOI: 10.1038/s41467-021-27645-2.
62 N. Ramakutty, Z. Mehrabi, K. Waha, L. Jarvis, C. Kremen, M. Herrero, *et al.*, Trends in global agriculture land use: Implications for environmental health and food security, *Annu. Rev. Plant Biol.*, 2019, **69**, 789–815, DOI: 10.1146/annurev-arplant-042817-040256.
63 S. J. Cooke, J. R. Bennett and H. P. Jones, We have a long way to go if we want to realize the promise of the "Decade on Ecosystem Restoration", *Conserv. Sci. Pract.*, 2019, **1**(12), e129, DOI: 10.1111/csp2.129.
64 M. M. Rahman, I. Khan, D. L. Field, K. Techato and K. Alameh, Powering agriculture: Present status, future potential, and challenges of renewable energy

applications, *Renewable Energy*, 2022, **188**, 731–749, DOI: 10.1016/j.renene.2022.02.065.
65 M. Trommsdorff, I. S. Dhal, Ö. E. Özdemir, D. Ketzer, N. Weinberger and C. Rösch, Chapter 5 - Agrivoltaics: solar power generation and food production, in *Solar Energy Advancements in Agriculture and Food Production Systems*, ed. S. Gorjian and P. E. Campana, Academic Press, 2022, pp. 159–210, DOI: DOI: 10.1016/B978-0-323-89866-9.00012-2.
66 D. Knorr and M. A. Augustin, Vanishing Water: Rescuing the Neglected Food Resource, *Food Eng. Rev.*, 2023, **15**, 609–624, DOI: 10.1007/s12393-023-09349-z.
67 S. Pratiwi and N. Juerges, Review of the impact of renewable energy development on the environment and nature conservation in Southeast Asia, *Energy Ecol. Environ.*, 2020, **5**(4), 221–239, DOI: 10.1007/s40974-020-00166-2.
68 O. Arodudu, K. Helming, H. Wiggering and A. Voinov, Towards a more holistic sustainability assessment framework for agro-bioenergy systems — A review, *Environ. Impact Assess. Rev.*, 2017, **62**, 61–75, DOI: 10.1016/j.eiar.2016.07.008.
69 T. Ulian, M. Diazgranados, S. Pironon, S. Padulosi, U. Liu, L. Davies, *et al.*, Unlocking plant resources to support food security and promote sustainable agriculture, *Plants People Planet*, 2020, **2**, 421–425, DOI: 10.1002/ppp3.10145.
70 M. Chapman, B. R. Goldstein, C. J. Schell, J. S. Brashares, N. H. Carter, D. Ellis-Soto, *et al.*, Biodiversity monitoring for a just planetary future, *Science*, 2024, **383**(6678), 34–36, DOI: 10.1126/science.adh8874.
71 E. Nicholson, A. Andrade, T. M. Brooks, A. Driver, J. R. Ferrer-Paris, H. Grantham, *et al.*, Roles of the Red List of Ecosystems in the Kunming-Montreal Global Biodiversity Framework, *Nat. Ecol. Evol.*, 2024, **8**, 614–621, DOI: 10.1038/s41559-023-02320-5.
72 S. Díaz, N. Zafra-Calvo, A. Purvis, P. H. Verburg, D. Obura, P. Leadley, *et al.*, Set ambitious goals for biodiversity and sustainability, *Science*, 2020, **370**(6515), 411–413, DOI: 10.1126/science.abe1530.
73 Y. Chiffoleau, T. Dourian, G. Enderli, D. Mattioni, G. Akermann, A. Loconto, *et al.*, Reversing the trend of agrobiodiversity decline by co-developing food chains with consumers: A European survey for change, *Sustain. Prod. Consum.*, 2024, **46**, 343–354, DOI: 10.1016/j.spc.2024.02.032.
74 M. Funabashi, Human augmentation of ecosystems: objectives for food production and science by 2045, *npj Sci. Food*, 2018, **2**(1), 16, DOI: 10.1038/s41538-018-0026-4.
75 M. I. Williams, C. L. Farr, D. S. Page-Dumroese, S. J. Connolly and E. Padley, Soil Management and Restoration, in *Forest and Rangeland Soils of the United States under Changing Conditions: A Comprehensive Science Synthesis*, ed. R. V. Pouyat, D. S. Page-Dumroese, T. Patel-Weynand and L. H. Geiser, Springer International Publishing, Cham, 2020, pp. 145–167, DOI: 10.1007/978-3-030-45216-2_8.
76 M. A. Ayub, M. Usman, T. Faiz, M. Umair, M. A. ul Haq and M. Rizwan, *et al.*, Restoration of Degraded Soil for Sustainable Agriculture, in *Soil Health Restoration and Management*, ed. R. S. Meena, Springer Singapore, Singapore, 2020, pp. 31–81, DOI DOI: 10.1007/978-981-13-8570-4_2.
77 W. L. Silver, T. Perez, A. Mayer and A. R. Jones, The role of soil in the contribution of food and feed, *Philos. Trans. R. Soc., B*, 2020, **376**, 20200181, DOI: 10.1098/rstb.2020.0181.
78 R. S. Meena, S. Kumar, R. Datta, R. Lal, V. Vijayakumar, M. Brtnicky, *et al.*, Impact of Agrochemicals on Soil Microbiota and Management: A Review, *Land*, 2020, **9**(2), 34, DOI: 10.3390/land9020034.
79 M. Banov, S. Rousseva and P. Pavlov, Sustainable Management and Restoration of the Fertility of Damaged and Contaminated Lands and Soils, in *Soil Health Restoration and Management*, ed. R. S. Meena, Springer Singapore, Singapore, 2020, pp. 113–159, DOI: DOI: 10.1007/978-981-13-8570-4_4.
80 J. de Vrieze, The littlest farmhands, *Science*, 2015, **349**(6249), 680–683, DOI: 10.1126/science.349.6249.680.
81 F. Bastida, N. Selevsek, I. F. Torres, T. Hernández and C. García, Soil restoration with organic amendments: linking cellular functionality and ecosystem processes, *Sci. Rep.*, 2015, **5**(1), 15550, DOI: 10.1038/srep15550.
82 A. K. H. Priyashantha, D. Q. Dai, D. J. Bhat, S. L. Stephenson, I. Promputtha, P. Kaushik, *et al.*, Plant-Fungi Interactions: Where It Goes?, *Biology*, 2023, **12**(6), 809, DOI: 10.3390/biology12060809.
83 B. Lopez, P. J. Hines and C. Ash, The unrecognized value of grass, *Science*, 2022, **377**(6606), 590–591, DOI: 10.1126/science.add6362.
84 E. Buisson, S. Archibald, A. Fidelis and K. N. Suding, Ancient grasslands guide ambitious goals in grassland restoration, *Science*, 2022, **377**(6606), 594–598, DOI: 10.1126/science.abo4605.
85 Y. Bai and M. F. Cotrufo, Grassland soil carbon sequestration: Current understanding, challenges, and solutions, *Science*, 2022, **377**(6606), 603–608, DOI: 10.1126/science.abo2380.
86 E. N. Ponnampalam and B. W. B. Holman, Chapter 22 - Sustainability II: Sustainable animal production and meat processing, in *Lawrie's Meat Science*, ed. F. Toldrá, Woodhead Publishing, 2023, pp. 727–798, DOI: 10.1016/B978-0-323-85408-5.00001-7.
87 D. Henn, C. Duffy, J. Humphreys, J. Gibbons, K. A. Byrne and D. Styles, Cattle production strategies to deliver protein with less land and lower environmental impact, *J. Environ. Manage.*, 2024, **356**, 120569, DOI: 10.1016/j.jenvman.2024.120569.
88 J. A. Gephart, P. J. G. Henriksson, R. W. R. Parker, A. Shepon, K. D. Gorospe, K. Bergman, *et al.*, Environmental performance of blue foods, *Nature*, 2021, **597**(7876), 60–365, DOI: 10.1038/s41586-021-03889-2.
89 M. Sharifinia, Improve aquaculture with insect meal, *Science*, 2024, **383**(6685), 838, DOI: 10.1126/science.ado0380.
90 H. K. Alleway, T. J. Waters, R. Brummett, J. Cai, L. Cao, M. R. Cayten, *et al.*, Global principles for restorative

aquaculture to foster aquaculture practices that benefit the environment, *Conserv. Sci. Pract.*, 2023, **5**(8), e12982, DOI: 10.1111/csp2.12982.

91 R. K. F. Unsworth, L. C. Cullen-Unsworth, B. L. H. Jones and R. J. Lilley, The planetary role of seagrass conservation, *Science*, 2022, **377**(6606), 609–613, DOI: 10.1126/science.abq6923.

92 R. Felger and M. B. Moser, Eelgrass (Zostera marina L.) in the Gulf of California, *Science*, 1973, **181**(4097), 355–356, DOI: 10.1126/science.181.4097.355.

93 Project Seagrass, *Our plan to save the world's seagrass*, 2024, https://www.projectseagrass.org/our-strategy/, accessed 23 March 2024.

94 F. Gilck and P. Poschlod, The origin of alpine farming: A review of archaeological, linguistic and archaeobotanical studies in the Alps, *Holocene*, 2019, **29**(9), 1503–1511, DOI: 10.1177/0959683619854511.

95 L. Battaglini, S. Bovolenta, F. Gusmeroli, S. Salvador and E. Sturaro, Environmental Sustainability of Alpine Livestock Farms, *Ital. J. Anim. Sci.*, 2014, **13**(2), 3155, DOI: 10.4081/ijas.2014.3155.

96 D. H. DeJong, Chapter 9 - American Indian Agriculture, in *A Companion to American Agricultural History*, ed. R. D. Hurt, Wiley Online Library, 2022, pp. 115–128, DOI: 10.1002/9781119632214.ch9.

97 Native Tribe Info, *Native American Farming: Traditional Practices and Sustainable Agriculture*, 2023, https://nativetribe.info/native-american-farming-traditional-practices-and-sustainable-agriculture/, accessed 19 March 2024.

98 N. Kurashima, L. Fortini and T. Ticktin, The potential of indigenous agricultural food production under climate change in Hawaii, *Nat. Sustain.*, 2019, **2**(3), 91–199, DOI: 10.1038/s41893-019-0226-1.

99 WWF, *Return of indigenous farming, foods & fire could help regenerate Australia*, 2021, https://wwf.org.au/news/2021/return-of-indigenous-farming-foods-fire-could-help-regenerate-australia/, accessed 6 June 2024.

100 T. Guo, M. García-Martín and T. Plieninger, Recognizing indigenous farming practices for sustainability: a narrative analysis of key elements and drivers in a Chinese dryland terrace system, *Ecosystems People*, 2021, **17**(1), 279–291, DOI: 10.1080/26395916.2021.1930169.

101 Z. Bharucha and J. Pretty, The roles and values of wild foods in agricultural systems, *Philos. Trans. R. Soc., B*, 2010, **365**(1554), 2913–2926, DOI: 10.1098/rstb.2010.0123.

102 A. Ray, R. Ray and E. A. Sreevidya, How Many Wild Edible Plants Do We Eat—Their Diversity, Use, and Implications for Sustainable Food System: An Exploratory Analysis in India, *Front. Sustain. Food Syst.*, 2020, **4**, 56, DOI: 10.3389/fsufs.2020.00056.

103 M. E. Valverde, T. Hernández-Pérez and O. Paredes-López, Edible mushrooms: improving human health and promoting quality life, *Int. J. Microbiol.*, 2015, **2015**, 376387, DOI: 10.1155/2015/376387.

104 H. El Enshasy, E. A. Elsayed, R. Aziz and M. A. Wadaan, Mushrooms and truffles: historical biofactories for complementary medicine in Africa and in the middle East, *J. Evidence-Based Complementary Altern. Med.*, 2013, **2013**, 620451, DOI: 10.1155/2013/620451.

105 P. Procházka, J. Soukupová, K. J. Mullen, K. Tomšík Jr and I. Čábelková, Wild Mushrooms as a Source of Protein: A Case Study from Central Europe, Especially the Czech Republic, *Foods*, 2023, **12**(5), 935, DOI: 10.3390/foods12050934.

106 G. W. Sileshi, D. D. Tibuhwa and A. Mlambo, Underutilized wild edible fungi and their undervalued ecosystem services in Africa, *CABI Agric. Biosci.*, 2023, **4**(1), 3, DOI: 10.1186/s43170-023-00145-7.

107 M. Halwart, Biodiversity, nutrition and livelihoods in aquatic rice-based ecosystems, *Biodiversity*, 2008, **9**(1–2), 6–40, DOI: 10.1080/14888386.2008.9712879.

108 A. Thattantavide, S. Sreedharan, N. Sharma, I. Uthirchakkavu, A. Surendran and A. Kumar, An Introduction to Wild Food Plants for Zero Hunger and Resilient Agriculture, in *Wild Food Plants for Zero Hunger and Resilient Agriculture*, ed. A. A. Kumar, P. Singh, S. Singh and B. Singh, Springer Nature Singapore, Singapore, 2023, pp. 1–41, DOI: 10.1007/978-981-19-6502-9_1.

109 P. M. de Medeiros, D. M. Barbosa, G. M. C. dos Santos and R. R. V. da Silva, Wild Food Plant Popularization and Biocultural Conservation: Challenges and Perspectives, in *Local Food Plants of Brazil*, ed. M. C. M. Jacob and U. P. Albuquerque, Springer International Publishing, Cham, 2021, pp. 341–349, DOI: 10.1007/978-3-030-69139-4_16.

110 R. P. Harisha, R. Siddappa Setty and G. Ravikanth, Wild Food Plants: History, Use, and Impacts of Globalization, in *Wild Food Plants for Zero Hunger and Resilient Agriculture*, ed. A. Kumar, P. Singh, S. Singh and B. Singh, Springer Nature Singapore, Singapore, 2023, pp. 5–92, DOI DOI: 10.1007/978-981-19-6502-9_3.

111 S. Heppner and Y. D. Livney, Green leaves as a promising source for sustainable food protein: Seeking the productivity-functionality balance, *Trends Food Sci. Technol.*, 2023, **142**, 104207, DOI: 10.1016/j.tifs.2023.104207.

112 J. Widmer, B. Christ, J. Grenz and L. Norgrove, Agrivoltaics, a promising new tool for electricity and food production: A systematic review, *Renewable Sustainable Energy Rev.*, 2024, **192**, 114277, DOI: 10.1016/j.rser.2023.114277.

113 C. Balfany, J. Gutierrez, M. Moncada and S. Komarnytsky, Current Status and Nutritional Value of Green Leaf Protein, *Nutrients*, 2023, **15**(6), 1327, DOI: 10.3390/nu15061327.

114 É. Domokos-Szabolcsy, S. R. Yavuz, E. Picoli, M. G. Fári, Z. Kovács, C. Tóth, *et al.*, Green Biomass-Based Protein for Sustainable Feed and Food Supply: An Overview of Current and Future Prospective, *Life*, 2023, **13**(2), 307, DOI: 10.3390/life13020307.

115 N. W. Pirie, Leaf Protein as a Human Food, *Science*, 1966, **152**(3730), 1701–1705, DOI: 10.1126/science.152.3730.1701.

116 N. W. Pirie, Leaf protein: a beneficiary of tribulation, *Nature*, 1975, **253**(5489), 239–241, DOI: 10.1038/253239a0.

117 S. Pérez-Vila, M. A. Fenelon, J. A. O'Mahony and L. G. Gómez-Mascaraque, Extraction of plant protein from green leaves: Biomass composition and processing considerations, *Food Hydrocoll.*, 2022, **133**, 107902, DOI: 10.1016/j.foodhyd.2022.107902.

118 X. Guo, K. Aganovic, U. Bindrich, A. Juadjur, C. Hertel, E. Ebert, *et al.*, Extraction of protein from juice blend of grass and clover pressed by a pilot pressing facility combined with a pulsed electric field treatment, *Future Foods*, 2022, **6**, 100173, DOI: 10.1016/j.fufo.2022.100173.

119 A. A. Anoop, P. K. S. Pillai, M. Nickerson and K. V. Ragavan, Plant leaf proteins for food applications: Opportunities and challenges, *Compr. Rev. Food Sci. Food Saf.*, 2023, **22**(1), 473–501, DOI: 10.1111/1541-4337.13079.

120 G. A. Barron-Gafford, M. A. Pavao-Zuckerman, R. L. Minor, L. F. Sutter, I. Barnett-Moreno, D. T. Blackett, *et al.*, Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands, *Nat. Sustain.*, 2019, **2**(9), 848–855, DOI: 10.1038/s41893-019-0364-5.

121 S. Edouard, D. Combes, M. Van Iseghem, M. Ng Wing Tin and A. J. Escobar-Gutiérrez, Increasing land productivity with agriphotovoltaics: Application to an alfalfa field, *Appl. Energy*, 2023, **329**, 20207, DOI: 10.1016/j.apenergy.2022.120207.

122 S. J. Davis, K. Alexander, J. Moreno-Cruz, C. Hong, M. Shaner, K. Caldeira, *et al.*, Food without agriculture, *Nat. Sustain.*, 2024, **7**(1), 90–95, DOI: 10.1038/s41893-023-01241-2.

123 R. Eibl, Y. Senn, G. Gubser, V. Jossen, C. van den Bos and D. Eibl, Cellular Agriculture: Opportunities and Challenges, *Annu. Rev. Food Sci. Technol.*, 2021, **12**, 51–73, DOI: 10.1146/annurev-food-063020-123940.

124 M. A. Augustin, C. J. Hartley, G. Maloney and S. Tyndall, Innovation in precision fermentation for food ingredients, *Crit. Rev. Food Sci. Nutr.*, 2024, **64**, 6218–6238, DOI: 10.1080/10408398.2023.2166014.

125 T. S. Teng, Y. L. Chin, K. F. Chai and W. N. Chen, Fermentation for future food systems, *EMBO Rep.*, 2021, **22**(5), e52680, DOI: 10.15252/embr.202152680.

126 M. Holmes, Yeast, coal, and straw: J. B. S. Haldane's vision for the future of science and synthetic food, *Hist. Hum. Sci.*, 2023, **36**(3–4), 202–220, DOI: 10.1177/09526951231156729.

127 A. T. McPherson, Synthetic Food, *Nature*, 1973, **242**(5393), 144–145, DOI: 10.1038/242144c0.

128 T. Cai, H. Sun, J. Qiao, L. Zhu, F. Zhang, J. Zhang, *et al.*, Cell-free chemoenzymatic starch synthesis from carbon dioxide, *Science*, 2021, **373**(6562), 1523–1527, DOI: 10.1126/science.abh4049.

129 X. Lv, Y. Wu, M. Gong, J. Deng, Y. Gu, Y. Liu, *et al.*, Synthetic biology for future food: Research progress and future directions, *Future Foods*, 2021, **3**, 100025, DOI: 10.1016/j.fufo.2021.100025.

130 M. Ciani, A. Lippolis, F. Fava, L. Rodolfi, A. Niccolai and M. R. Tredici, Microbes: Food for the Future, *Foods*, 2021, **10**(5), 971, DOI: 10.3390/foods10050971.

131 K. R. Choi, H. E. Yu and S. Y. Lee, Microbial food: microorganisms repurposed for our food, *Microb. Biotechnol.*, 2022, **15**(1), 18–25, DOI: 10.1111/1751-7915.13911.

132 T. Linder, Making the case for edible microorganisms as an integral part of a more sustainable and resilient food production system, *Food Secur.*, 2019, **11**(2), 265–278.

133 T. J. Barzee, H. M. El Mashad, L. Cao, A. Chio, Z. Pan and R. Zhang, Cell-cultivated food production and processing: A review, *Food Bioeng.*, 2022, **1**(1), 4–25, DOI: 10.1002/fbe2.12009.

134 A. Nyyssölä, A. Suhonen, A. Ritala and K.-M. Oksman-Caldentey, The role of single cell protein in cellular agriculture, *Curr. Opin. Biotechnol.*, 2022, **75**, 102686, DOI: 10.1016/j.copbio.2022.102686.

135 J. H. Dupuis, L. K. Y. Cheung, L. Newman, D. R. Dee and R. Y. Yada, Precision cellular agriculture: The future role of recombinantly expressed protein as food, *Compr. Rev. Food Sci. Food Saf.*, 2023, **22**(2), 882–912, DOI: 10.1111/1541-4337.13094.

136 R. Wikandari, S. Baldermann, A. Ningrum and M. J. Taherzadeh, Application of cell culture technology and genetic engineering for production of future foods and crop improvement to strengthen food security, *Bioengineered*, 2021, **12**(2), 11305–11330, DOI: 10.1080/21655979.2021.2003665.

137 R. C. Rodrigues, H. S. Pereira, R. L. Senra, A. d. O. B. Ribon and T. A. d. O. Mendes, Understanding the emerging potential of synthetic biology for food science: Achievements, applications and safety considerations, *Food Chem. Adv.*, 2023, **3**, 100476, DOI: 10.1016/j.focha.2023.100476.

138 E. C. Hann, S. Overa, M. Harland-Dunaway, A. F. Narvaez, D. N. Le, M. L. Orozco-Cárdenas, *et al.*, A hybrid inorganic–biological artificial photosynthesis system for energy-efficient food production, *Nat. Food*, 2022, **3**(6), 461–471, DOI: 10.1038/s43016-022-00530-x.

139 D. Leger, S. Matassa, E. Noor, A. Shepon, R. Milo and A. Bar-Even, Photovoltaic-driven microbial protein production can use land and sunlight more efficiently than conventional crops, *Proc. Natl. Acad. Sci. U. S. A.*, 2021, **118**(26), e2015025118, DOI: 10.1073/pnas.2015025118.

140 S. H. El Abbadi and C. S. Criddle, Engineering the Dark Food Chain, *Environ. Sci. Technol.*, 2019, **53**(5), 2273–2287, DOI: 10.1021/acs.est.8b04038.

141 A. Alloul, J. Spanoghe, D. Machado and S. E. Vlaeminck, Unlocking the genomic potential of aerobes and phototrophs for the production of nutritious and palatable microbial food without arable land or fossil fuels, *Microb. Biotechnol.*, 2022, **15**(1), 6–12, DOI: 10.1111/1751-7915.13747.

142 R. Teutonico and D. Knorr, Plant tissue culture: Food applications and the potential reduction of nutritional stress factors, *Food Technol.*, 1984, **38**, 120–127.

143 S. T. Häkkinen, H. Nygren, L. Nohynek, R. Puupponen-Pimiä, R. L. Heiniö, N. Maiorova, *et al.*, Plant cell cultures as food-aspects of sustainability and safety, *Plant Cell Rep.*, 2020, **39**(12), 1655–1668, DOI: 10.1007/s00299-020-02592-2.

144 A. Ritala, R. L. Heiniö, S. T. Häkkinen, M. Lille, T. Hyytiäinen-Pabst and H. Rischer, Tailoring sensory properties of plant cell cultures for food use, *Food Res. Int.*, 2022, **157**, 111440, DOI: 10.1016/j.foodres.2022.111440.

145 M. Bianconi, L. Ceriotti, S. Cuzzocrea, E. Esposito, G. Pressi, E. Sgaravatti, *et al.*, Red Carrot Cells Cultured in vitro Are Effective, Stable, and Safe Ingredients for Skin Care, Nutraceutical, and Food Applications, *Front. Bioeng. Biotechnol.*, 2020, **8**, 575079, DOI: 10.3389/fbioe.2020.575079.

146 G. Gubser, S. Vollenweider, D. Eibl and R. Eibl, Food ingredients and food made with plant cell and tissue cultures: State-of-the art and future trends, *Eng. Life Sci.*, 2021, **21**(3–4), 87–98, DOI: 10.1002/elsc.202000077.

147 Z. Cai, H. Riedel, N. M. Thaw Saw, O. Kütük, I. Mewis, H. Jäger, *et al.*, Effects of Pulsed Electric Field on Secondary Metabolism of Vitis vinifera L. cv. Gamay Fréaux Suspension Culture and Exudates, *Appl. Biochem. Biotechnol.*, 2011, **164**(4), 443–453, DOI: 10.1007/s12010-010-9146-2.

148 C. Faustman, D. Hamernik, M. Looper and S. A. Zinn, Cell-based meat: the need to assess holistically, *J. Anim. Sci.*, 2020, **98**(8), skaa177, DOI: 10.1093/jas/skaa177.

149 S. David, A. Tsukerman, D. Safina, A. Maor-Shoshani, N. Lavon and S. Levenberg, *C*o-culture approaches for cultivated meat production, *Nat. Rev. Bioeng.*, 2023, **1**(11), 817–831, DOI: 10.1038/s44222-023-00077-x.

150 H. L. Tuomisto and M. J. Teixeira de Mattos, Environmental Impacts of Cultured Meat Production, *Environ. Sci. Technol.*, 2011, **45**(14), 6117–6123, DOI: 10.1021/es200130u.

151 N. Treich, Cultured Meat: Promises and Challenges, *Environ. Resour. Econ.*, 2021, **79**(1), 33–61, DOI: 10.1007/s10640-021-00551-3.

152 S. Chriki and J.-F. Hocquette, The Myth of Cultured Meat: A Review, *Front. Nutr.*, 2020, **7**, 7, DOI: 10.3389/fnut.2020.00007.

153 K. D. Hyde, J. Xu, S. Rapior, R. Jeewon, S. Lumyong, A. G. T. Niego, *et al.*, The amazing potential of fungi: 50 ways we can exploit fungi industrially, *Fungal Diversity*, 2019, **97**(1), 1–136, DOI: 10.1007/s13225-019-00430-9.

154 R. Majumder, S. Miatur, A. Saha and S. Hossain, Mycoprotein: production and nutritional aspects: a review, *Sustainable Food Technol.*, 2024, **2**(1), 81–91.

155 G. Lawton, Fungi ahoy, *New Sci.*, 2024, **261**(3477), 37–39, DOI: 10.1016/S0262-4079(24)00274-4.

156 S. C. Gonçalves, D. Haelewaters, G. Furci and G. M. Mueller, Include all fungi in biodiversity goals, *Science*, 2021, **373**(6553), 403, DOI: 10.1126/science.abk1312.

157 E. S. Lipinsky, J. H. Litchfield and D. I. C. Wang, Algae, bacteria, and yeasts as food or feed, *Crit. Rev. Food Sci. Nutr.*, 1970, **1**, 581–618, DOI: 10.1080/10408397009558517.

158 C. J. Diaz, K. J. Douglas, K. Kang, A. L. Kolarik, R. Malinovski, Y. Torres-Tiji, *et al.*, Developing algae as a sustainable food source, *Front. Nutr.*, 2022, **9**, 1029841, DOI: 10.3389/fnut.2022.1029841.

159 UNEP, *Seaweed Farming: Assessment of the potential of sustainable upscaling for climate, communities and the planet*, Nairobi, 2023, ISBN: 978-92-807-4032-5, https://www.unep.org/resources/report/seaweed-farming-assessment-sustainable-upscaling, accessed 21 March 2024.

160 B. Naik, R. Mishra, V. Kumar, S. Mishra, U. Gupta, S. Rustagi, *et al.*, Micro-algae: Revolutionizing food production for a healthy and sustainable future, *J. Agric. Food Res.*, 2024, **15**, 100939, DOI: 10.1016/j.jafr.2023.100939.

161 M. L. Wells, P. Potin, J. S. Craigie, J. A. Raven, S. S. Merchant, K. E. Helliwell, *et al.*, Algae as nutritional and functional food sources: revisiting our understanding, *J. Appl. Phycol.*, 2017, **29**(2), 949–982, DOI: 10.1007/s10811-016-0974-5.

162 S. Spillias, H. Valin, M. Batka, F. Sperling, P. Havlík, D. Leclère, *et al.*, Reducing global land-use pressures with seaweed farming, *Nat. Sustain.*, 2023, **6**(4), 380–390, DOI: 10.1038/s41893-022-01043-y.

163 F. U. Jehn, F. J. Dingal, A. Mill, C. Harrison, E. Ilin, M. Y. Roleda, *et al.*, Seaweed as a Resilient Food Solution After a Nuclear War, *Earth's Future*, 2024, **12**(1), e2023EF003710, DOI: 10.1029/2023EF003710.

164 K. Hilgendorf, Y. Wang, M. J. Miller and Y.-S. Jin, Precision fermentation for improving the quality, flavor, safety, and sustainability of foods, *Annu. Rev. Food Sci. Technol.*, 2024, **86**, 103084, DOI: 10.1016/j.copbio.2024.103084.

165 H. Rischer, G. R. Szilvay and K. M. Oksman-Caldentey, Cellular agriculture — industrial biotechnology for food and materials, *Curr. Opin. Biotechnol.*, 2020, **61**, 128–134, DOI: 10.1016/j.copbio.2019.12.003.

166 C. A. Voigt, Synthetic biology 2020-2030: six commercially-available products that are changing our world, *Nat. Commun.*, 2020, **11**(1), 6379, DOI: 10.1038/s41467-020-20122-2.

167 M. I. Ahmad, S. Farooq, Y. Alhamoud, C. Li and H. Zhang, Soy Leghemoglobin: A review of its structure, production, safety aspects, and food applications, *Trends Food Sci. Technol.*, 2023, **141**, 104199, DOI: 10.1016/j.tifs.2023.104199.

168 M. B. Nielsen, A. S. Meyer and J. Arnau, The Next Food Revolution Is Here: Recombinant Microbial Production of Milk and Egg Proteins by Precision Fermentation, *Annu. Rev. Food Sci. Technol.*, 2023, **15**, DOI: 10.1146/annurev-food-072023-034256, online ahead of print.

169 S. Govorushko, Global status of insects as food and feed source: A review, *Trends Food Sci. Technol.*, 2019, **91**, 436–445, DOI: 10.1016/j.tifs.2019.07.032.

170 P. Sathoria and B. Roy, Sustainable food production through integrated rice-fish farming in India: a brief review, *Renew. Agric. Food Syst.*, 2022, **37**(5), 527–535, DOI: 10.1017/S1742170522000126.

171 D. Knorr, C. S. H. Khoo and M. A. Augustin, Food for an Urban Planet: Challenges and Research Opportunities, *Front. Nutr.*, 2018, **4**, 73, DOI: 10.3389/fnut.2017.00073.

172 N. M. de Carvalho, A. R. Madureira and M. E. Pintado, The potential of insects as food sources - a review, *Crit. Rev. Food Sci. Nutr.*, 2020, **60**(21), 3642–3652, DOI: 10.1080/10408398.2019.1703170.

173 D. Raheem, C. Carrascosa, O. B. Oluwole, M. Nieuwland, A. Saraiva, R. Millán, *et al.*, Traditional consumption of and rearing edible insects in Africa, Asia and Europe, *Crit. Rev. Food Sci. Nutr.*, 2019, **59**(14), 2169–2188, DOI: 10.1080/10408398.2018.1440191.

174 B. A. Rumpold and O. K. Schlüter, Nutritional composition and safety aspects of edible insects, *Mol. Nutr. Food Res.*, 2013, **57**(5), 802–823, DOI: 10.1002/mnfr.201200735.

175 A. M. Liceaga, Edible insects, a valuable protein source from ancient to modern times, *Adv. Food Nutr. Res.*, 2022, **101**, 129–152, DOI: 10.1016/bs.afnr.2022.04.002.

176 A. M. Liceaga, J. E. Aguilar-Toalá, B. Vallejo-Cordoba, A. F. González-Córdova and A. Hernández-Mendoza, Insects as an Alternative Protein Source, *Annu. Rev. Food Sci. Technol.*, 2022, **13**, 19–34, DOI: 10.1146/annurev-food-052720-112443.

177 A. van Huis and D. G. A. B. Oonincx, The environmental sustainability of insects as food and feed, A review, *Agron. Sustainable Dev.*, 2017, **37**(5), 43, DOI: 10.1007/s13593-017-0452-8.

178 S. Ites, S. Smetana, S. Toepfl and V. Heinz, Modularity of insect production and processing as a path to efficient and sustainable food waste treatment, *J. Cleaner Prod.*, 2020, **248**, 119248, DOI: 10.1016/j.jclepro.2019.119248.

179 A. van Huis, Prospects of insects as food and feed, *Org. Agric.*, 2021, **11**(2), 301–308, DOI: 10.1007/s13165-020-00290-7.

180 K. U. Rehman, C. Hollah, K. Wiesotzki, V. Heinz, K. Aganovic, R. U. Rehman, *et al.*, Insect-Derived Chitin and Chitosan: A Still Unexploited Resource for the Edible Insect Sector, *Sustainability*, 2023, **15**(6), 4864, DOI: 10.3390/su15064864.

181 D. Elieh-Ali-Komi and M. R. Hamblin, Chitin and Chitosan: Production and Application of Versatile Biomedical Nanomaterials, *Int. J. Adv. Res.*, 2016, **4**(3), 411–427.

182 T. Huq, A. Khan, D. Brown, N. Dhayagude, Z. He and Y. Ni, Sources, production and commercial applications of fungal chitosan: A review, *J. Bioresour. Bioprod.*, 2022, **7**(2), 85–98, DOI: 10.1016/j.jobab.2022.01.002.

183 D. Grimm, A. Kuenz and G. Rahmann, Integration of mushroom production into circular food chains, *Org. Agric.*, 2021, **11**(2), 309–317, DOI: 10.1007/s13165-020-00318-y.

184 M. P. Thakur, Advances in mushroom production: key to food, nutritional and employment security: A review, *Indian Phytopathol.*, 2020, **73**(3), 377–395, DOI: 10.1007/s42360-020-00244-9.

185 G. Zou, T. Li, I. Mijakovic and Y. Wei, Synthetic biology enables mushrooms to meet emerging sustainable challenges, *Front. Microbiol.*, 2024, **15**, 1337398, DOI: 10.3389/fmicb.2024.1337398.

186 G. Zou, J. B. Nielsen and Y. Wei, Harnessing synthetic biology for mushroom farming, *Trends Biotechnol.*, 2023, **41**(4), 480–483, DOI: 10.1016/j.tibtech.2022.10.001.

187 D. C. Zied, A. Geösel and A. Pardo-Giménez, Chapter 8: Cultivation of Mushrooms Widely Appreciated by Consumers, in *Edible Fungi: Chemical Composition, Nutrition and Health Effects*, ed. D. Stojković and L. Barros, The Royal Society of Chemistry, 2022, DOI: 10.1039/9781839167522-00304.

188 J. H. Litchfield, Single-Cell Proteins, *Science*, 1983, **219**(4585), 740–746, DOI: 10.1126/science.219.4585.740.

189 M. E. Jach, A. Serefko, M. Ziaja and M. Kieliszek, Yeast Protein as an Easily Accessible Food Source, *Metabolites*, 2022, **12**(1), 63, DOI: 10.3390/metabo12010063.

190 D. Knorr, K. J. Shetty and J. E. Kinsella, Enzymatic lysis of yeast cell walls, *Biotechnol. Bioeng.*, 1979, **21**(11), 2011–2021, DOI: 10.1002/bit.260211109.

191 P. R. Pereira, C. S. Freitas and V. M. F. Paschoalin, Paschoalin, Saccharomyces cerevisiae biomass as a source of next-generation food preservatives: Evaluating potential proteins as a source of antimicrobial peptides, *Compr. Rev. Food Sci. Food Saf.*, 2021, **20**(5), 4450–4479, DOI: 10.1111/1541-4337.12798.

192 A. Peterson, C. Baskett, W. Ratcliff and A. Burnetti, Using light for energy: examining the evolution of phototrophic metabolism through synthetic construction, *bioRxiv*, 2023, DOI: 10.1101/2022.12.06.519405. https://www.biorxiv.org/content/10.1101/2022.12.06.519405v2, accessed 6 June 2024.

193 S. Matassa, N. Boon, I. Pikaar and W. Vertstraete, Microbial protein: future sustainable food supply routewith low environmental footprint, *Microb. Biotechnol.*, 2016, **9**, 68–575, DOI: 10.1111/1751-7915.12369.

194 B. C. Bratosin, S. Darjan and D. C. Vodnar, Single Cell Protein: A Potential Substitute in Human and Animal Nutrition, *Sustainability*, 2021, **13**, 9284, DOI: 10.3390/su13169284.

195 F. Humpenöder, B. L. Bodirsky, I. Weindl, H. Lotze-Campen, T. Linder and A. Popp, Projected environmental benefits of replacing beef with microbial protein, *Nature*, 2022, **605**(7908), 90–96, DOI: 10.1038/s41586-022-04629-w.

196 E. J. Derbyshire and J. Delange, Fungal Protein – What Is It and What Is the Health Evidence? A Systematic Review Focusing on Mycoprotein, *Front. Sustain. Food Syst.*, 2021, **5**, 581682, DOI: 10.3390/su13169284.

197 M. I. Ahmad, S. Farooq, Y. Alhamoud, C. Li and H. Zhang, A review on mycoprotein: History, nutritional composition, production methods, and health benefits, *Trends Food Sci. Technol.*, 2022, **121**, 14–29, DOI: 10.1016/j.tifs.2022.01.027.

198 F.-M. Kerckhof, M. Sakarika, M. Van Giel, M. Muys, P. Vermeir, J. De Vrieze, *et al.*, From Biogas and Hydrogen to Microbial Protein Through Co-Cultivation of Methane and Hydrogen Oxidizing Bacteria, *Front. Bioeng. Biotechnol.*, 2021, **9**, 733753, DOI: 10.3389/fbioe.2021.733753.

199 H. Zheng, H. Huang, C. Chen, Z. Fu, H. Xu, S. Tan, *et al.*, Traditional symbiotic farming technology in China promotes the sustainability of a flooded rice production system, *Sustain. Sci.*, 2017, **12**(1), 155–161, DOI: 10.1007/s11625-016-0399-8.

200 O. J. Hasimuna, S. Maulu, K. Nawanzi, B. Lundu, J. Mphande, C. J. Phiri, *et al.*, Integrated agriculture-aquaculture as an alternative to improving small-scale fish production in Zambia, *Front. Sustain. Food Syst.*, 2023, **7**, 1161121, DOI: 10.3389/fsufs.2023.1161121.
201 N. Ahmed and G. M. Turchini, The evolution of the blue-green revolution of rice-fish cultivation for sustainable food production, *Sustain. Sci.*, 2021, **16**(4), 1375–1390, DOI: 10.1007/s11625-021-00924-z.
202 L. Ignowski, B. Belton, H. Ali and S. H. Thilsted, Integrated aquatic and terrestrial food production enhances micronutrient and economic productivity for nutrition-sensitive food systems, *Nat. Food*, 2023, **4**(10), 866–873, DOI: 10.1038/s43016-023-00840-8.
203 L. Hu, J. Zhang, W. Ren, L. Guo, Y. Cheng, J. Li, *et al.*, Can the co-cultivation of rice and fish help sustain rice production?, *Sci. Rep.*, 2016, **6**(1), 28728, DOI: 10.1038/srep28728.
204 P. Roberts, W. C. Carleton, N. Amano, D. M. Findley, R. Hamilton, S. Y. Maezumi, *et al.*, Using urban pasts to speak to urban presents in the Anthropocene, *Nat. Cities*, 2024, **1**(1), 30–41, DOI: 10.1038/s44284-023-00014-4.
205 J. McEldowney, Urban agriculture in Europe, *Patterns, challenges and policies*, 2017, https://www.europarl.europa.eu/thinktank/en/document/EPRS_IDA(2017)614641, accessed 27 March 2024.
206 G. N. Yuan, G. P. B. Marquez, H. Deng, A. Iu, M. Fabella, R. B. Salonga, *et al.*, A Review on Urban Agriculture: Technology, Socio-Economy, and Policy, *Heliyon*, 2022, **8**, e11583, DOI: 10.1016/j.heliyon.2022.e11583.
207 S. Rajendran, T. Domalachenpa, H. Arora, P. Li, A. Sharma and G. Rajauria, Hydroponics: Exploring innovative sustainable technologies and applications across crop production, with Emphasis on potato mini-tuber cultivation, *Heliyon*, 2024, **10**(5), e26823, DOI: 10.1016/j.heliyon.2024.e26823.
208 K. Benke and B. Tomkins, Future food-production systems: vertical farming and controlled-environment agriculture, *Sustain. Sci. Pract. Policy*, 2017, **13**(1), 13–26, DOI: 10.1080/15487733.2017.1394054.
209 G. E. Barrett, P. D. Alexander, J. S. Robinson and N. C. Bragg, Achieving environmentally sustainable growing media for soilless plant cultivation systems – A review, *Sci. Hortic.*, 2016, **212**, 220–234, DOI: 10.1016/j.scienta.2016.09.030.
210 M. Gonnella and M. Renna, The Evolution of Soilless Systems towards Ecological Sustainability in the Perspective of a Circular Economy. Is It Really the Opposite of Organic Agriculture?, *Agronomy*, 2021, **11**, 950, DOI: 10.3390/agronomy11050950.
211 D. Braun, The best of both worlds: The hybrid farms are bridging agriculture systems, in *Agritecture*, 2023. https://www.agritecture.com/blog/2023/5/23/the-best-of-both-worlds-hybrid-farms-are-bridging-agriculture-systems, accessed 6 April 2024.
212 A. Hebinck, O. Selomane, E. Veen, A. de Vrieze, S. Hasnain, M. M. Sellberg, *et al.*, Exploring the transformative potential of urban food, *npj Urban Sustainability*, 2021, **1**, 38, DOI: 10.31235/osf.io/4k6dh.
213 J. K. Hawes, B. P. Goldstein, J. P. Newell, E. Dorr, S. Caputo, R. Fox-Kämper, *et al.*, Comparing the carbon footprints of urban and conventional agriculture, *Nat. Cities*, 2024, **1**(2), 164–173, DOI: 10.1038/s44284-023-00023-3.
214 K. Yu, *Green Infrastructure through the Revival of Ancient Wisdom*, American Academy of Arts and Sciences, 2017, https://www.amacad.org/news/green-infrastructure-through-revival-ancient-wisdom, accessed 8 April 2024.
215 J. Rushton, B. J. McMahon, M. E. Wilson, J. A. K. Mazet and B. Shankar, *A food system paradigm shift: from cheap food at any cost to food within a one health framework*, National Academy of Medicine, 2021, https://nam.edu/a-food-system-paradigm-shift-from-cheap-food-at-any-cost-to-food-within-a-one-health-framework/, accessed 23 March 2024.
216 D. Hering, C. Schürings, F. Wenskus, K. Blackstock, A. Borja, S. Birk, *et al.*, Securing success for the Nature Restoration Law, *Science*, 2023, **382**(6676), 1248–1250, DOI: 10.1126/science.adk1658.
217 N. B. Dise, Environmental science. Peatland response to global change, *Science*, 2009, **326**(5954), 810–811, DOI: 10.1126/science.1174268.
218 I. Delabre, L. O. Rodriguez, J. M. Smallwood, J. P. W. Scharlemann, J. Alcamo, A. S. Antonarakis, *et al.*, Actions on sustainable food production and consumption for the post-2020 global biodiversity framework, *Sci. Adv.*, 2021, **7**(12), eabc8259, DOI: 10.1126/sciadv.abc8259.
219 D. Knorr and M. A. Augustin, The future of foods, *Sustain. Food Technol.*, 2024, **2**, 253–265, DOI: 10.1039/D3FB00199G.
220 L. Aguirre-Sánchez, R. Teschner, N. K. Lalchandani, Y. El Maohub and L. S. Suggs, Climate Change Mitigation Potential in Dietary Guidelines: A Global Review, *Sustain. Prod. Consum.*, 2023, **40**, 558–570, DOI: 10.1016/j.spc.2023.07.015.
221 J. Ammann, A. Arbenz, G. Mack, T. Nemecek and N. El Benni, A review on policy instruments for sustainable food consumption, *Sustain. Prod. Consum.*, 2023, **36**, 338–353, DOI: 10.1016/j.spc.2023.01.012.
222 J. von Braun, K. Afsana, L. O. Fresco and M. Hassan, Science and Innovati on for Food Systems Transformation and Summit Actions, *Papers by the Scientific Group and its partners in support of the UN Food Systems Summit*, 2021, accessed 30 May 2024, https://sc-fss2021.org/.
223 L. Fobbe, Analysing Organisational Collaboration Practices for Sustainability, *Sustainability*, 2020, **12**(6), 2466, DOI: 10.3390/su12062466.
224 R. Akinola, L. M. Pereira, T. Mabhaudhi, F.-M. de Bruin and L. Rusch, A Review of Indigenous Food Crops in Africa and the Implications for more Sustainable and Healthy Food Systems, *Sustainability*, 2020, **12**, 3493, DOI: 10.3390/su12083493.
225 T. C. Tran, N. C. Ban and J. Bhattacharyya, A review of successes, challenges, and lessons from Indigenous protected and conserved areas, *Biol. Conserv.*, 2020, **241**, 108271, DOI: 10.1016/j.biocon.2019.108271.

226 M. Zhang and P. Dannenberg, Opportunities and Challenges of Indigenous Food Plant Farmers in Integrating into Agri-Food Value Chains in Cape Town, *Land*, 2022, **11**, 2267, DOI: 10.3390/land11122267.
227 J. A. Raven, Rubisco: still the most abundant protein of Earth?, *New Phytol.*, 2013, **198**(1), 1–3, DOI: 10.1111/nph.12197.
228 Z. F. Bhat, H. Bhat and S. Kumar, Chapter 73 - Cultured meat—a humane meat production system, in *Principles of Tissue Engineering*, ed. R. Lanza, R. Langer, J. P. Vacanti and A. Atala, Academic Press, 5th edn, 2020, pp. 1369–1388, DOI: 10.1016/B978-0-12-818422-6.00075-7.
229 K. Castellanos-Reyes, R. Villalobos and T. Beldarrain-Iznaga, Fresh mushroom preservation techniques, *Foods*, 2021, **10**, 2126, DOI: 10.3390/foods10092126.
230 A. E. Graham and R. Ledesma-Amaro, The microbial food revolution, *Nat. Commun.*, 2023, **14**, 2231, DOI: 10.1038/s41467-023-37891-1.
231 C. Queiroz, A. V. Norström, A. S. Downing, Z. V. Harmáčková, C. de Coning, V. Adams, *et al.*, Investment in resilient food systems in the most vulnerable and fragile regions is critical, *Nat. Food*, 2021, **2**, 546–551, DOI: 10.1038/s43016-021-00345-2.
232 J. D. Ford, N. King, E. K. Galappaththi, T. Pearce, G. McDowell and S. L. Harper, The Resilience of Indigenous Peoples to Environmental Change, *One Earth*, 2020, **2**(6), 532–543, DOI: 10.1016/j.oneear.2020.05.014.
233 A. Black and J. M. Tylianakis, Teach Indigenous knowledge alongside science, *Science*, 2024, **383**(6683), 592–594, DOI: 10.1126/science.adi9606.
234 P. Thornton, D. Mason D'Croz, C. Kugler, R. Remans, H. Zornetzer and M. Herrero, Enabling food system innovation: accelerators for change, *Glob. Food Sec.*, 2024, **40**, 100738, DOI: 10.1016/j.gfs.2023.100738.
235 J. Ingram, W. Bellotti, M. Brklacich, T. Achterbosch, B. Balázs, M. Banse, *et al.*, Further concepts and approaches for enhancing food system resilience, *Nat. Food*, 2023, **4**(6), 440–441, DOI: 10.1038/s43016-023-00762-5.
236 D. Knorr and R. Sevenich, Processed foods: From their emergence to resilient technologies, *Compr. Rev. Food Sci. Food Saf.*, 2023, **22**(5), 3765–3789, DOI: 10.1111/1541-4337.13205.

