Sustainable Food Technology

ROYAL SOCIETY OF CHEMISTRY

REVIEW

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Cite this: *Sustainable Food Technol.*, 2024, **2**, 253

Received 22nd October 2023
Accepted 12th December 2023

DOI: 10.1039/d3fb00199g

rsc.li/susfoodtech

The future of foods

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Current food systems reduce, deplete and pollute our limited global resources. Radical changes are required to ensure future food security and safety. Worldwide biodiversity losses and mass extinction of species, increasing urban populations, growing human vulnerability and climate change are extending the challenges to achieve food security.

Sustainability spotlight

This paper discusses strategies aimed at overcoming global biodiversity loss and improving ecosystem resilience. It considers the need for holistic actions to end loss of natural ecosystems and to conserve diversity. It shows how unlocking technology and ecosystem interactions coupled with increased human responsibilities are necessary to make constructive use of natural resources. Responsible management of ecosystem resources demands increased respect for the value of food, the environment and our natural resources. There needs to be a change of human diets and behavior towards greater food diversity and increased attention to consumer food needs and health. Symbiotic relationships exist between microorganisms and plants with positive reciprocal influences on each other. A better understanding of these interactions and their use, especially under changing environmental conditions will be important for the future generation of food. For future food processing, increasing the potential of biotechnological processes and interlinking food resources with food processing approaches are needed. Food product-oriented processing aimed at improving the quality and functionality within symbiotic food systems needs to include all actors.

Introduction

"I never think of the future, it comes soon enough" Albert Einstein.

Future foods will depend on the resources of planet Earth. However, current food production systems are being depleted due to pollution and loss of water, nutrient loss, erosion of soils, air pollution, biodiversity loss and climate change.[1–7] We have to deal with and use the resource available for food production. This was highlighted back in 1955 by Harrar[8] who then suggested that "the basic approach to food for the future is not through the distribution of more plows but rather through the wider dissemination of knowledge". The author[8] concluded that "if we have the intelligence and wisdom to recognize human responsibilities and to make constructive use of our natural resources, we can look forward to a better world in the future".[8] The constructive use of natural resources requires that humans do not continue to deplete nature and its resources. There is a need to create symbiotic interactions to increase our understanding of existing environmental connections, such as between plants and fungi, for food production, processing and consumption within symbiotic food systems.

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Global resources

The sum of the total biomass on Earth is ~550 gigatons of carbon (Gt C) which comprises of plants, primarily terrestrial (~450 Gt C), bacteria (~70 Gt C), archaea which are predominantly located in deep surface environments (~7 Gt C) and animals, mainly marine (~2 Gt C).[9] The biomass of humans is ~0.06 Gt C, with the biomass of livestock being ~0.1 Gt C, domesticated poultry ~0.005 Gt C, wild mammals ~0.007 Gt C and wild birds ~0.002 Gt C.9.[9]

Current food systems issues

Global biodiversity loss and mass extinction of species have been identified as two of the most critical issues the world is currently facing.[4] The requirements for a system-based approach to developing sustainable food systems that include improving natural resources use, reducing environmental impact, examining new food resources, enhancing consumer trust and understanding and developing profitable market opportunity-led solutions for food and nutrition security have been stressed.[10] The need for inter-connectedness of food markets requires regional and global goals which go far beyond today's United Nations Sustainable Development Goals (SDGs) and has been seen as a requirement for a transition process of our food system.[7,11]

The unlocking of technology and ecosystem interactions is essential for improved long-term sustainability. Failing to overcome the current coupled climate emergency and loss of biodiversity crisis will increase human vulnerability, poverty, food insecurity, involuntary displacement, political instability and conflict.[12] There is an urgent need for food systems transformation towards sustainability and healthy diets.[7] Overcoming global biodiversity loss and improving ecosystem sustainability will require holistic actions that aim to (1) end the net loss of natural ecosystems, ensuring no loss of rare, vulnerable and essential ecosystems for planetary function, (2) expand ecosystem restoration, (3) reduce extinction risk and rate and (4) conserve genetic diversity (>90%). The contribution of nature to people (secure food, water, health) and developing nature-based solutions to reduce climate risk should be recognized.[13] Careful and responsible management of ecosystem resources using the microbiome-targeted interventions (microbiome stewardship) is recommended.[4]

Global food challenges

Feeding the world population is a major global challenge. The global food demand is projected to increase by 50–60% between 2019 and 2050, with indications of the slowing of rice demand, a growing share of palm oil in worlds oil and fat markets and a continued shift to poultry as the dominant form of meat consumption.[14] These authors further demonstrated the value of a commodity-by-region approach for understanding the complexities in the world food systems. Higher global temperatures and the increasing the frequency of rapidly arising flash drought that are being experienced will affect agriculture and ecosystems and impact crop yields.[15] The global panel on agriculture and food systems for nutrition[16] reported an expected 187.4% increase in greenhouse gas emissions between 2010 and 2050, 167.1% for cropland use, 165.0% for bluewater use, 151.4% for nitrogen and 153.8% for phosphorus application. Falcon *et al.*[14] project a 130.8% increase in poultry consumption between 2019 and 2050, 65.6% for fish and 139.9 for plant oils (palm oil and soybean oil). Recent data[17] show a worldwide increase in slaughtered chicken from 11.389 billion in 1971 to 73.791 billion in 2021, ducks 351 million to 4.310 billion, geese from 75 million to 749 million and turkey 210 million to 604 million. This is not in line with the Great Food Transformation proposed by the EAT-Lancet commission[18] which include reorienting agricultural priorities for producing "more" food and towards producing "better" food; sustainably intensifying food production; generating more high-quality output and; at least halving food losses and waste.

Many of the UN SDGs are moderately to severely off track, as outlined in the UN General Assembly report.[19] There are various reports which suggest priorities to transform food systems towards sustainable healthy diets.[7,19–21] Key messages of the future of food and agriculture – alternative pathways to 2050 report[22] include (1) food and agricultural systems are affected by trends that could jeopardize their future sustainability, (2) changing course is critical - "business as usual" is no longer an option, (3) raising consumer awareness will help contain the need to unnecessarily expand food production and reduce the burden of malnutrition but processing more will be unavoidable, and the way forward is doing so with less, and (4) food and agricultural sector are key, but are no longer enough on their own to ensure equitable access to food. Table 1 summarizes a selection of suggestions and actions to improve food security and sustainability, and help achieve some of the SDGs.

Table 1 Considerations for food and nutrition security

Food and nutriton security
Challenges[23]
• Eradicate extreme poverty, ensure that vulnerable people who escape poverty do not fall back into it, and take action to reduce inequalities
• Pro-poor growth must go beyond agriculture, and involve both rural and urban areas while supporting job creation and income diversification
• Re-think food systems for meeting current and future challenges
Needs[19]
• End poverty in all its forms everywhere
• End hunger, achieve food security and improved nutrition, and promote sustainable agriculture
• Ensure healthy lives and promote well-being for all at all ages
• Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
• Achieve gender quality and empower all women and girls
Framing solutions for improved food security – Wedges framework[20]
• Reduce demand for food
• Fill the production shortfall
• Avoid losses or future production potential
Policy actions[7]
• Make sufficient nutrient rich staple foods produced sustainably available to all
• Ensure foods move along value chains more efficiently, improving accessibility and resulting in lower cost and less loss
• Empower consumers to make informed choices, fuel rising demand for sustainable healthy diets
• Ensure sustainable healthy diets are affordable to all, with lower demand for ultra-processed products (that are unhealthy)
Strategies for increasing food sources and biodiversity (various sources)
• Increase recognition that agricultural biodiversity (wild and cultivated) underpins agricultural system sustainability[24]
• Develop understanding of the link between biodiversity and nutrition to inform policy[25]
• Develop national food policy for formal cultivation and promotion of wild edible plants[26,27]
• Explore use of unconventional terrestrial and aquatic sources for protein[28,29]
Reshaping Australia food systems – priority actions[21]
• Enable equitable access to healthy and sustainable diets
• Minimize waste and improving circularity
• Facilitate Australia's transition to net zero emissions
• Align resilience with socioeconomic and environmental sustainability
• Increase value and productivity

Future of foods

Future foods are defined as "foods for which our ability to produce considerable volume is rapidly developing as a result of technological developments that offer the potential to scale production levels up and/or reduce the production cost out of concern for the environment".[29] The stress on food security continues to grow as climate change further strains the agricultural sector and the livelihoods of many industrialized and developing countries.[30]

Food choices are shifting globally in ways that are affecting both human health and the environment. There is an unmapped complexity of the human diet, and there is potential for improving health by accurately mapping the diet and integrating changes in diet with the role of the microbiome and personalized dietary patterns.[31] This unmapped complexity of our diet had been reported and has been previously emphasized.[32] An estimation and recording of the environmental impacts of food products have been presented for 57 000 products[33] and this needs to be part of the considerations for our food choices. Within this context, understanding, respecting, and learning from the resilience of Indigenous peoples to environmental changes is of additional importance.

The projected environmental benefits of replacing beef with microbial protein[34] indicates that substitution of 20% per capita of ruminant meat consumption with edible microbial biomass globally by 2050 (on a protein basis) offsets further increases in global pasture areas, cutting annual deforestation and related CO_2 emission roughly in half, while also lowering methane emission. However, further upscaling, of microbial protein, results in a non-linear saturation effect on reduced deforestation and related CO_2 emissions, an effect that could not be captured with the method of static life cycle analysis used.[34] Further, the urgently needed diet changes can also provide a potential solution to reduced water use.[35,36] A large scale study on reducing food's environmental impacts through the supply chain (farmers, producers, packaging types, retailers) has been published.[37] Consumers support an approach where producers monitor their own impact, flexibly meet environmental targets by choosing from multiple practices and communicate (environmental labels, taxes or subsidies designed to reflect environmental costs in product prices, broader education on the true cost of food) their communicate their impacts to consumers.[37]

For current food systems, the main points that cause tensions between local and global narratives have been identified as: (1) food insecurity and trade, (2) interconnected environmental and nutritional decline, (3) inequity and governance and (4) food system illiteracy.[38] Transformative pathways to address these challenges for increased the resilience of food systems include: (1) nurtured diversity at all scales, (2) managed connectivity, (3) equitable distribution of power and benefits and (4) increased traceability and transparency regarding the current local-global food system debate.[38] Addressing the resilience of the food systems also requires attention to strategies for feeding a growing urban population and accounting for sustainability and security of food, water, nutrition, and biodiversity.[39,40]

Based on the above, we propose the following needs for future food sustainability: (1) change of human attitude: increased respect for values of foods, nature, environment, biodiversity and resources (*e.g.*, water, energy, soil), (2) change of human diet: increase consumption of plant and microbial derived foods, increase of underutilized foods use and preserve biodiversity, (3) change of human behavior: increase focus on consumer education and campaigns to educate consumers to influence and support consumer behavioral change towards more sustainable nutritional food shopping choices, and (4) change of food systems: increased diversity of food supply, exploration and recording the diversity of edible foods and microbial biodiversity, and exploration of their benefits to human and environmental health.

Food production for a sustainable future

The global food system is a major driver of climate change, changes in land use, depletion of fresh water resources, and pollution of aquatic and terrestrial ecosystems through excessive nitrogen and phosphorus input.[6] It is suggested that a revolutionary change in human society to meet the challenge of food security demands requires a combination of the agricultural revolution with the industrial revolution.[1]

Water

We believe that water resilience will be one of the key future challenges[36,41] to be able to meet increasing food demands. Water is a neglected food resource.[36] Water for irrigation is the largest water use sector accounting in 2014 for 70% of global water withdrawal and nearly 90% of consumptive water use.[3] The amount of water consumed annually to produce food ranges from 6.0×10^5 to 2.5×10^6 L per capita per year and global water demand for all uses is expected to increase by 20% to 30%.[42,43] Traditionally research has focused on the scarcity of blue water (ground water and surface water). However, it is important that green water (rainfall over land) should explicitly be part of any assessment of water scarcity, food security and bioenergy potential.[44]

Energy

The agri-food value chain uses 30% of the world's energy. There is a need to shift from the use of fossil fuels to more sustainable renewable sources of energy.[45] Examples of where renewable energy has been used include (1) biogas digestors for colling of milk in Tanzania, (2) crop waste as bioenergy in India, and (3) solar powdered irrigation in Rwanda.[45] The sun has been and is the most important source of energy and solar energy as well as harnessing the energy of continuous ocean waves and geothermal energies need to become key future sources. Ancient energy sources such as wind and water (*e.g.*, windmills, water mills) should be reactivated to a high degree and with improved efficiency than currently practiced.

Food crops and food protein

There needs to be a re-consideration of the crops we grow for food and an exploration of alternative sources of food. Enhancing photosynthesis is one of the most effective avenues to increase crop yields. However, our ancestors did not select the plants to be domesticated based on photosynthetic performance, thus leaving room for the future selection of more photosynthetic efficient plants.[46] Overexpressing a transcription factor in wild rice and in wheat resulted in increased nitrogen uptake and boosted photosynthesis, resulting in yield increases of 12–40% and 10% respectively.[47] Recent data suggest that yeast can also be made less dependent on carbohydrates by enabling it to use light as energy.[48] A model including photovoltaic electricity generation (solar panels), direct air capture of carbon dioxide, electrosynthesis of an electron donor and/or carbon source for microbial growth (hydrogen, formate, methanol), microbial cultivation and processing of biomass and protein has been presented.[49] These authors show the potential of 10-fold higher protein yield and at least twice the caloric yield compared with any staple crop and per unit of land.[49] Electromicrobial protein production that combine renewable energy and microbial metabolism can increase energy efficiency of chemical production, as demonstrated by engineered CO_2 and N_2 fixing organisms that produce amino acids at approximately one order of magnitude higher than any previous estimate.[50]

Agroecological symbioses

An agroecological symbiosis for "re-configuring the primary production of food in agriculture, the processing of food and the development of a food community to work towards system-level sustainability" has been proposed.[51] These authors defined Agroecological symbiosis as: "a form of food production and processing in which the farms, the food processor, and the energy producer function in an integrated manner".[51]

Truffles, one of the most expensive and rare foods, are fruiting bodies (spore-producing organs) of a fungus living underground.[52] Spores evolved to allow fungi to disperse themselves. Truffles solved this by smell which attracts animals depositing the spores with their feces.[52] The microbiota of the fruiting bodies of the of truffles are made up of bacteria, yeasts, guest filamentous fungi and viruses. The bacteria in the spore contribute to the aroma of truffles. It is this aroma that attracts mycophagous animals that eat them and disperse the truffle spores. The spores deposited in the soil mediates the interactions between the plant roots and the microorganisms.[53] Ironically, humans, using animals just to locate the rare truffles interrupt this spore dispersion process, thus making truffles even rarer. The kingdom of Prussia in Berlin had hired Albert Frank "to promote the possibility of truffles cultivation," who by doing so realized relationships between tree roots and fungi which he called symbiosis. Even back in 1885, it was suggested that "certain trees that cannot nurture themselves but their entire root system is in symbiosis with fungal mycelium which serves as foster mother and takes care of nurturing the tree from the soil".[54] Biofertilizers competitively colonizing root systems (mostly symbiotic nutrient fixing microorganisms) have been promoted to ensure food security and food safety by replacing agricultural chemicals such as fertilizers, pesticides and herbicides.[55]

Symbiotic relationships positively influence both plants and fungi and help plants to protect themselves from pathogens.[56] Importantly, they also interact under changing environmental conditions which makes the understanding of these interactions indispensable for future sustainable food production.[56] For example, it has been shown that ingestion of a symbiont does not preclude the evolution of beneficial interactions beyond simply host nutrition.[57] It was also hypothesized that fungi may interact as necessary symbionts with members of other human microbiome communities.[58] This fungal-dependent regulatory role ("regulobiosis") in human biology additionally stresses the importance of creating science and technology based symbiotic human–environment–food interactions.[58]

Further information on the inter-relations and inter-dependences of our food supply with and on the world's ecosystem and organisms for unlocking the benefits of ecosystem symbioses has been previously discussed.[11] For example, the use of symbiotics (association of one or mor probiotics with one or more prebiotic) may be used for improving or preventing gastrointestinal diseases.[59] An alternative functioning agri-food system model (symbiotic food system) for feeding residents in a fast-growing city in South Africa includes small scale rural food producers and urban eaters and other forms of collaborative interactions.[60] This system demonstrates the ways in which various players in the agrifood system can work together in an inclusive manner to improve livelihoods of small producers.[60]

Improving future food production

To overcome the coupled climate emergency and biodiversity crisis, actions that need to be taken for improved food production include: (1) increase climate smart agriculture, (2) improve livestock and grazing management, (3) reduce food waste and implement dietary change leading to sustainable agriculture, (4) increase sustainable fisheries and (5) reduce pressure on ecosystems.[12] Alternatives to current food mainstream production systems have been developed for terrestrial,[61,62] and marine systems.[63] The current EU Common Agricultural Policy budgets allocated for various objectives comprise: (1) viable farm income 60.6%, (2) increased competitiveness 11.4%, (3) climate change action 8.8%, (4) biodiversity and landscape 8.5%, (5) vibrant rural areas 5.8%, (6) management of natural resources 2.3%, (7) protect food and health quality 1.8%, and (8) support generational renewal 0.7%. Clearly this requires a change of mind-set and conditions for reform.[64] The priority recommendations and actions for sustainable production of food for future food system resilience are given in Table 3.

The world will fail to deliver both the UN SDGs and the Paris Climate Agreement without a significant food system transformation.[5] Food from forests (*e.g.*, wild plants, animals, fungi) and forests regrowth[65] as well as utilizing forests soil health and biodiversity for identifying new food sources (*e.g.*, insects, microorganisms, fungi) need to be explored further to expand our food supply. Dark food chain generation (chemoautotrophy) has also been promoted[66,67] based upon assimilation of

CH_4 and CO_2 by methane- and hydrogen-oxidizing bacteria, and as intensively researched with single cell proteins (SCP) as potential food source during mid-20th century[68] can also be a developed into a future food production route. For example, Raschke[69] showed that pulsed electric field treatment (10 kJ kg^{-1}) can aid the extraction of proteins as well as removal of DNA (71%), or a combined zymolyase and lysozyme treatment also reduced the nucleic acid content of yeast,[70] a stumbling stone in past SCP development.

An analysis of 12 650 research titles between 1969 and 2018 on how to feed the world, using total food production, per capita food demand and population as indicators, showed that studies are increasingly likely to focus on food production only rather than also addressing the other two levers of population size and diet.[71] Attaining future food security requires staying within four interlinked terrestrial planetary boundaries (biosphere integrity, land-system change, freshwater use, nitrogen flows).[2] To achieve this, key prerequisites are spatially redistributed cropland, improved water-nutrient management, food waste reduction and dietary changes.[2] Others have suggested that future nutritious and sustainable food options could include sources such as microalgae, mycoprotein and mealworm, in face of acute biotic and abiotic stressors.[72]

Capitalizing on plant and fungi behavior

Recent data regarding the abilities of plants and fungi, their mutual beneficial interactions, and their adaptions to stressors and environmental changes offer new insights for future food production and processing.[52,73,74] Better interactions with natural resources rather than depleting them[55,75,76] have the potential for radical changes of our current food systems. Examples for unlocking the nutritional and functional benefits of foods can include fungi–plant–soil interactions, nutrient fixing microorganisms and plants, increased food diversity including underutilized plant and fungal sources, biofertilizers, alternative agricultural practices, product specific tailor-made innovative food processes, and environmentally responsible food handling, preparation and consumption.

The fungal kingdom, consisting of at least 6 million eukaryotic species, has remarkable impact on global health, biodiversity, ecology, agriculture, manufacturing and biomedical research.[77] Approximately 625 fungal species have been reported to infect vertebrates, with fungal pathogens causing > 1billion human infections annually.[77,78] Control strategies put forward include increasing diversity of agricultural ecosystems, species mixtures as opposed to monocultures and mixed cropping systems to increase soil microbial diversity, including mutualistic symbionts adding to improve plant health.[77] The lack of a fundamental understanding of fungal biodiversity and ecology has been considered as the biggest knowledge gap regarding fungal pathogens.[78]

Plants are as able as humans or animals to effectively react to their ever-changing environment. In a recent book "Planta sapiens: the intelligent behavior of plants and fungi", the author suggests that plants have an intelligence with flexible, forward-looking and goal-directed behaviors.[79] Plant cells possess a network-type communication system. They also possess the ability to learn from experience and to memorize previous experiences for effective acclimation to environmental stresses.[74,79] These abilities are a form of intelligence, which is also exemplified by the versatility of plant to deal with abiotic stress and microbial of insect attacks.[74]

As for fungi, production of patterns of electrical activity, similar to neurons, have been identified with low and high frequency oscillations and spike trains.[73] The authors[73] considered this neural-like electric activity as a manifestation of fungal intelligence. For example, it has been reported about an experiment with fungal hyphae finding the shortest ways out of a constructed labyrinth by diverting themselves around an obstacle.[52] How Passiflora tendrils track a support moved to different locations, indicating they must make choices.[79] Plants have been viewed as inventors of 7 basic forms (crystal form, sphere, plane, rod, band, screw, cone), which are "the basic technical forms of the entire world".[80] Examples of potential abilities of plants and fungi to be implemented for stimulation of their biosynthetic abilities are presented in Table 2. Some specific examples of symbiotic fungal–plant interactions that are beneficial for the food production include (1) the interplay between plant and fungi that result in triggering plant immunity, increased resistance to pathogens, herbivores and stress,[81] and (2) the promotion of plant growth by fungal secondary metabolites.[82]

Table 2 Examples of interactions and communication between plants and fungi for potential implementation of their biosynthetic abilities[a]

Capabilities of plants and fungi
Abilities of plants
• "Smelling" of volatile substance
• Mobilization of defense systems
• "Tasting" chemical compounds
• Adjustment to gravity forces
• Adjusting to "feeling," touch, wind
• Ability to adhere
• "Learning" to react to challenge
• Habituate to repetitive signals
• Ability to defend against predators
• Possibly can "hear"
• "Remembering" induced signals
• Structure and barrier building (cell wall)
• Ability for uptake of air, light, nutrients, water
• Information acquisition, learning, decision making
Abilities of fungi (cognitive tasks performed)
• Decision-making and spatial recognition
• Short -term memory and learning
• Long-distance communication
• Photo-tropism
• Gravi-tropism
• Chemo-tropism and chemical sensitivity
• Sensing touch and weight
• Self *vs.* non-self-recognition
• Fighting behavior
• Trade behavior
• Manipulating other organisms

[a] Ref. 73, 74, 83 and 84.

Food processing and preparation – requirements for future food sustainability

Food processing is "the alteration of food from the state in which they are harvested or raised to better preserve them and feed the consumer".[85] Food processing has an important contribution to nutrition and thus an essential part of the global food system.[11,86] A more recent approach to future food processes, taking advantage of the vast existing knowledge base on processing effects as related to food safety, food consistency and properties, has been suggested.[76] The authors suggest developing processing scenarios that allow the application of the most fitting process(es) to retain (or even enhance) the inherent quality and functional characteristics of a given food raw material.[76] Such resilient food product-oriented food processes provide the potential for entirely new and unique food products and processing concepts. A simplified resilient technology processes triangle has additionally been developed,[76] stressing the importance of the inter-relations between food safety, food structure and food function.

Improved food preparation methods require improved consumer skills and knowledge (*e.g.*, meal planning, storage, leftover use) and changed consumer behavior (*e.g.*, healthy nutritious foods, food waste reduction), and in-package preparation with sustainable packaging materials and in-package shelf-life sensors. Improved equipment would include smart stoves selecting the best preparation condition, refrigerators with different temperature zones for optimum storage and shelf-life and inedible food waste converters for collection and upscaling. To achieve such goals, raising consumer awareness regarding the needs and values of food and drink and realizing the high importance of eating healthy foods will be essential.

Food processing technologies

Landmarks in the historical development of twenty first century food processing technologies including low temperature and high temperature preservation, hurdle technologies, cold plasma, pressurized fluids, electro-technologies (pulsed electric fields, electromagnetic heating, radio frequency electric fields), ultrasound and megasonics, high hydrostatic pressure, high pressure homogenization, hyperbaric storage and negative pressure cavitation extraction.[87] Food processing requirements for 2050 will have to include highly flexible, modular processing units, especially for urban food processing, and technologies with low resource (water, energy) requirements and product losses, such as hydrostatic pressure-based technologies (*e.g.*, pasteurization, sterilization), electric field processes (*e.g.*, pulsed electric fields, dielectric heating, cold plasma), light-based applications (*e.g.*, infrared, ultraviolet lights, solar energy driven equipment), sound-based procedures (*e.g.*, ultrasound), solar energy driven extruders, combination processes (*e.g.*, pulsed electric fields and extrusion, cold plasma and 3D extrusion).

The state of the art of green-biomass originated protein in Europe and America as well as the results of an extensive internet search with keywords "plant based foods" and "plant based protein" have been summarized.[88] There is a need for a science-based approach to design healthy and sustainable plant based foods.[89] A roadmap for plant proteins for future foods has been presented, focusing on means to enhance protein functionalities.[90]

For processing of food from plants, it is useful to understand the characteristics of plant cell walls and the cell biology that underpins their synthesis. This understanding aids in developing processes to maintain cell integrity or disrupt cell walls, as appropriate, to tailor desired food properties. There is comparatively little known about plant cell walls growth and how they are synthetized[91] and modified, despite their importance for daily applications such as food and feed. Also, with such knowledge, targeted and gentle processes could be developed when interfaced and linked with understanding of plant production and growth.

Table 3 Recommendations for sustainable production of food and resilient food processing

Recommendations
Food production
• Change of mindset: integration of benefits all potential production systems instead of either/or approaches
• Increase production efficiency: land, water, energy, fertilizer
• Increase biodiversity: increased diversity of food supply, increased environmental biodiversity
• Explore new food sources: food selection based on energy and resource efficiency, drought, heat and saline tolerant plants, nitrogen use efficiency and nitrogen fixing plants, increased photosynthetic efficiency
• Apply reduced energy use systems: an example is Amish farming practices[61]
• Develop new energy generation systems: photovoltaic microorganisms, underwater greenhouses for temperature control, sun/solar energy driven products
• Re-cycle waste and up-cycle by-products: examples for developing uses for plant cuttings, leafy parts, animal wastes
• Use urine as a nitrogen source[98]
• Connect sustainable agriculture with resilient food processing and sustainable consumption.[76,99]
• Develop artificial photosynthesis systems to capture CO_2 to produce concentrated acetate for energy efficient food production.[100]
Food processing
• Increase food processing literacy of consumers
• Evaluate existing food processes in terms of resource efficiency
• Enhance the nutritional potential of foods *via* resilient processing
• Enlarge biodiversity of food supplies *via* production-processing interlinking
• Increase availability of edible microbial biomass and fermented products
• Design resource efficient fermentation processes
• Decrease food processing losses and waste
• Develop conversion processes for food processing and preparation wastes
• Enhance use of alternative energy resources in food processing
• Improve resource efficiency in food preparation, packaging and distribution

Food biotechnology

Biotechnological approaches offer more sustainable biological-based processes. Biotechnology has a long history in production and processing of foods. The food processing industry has been the oldest and largest user of biotechnology processes.[92] Advances in food biotechnology are underpinned by basic studies on structure–function relationships of food materials, fundamental studies in the cell physiology and biochemistry of raw materials and improvement of food grade microorganisms. The term "Food Biotechnology" was coined[93] and a widely accepted definition of biotechnology adopted by the European Federation is "the integrated use of biochemistry, microbiology, and engineering science to achieve the technological application of the capacities of microbes, culture tissue cells, and parts thereof." Agricultural biotechnology has potential to contribute to reduced environmental impacts and improve food security. Advances in synthetic biology enables generation of sustainable biological technologies for production of chemicals and materials.[94]

The role of food biotechnology in food production comprises: (1) raw material improvement (feed efficiency, single cell protein, nitrogen fixation of plants, use of monoclonal antibodies, transfer of DNA from one species to another, use of genetic diversity in plants, and new plant and animal sources), (2) raw material modification and improvement (conversion of raw materials, increase of stress resistance, improvement in nutritional quality and functionality), (3) raw material preservation by biological processes (production of silage, fermentation), (4) production of additives and processing aids (vaccines, growth regulators, flavors, vitamins, metabolite production by cell cultures, antimicrobials, sweeteners, amino acids, enzymes) and (5) production methods (high performance bioreactors, biocatalysts, cell membrane permeabilization, immobilization techniques).[92] Applying food biotechnology can be used for (1) product modification which involves functionality monitoring, enzymatic modification, microbial product processes, (2) product preservation encompassing classical fermentations, use of monoclonal antibodies, use of biosensors and hybridization, tissue culture and genetic methods, (3) processing methods which include product purification and recovery, ultrafiltration, two phase systems, supercritical extraction, enzyme and co-fermentation processes, and (4) treatment and utilization of process waste which includes protein recovery, biomass recovery, ultrafiltration, bioconversion.[92]

There has been a rise in the use of precision fermentation to produce food ingredients due to the convergence of advances in

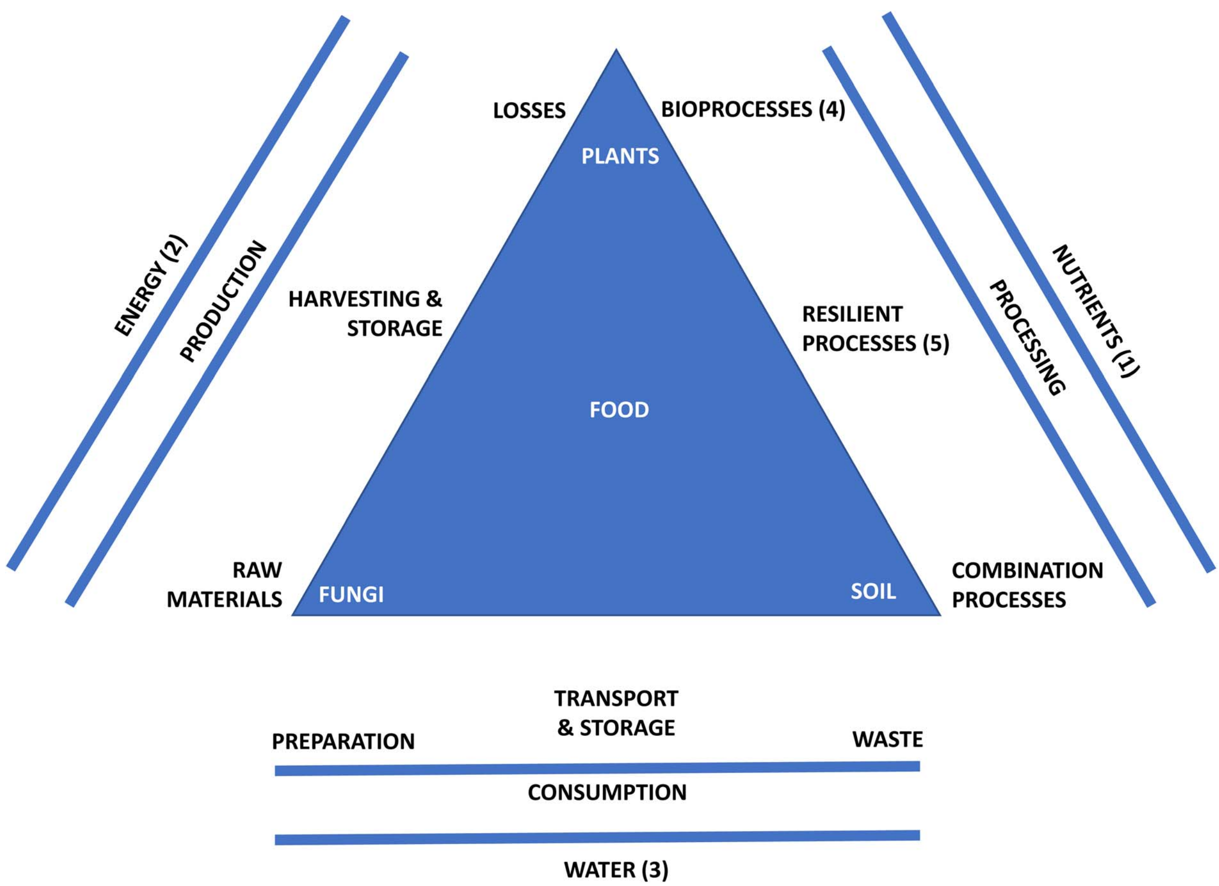

Fig. 1 Interconnections between environmental resources, fungi (biodiversity and productivity), plants (diversity) and soil (health), raw material production, processing and preparation of plant and microbial derived foods. Legends: (1) resources: NUTRIENTS (biofertilizers, plant growth promoters),[55] (2) resources ENERGY (sun, wind, water), (3) resources: WATER,[36] (4) bioprocesses (fermentation, enzyme processes), (5) resilient processes.[76]

genome-based technologies and traditional fermentation. While precision fermentation has been used for production of high-value food ingredients and nutraceuticals (*e.g.*, colors, enzymes, vitamins), there is an increasing interest in the use of microbes *via* precision fermentation. There is a growing number of fermentation companies that have interest in the production of alternative sources of animal-free protein (*e.g.*, recombinant dairy proteins, egg protein), lipids (*e.g.*, palm oil substitutes), and carbohydrates (*e.g.*, oligosaccharides).[95]

An interlinked food resource – food processing approach

Transparent, gentle, resource efficient and consumer oriented resilient technologies for processing of sustainably produced diverse agricultural food sources into safe, nutritious and consumer acceptable food products are a necessity for improving food security. A conversion of the food processing sector into a consumer oriented transparent and resource efficient part of interactive food systems[75] by food product (raw material) adapted processing with the aim to increase the benefits of food products has been proposed.[76] This can be improved further *via* the creation of symbiotic food systems.

Optimization of access to food resources, resilient food processing and sustainable food biotechnology need to be considered to: (1) address technology innovation and ecosystem interactions for long term sustainability,[75] (2) develop the necessary transition from linear food value chains to realizing the intra- and interconnections of food webs,[11] (3) realize the decentralization of processing facilities as well as the use of small-scale food processing,[96] while taking into account the necessity of inter-, trans- and multi-disciplinary approaches for our increasingly urban planet,[93] as well as the importance of consumer acceptance and trust of existing and emerging food processing technologies.[97]

The significant role of food science and technology as well as of food product and process engineering will be to (a) identify in collaboration with agricultural and nutritional science high quality raw materials, (b) select the most appropriate process or process combination to retain or improve product quality, functionality and safety, and (c) enable the transformations necessary for food systems. Based on the above we propose collaborative, mutually beneficial "symbiotic food systems" involving all actors within this alternative food resource to food consumer concept. Table 3 provides recommendations for improving the link between food resources and resilient food processing technologies.

The interconnections between resources, fungal biodiversity and productivity, plant diversity and soil health for raw material production and for further processing and preparation of plant or microbial derived foods are exemplified in Fig. 1.

Conclusions

The key aims of this paper are to highlight the importance of improving the environmental biodiversity including that of our food resources, to integrate all the most fitting and resilient food production practices and to re-evaluate existing food processes for resource efficiency and food safety, quality and functionality improvements. We are in in agreement with Chu and Karr[101] who stated, "over the past two centuries humans have disrupted living and nonliving systems everywhere. Understanding the nature and consequences of humans' environmental impact – and managing these impacts to protect the wellbeing of human society and other life on earth – is humanity's greatest challenge". We believe that sustainability and food security can go hand in hand if we use all the past and present interdisciplinary expertise. For example, oases as water and food sources have been life savers throughout human history and have empowered indigenous cultures throughout history are now being "discovered" as source of extraordinary biodiversity and need to be better understood.[102] Our ancestors used non-thermal processing methods (grinding, pounding, cutting, mashing) and thermal methods (cooking, steaming, boiling, stewing, braising, grilling, roasting, smoking). The energetic consequence of processing was important in human evolution ever since there was control of fire.[76,103] Now the energetic consequences and resource depletion of food production, processing, transportation and consumption require drastic changes. As has been put "the global food system transformation to a future where healthy, culturally appropriate and adequate diets are available for all, from food systems that operate within planetary boundaries, is one of the grand transformation challenges for humanity over the coming decades" with the entry statement "Food is failing us".[5] There is an urgent need to reverse this "food is failing us" statement. The ultimate goal of our efforts to reverse the current trends and to abolishing unsustainable food production, processing and consumption practices[104] within the current food systems must be of utmost importance and "new approaches to include different food systems' actors perceptions and goals are needed to build food systems that are better positioned to address challenges of the future".[105] However, it is also necessary to appreciate that there are activities beyond the food supply chain that affect biodiversity and the ecosystem. Land-use change due to agricultural expansion and exploitation and sea-use change are the top-ranked drivers of biodiversity loss,[106] with other causes being climate change, urbanization, insecticide-driven degradation of the aquatic environment, microplastic pollution, nitrogen deposition and eutrophication, and the spread of invasive species.[107] Addressing biodiversity loss and ecosystem resilience requires a consideration of the interconnectedness of people, the planet, the economy. This requires integration efforts from all sectors for transformative actions to protect biodiversity, reduce greenhouse gas emissions and climate change impacts, restore ecosystem integrity by large-scale land- and ocean-based actions[108] and increase conservation investment.[106]

Author contributions

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

Conflicts of interest

The authors declare no competing interests.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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