Food systems research to positively impact the sustainable bioeconomy and transformation of smart food systems – an overview of gaps and future research agenda

Positioning paper

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Summary

This paper discusses the subject of the bioeconomy and smart systems in food giving a summary of the key impact areas. The paper covers recent research into relevant areas and on policy and government strategy. In addition, a new perspective on the landscape of funded projects in the areas of bioeconomy and smart systems is presented. This aims to identify key gaps in funding which, if addressed could provide important advances in addressing food sustainability, consumer diets, and improved agricultural efficiency. This paper offers a valuable evidence base for shaping strategic investment decisions.

1. Introduction

Bioeconomy is a concept that has emerged and developed over the past few years as a potential solution to the problems the world faces with climate change, environmental pollution and degradation and petrochemical resource depletion. The Global Bioeconomy Summit defined bioeconomy as:

"the production, utilization, conservation, and regeneration of biological resources, including related knowledge, science, technology, and innovation, to provide sustainable solutions (information, products, processes and services) within and across all economic sectors and enable a transformation to a sustainable economy" (Global Bioeconomy Summit Communiqué, 2020).

At its core, bioeconomy supports the exploitation of sustainable, renewable resources to produce food, materials and energy (European Commission, 2024). This will require a major shift in production methods, consumption, and how the environmental consequences of the food we produce are measured and mitigated. In this respect, the development of so-called smart food systems is one axis for the successful establishment and maintenance of a bioeconomy. Smart food systems have several definitions. The United Nations defines them as:

"a resource-smart or environmentally sustainable food system is one in which the environmental basis to deliver food security for future generations is not compromised" (UN Environment Programme, 2016),

*A*nd the Food and Agriculture Organization (FAO) as:

"a food system that delivers food security and nutrition for all in such a way that the economic, social and environmental bases to generate food security and nutrition for future generations are not compromised" (Nguyen, 2016).

Smart food systems are designed within the bioeconomy to address global issues (International Crops Research Institute for the Semi-Arid Tropics, 2020):

- **Good for the Consumer –** contributing to preventing poor diets (malnutrition to obesity); affordability.
- **Good for the Earth –** addressing climate issues such as water scarcity, climate change and degradation of the environment.
- **Good for the Farmers –** help to protect farmers and provide increased food sustainability.

Smart food systems from new developments in science and technology are urgently needed to provide solutions to these issues.

The bioeconomy and smart food system is multifaceted and involve a multitude of actors across agriculture, government, the broader food industry and the public. A sustainable food system requires changes across all of these from financial structures, policy, through farming practices, food businesses (including transport, storage, wholesale, retail etc.) and social innovations. This will require changes such as a true commitment to green policies from the UK government, agricultural innovations such as smart farming, novel approaches to food formulation including alternative protein sources and waste reduction, and a greater use of fresh, seasonal food resources from the public, and beyond. According to a recent report from the UN, the hidden costs of the global food system are equivalent to 10% of the global GDP and one fifth of this derives from environment-related factors. This clearly reinforces the importance of bioeconomy to address the food sustainability challenges (FAO, 2023).

2. Trends and drivers for Bioeconomy and smart food systems research

There are several current issues are driving the move towards a bioeconomy and sustainable food system. The most pressing are the impacts of climate change and the changes to water availability and environmental degradation that accompanies it. The effects of this are two-fold. Not only is climate change damaging to the planet and life, because of extreme weather events (high temperatures, drought, flooding, storms) but this leads to a shift in the productivity and geographic distribution of crops, and affects what can be produced efficiently in the UK along with impacts on overseas food production regions. Production rates, the supply chain and subsequent availability of food are therefore under threat. This raises questions about the strategies that can be proposed to slow or reverse climate change, and to mitigate any (possibly irreversible) changes that are already embedded in the earth's ecosystems.

Several trends that will emerge can be anticipated and which will require significant effort to ensure the sustainability of the UK food system. Increasing temperatures in the UK and overseas will impact on crops that we are able to grow domestically, and what we need to import. Improving the tolerance to high temperatures and to drought conditions of UK staple crops could go some way towards maintaining supply. This can, in part, be achieved by identifying drought-tolerant varieties that have evolved in other parts of the world but will also inevitably require a greater use of genetically engineered varieties. Significant sections of the public are opposed to GM crops mainly due to perceived environmental risks, even though evidence of their harm to the environment is scarce. Any transition to GM crops will require very careful, evidence-led, management of these social barriers.

The likely increase in water scarcity (drought) in the summer growing season is likely to also have a major impact. Here, greater irrigation of crops is unlikely to be feasible given that drought will also impact on water resources in other industries as well as domestic water supplies. We will need to become smarter in the way we manage agricultural irrigation. This may mean a shift to novel technologies that use less water such as vertical farming. Vertical farming has been questioned over its economic sustainability. Although proven to use less water and land, it is energy intensive and hence it is considered necessary to utilize renewable energy sources for it to be economically viable. This is because the closed environments used require artificial lighting with high electricity requirements even using energy-efficient LEDs. Alternatively (or in combination) we may see a shift towards precision agriculture. This combines sensor technology with robotics/automation to monitor crops (or animals) on an individual or on localized area basis. In crop systems this allows for localized responses to signs of drought, disease etc. where targeted management can be implemented improving overall efficiency of land use and increasing land productivity.

Climate change is likely to impact the food system in other ways. Increased temperatures are likely to lead to an increase in foodborne diseases or a change in the types we see. Rapid diagnostic testing and on-pack indicators of safety will need to evolve to keep up with this. Any increase in the need for the use of cold chains will inevitably lead to higher energy usage, and increased food storage and transport costs, which will be passed onto the consumer. More subtle effects may also be seen. For example, Falloon et al. (2022), have considered the consequence of climate change on eating habits. They consider that there may be a shift towards what we prefer to eat as opposed to what is available, for example, an increase in consumption of "barbecue food" i.e., meats, salad etc. in hot weather. In a global warming scenario, this might stress the food system if these foods are negatively impacted by a warmer climate, drought, floods, etc., but could also impact food safety (e.g. food preparation and storage outdoors in high temperatures).

What we eat is also changing due to the concerns over the effects of intensive agricultural systems on the environment. Over the past decade, there has been a move towards eating less meat and more plant protein – so-called flexitarianism. The alternative protein market experienced considerable growth in the UK and worldwide, due to the increased demand for healthier, more ethical and sustainable products amongst consumers. This is driven by expanding sales in alternative dairy and plant-based meat analogue products. The Good Food Institute (GFI) noted that the US market for plant-based foods was $US 8Bn in 2022, a 7% increase in 2021 (Good Food Institute, 2023b). Similarly, Mintel reports that in the UK plant-based meat sales increased 40% between 2014 and 2019 to £816M with plant-based dairy worth £260M in 2019. Plant-based meat is expected to grow to over £1Bn and plant-based dairy to over £500M by 2025 (Pilkinton, 2019).

However, there is evidence that this growth is stalling and projections may not be achieved with several plant-based meat companies reporting falling sales and a reduction in product range, and others ceasing trading (Webber, 2023; Flood, 2023; Southey, 2023). It is believed falling market growth is due to the inferior texture and taste of the products, and uncertainty over the health benefits and sustainability of these products compared to animal-based foods. GFI has surveyed plant-based food customers to identify barriers to the uptake of the products (Good Food Institute, 2023a). A quarter or more consumers give taste, cost and texture as reasons for why they have not tried plant-based foods or have tried once or twice but did not continue. A failure to meet expectations was also a major barrier. This is a pointer to where there are gaps in research knowledge. Understanding how structure affects dairy and meat analog texture and organoleptic properties as well as replacing less acceptable ingredients such as saturated plant fats (palm and coconut oil) is a critical challenge for the sector. With this knowledge in hand, the sector can better meet consumer expectations.

The alternative proteins market has largely been framed in the context of alternative plant protein sources. Others that are emerging as potential protein sources include microalgae, insects, fungi, etc. Each of these has advantages and disadvantages. Microalgae will require advances in photobioreactor efficiency to be economically viable at scale, whilst there is still a social barrier to the consumption of insects in Western countries. Fungi, in the form of products such as Quorn, have seen the greatest success in breaking into the alternative proteins market, and are seeing increased growth as more competitor companies enter the market. This success is based on a strategy to shape their products in familiar forms, which is known to help acceptance and an explicit targeting of the flexitarian market, which is much larger than the vegan+vegetarian market.

The impact of a transition of consumers from animal to plant proteins on nutritional adequacy also remains a concern, particularly in the UK as dairy and meat are traditionally the main contributors to important nutrients such as iodine and vitamin B12. This transition should be monitored through more regular dietary assessments, and population groups most at risk should be prioritized to prevent negative public health impacts. Although emerging plant-based alternatives are appealing to mainstream omnivores, they are often more expensive than their animal-based counterparts, both per weight and per protein content basis (Clegg et al., 2021) and come with nutritional shortcomings. These include incomplete amino acid profile or low bioavailability of proteins and essential micronutrients (e.g. Ca, Fe, Zn, etc) or absence of micronutrients without fortification (e.g. vitamins B12, D3), as well as the presence of anti-nutritional factors. Many of the current plant-based alternatives are also highly processed and contain chemically modified starch and other additives; almost 95% of meat alternatives contain more sodium than normal meat products (Bohrer, 2019).

The UK food system already faces obesogenic challenges related to the energy density of diets high in saturated fat, salt, and sugar with an estimated £6.1 bn annual NHS spend associated with diet-related chronic disease. Thus, future research should be directed at understanding how to ensure better nutritional security and health-based outcomes via transitioning into an alternative plant protein-based diet. The Good Food Institute (2023a) has reported statistics on the current funding scenario from UKRI on plant protein. Between 2012 and 2023 UKRI investment in alternative protein research was £43.1M, with £15.4M of this plant-based. Encouragingly, awards increased in size and frequency by 65% between Jan-May '23. The GFI report claims that it is necessary to increase UKRI funding by 2.5-4% to ensure the UK builds and maintains a leading research position in this area.

A longer-term potential solution to the perceived environmental issues with animal protein production systems comes from the drive towards cellular meat and dairy, more generally termed cellular agriculture. This involves attempts to grow animal cells (or in the case of dairy to express milk proteins recombinantly in microbial vectors) in large-scale fermenters. There has been huge investment in cellular meat companies worldwide despite contradictory studies on the economic and technical feasibility of the processes contained in the two most authoritative technical and economic assessments to date (Humbird, 2021; Good Food Institute, 2024). While strong claims are being made for the technology, there are no mass-market products yet and little sign these are imminent. It is imperative that comprehensive, independent research and analysis of the feasibility of cellular meat is carried out to de-risk any planned large-scale research investments. To this end, it is welcome that UKRI has recently invested £12M in a cellular agriculture centre (UKRI, 2023) that will hopefully add clarity to the feasibility of cellular agriculture. Cellular dairy is less risky as it is a more standard fermentation process producing recombinant protein with yeast or bacteria. However, despite recent claims, cellular dairy does not produce milk, it produces milk proteins. Products (e.g. cheese, yoghurt etc.) formed from this process are unlikely to have the same organoleptic properties as dairy products from milk. The reason is that the main milk proteins (caseins) are not synthesized in microorganisms as casein micelles, the structure required for e.g. cheese manufacture, but as individual proteins. To form the micelle, the building block of protein based dairy foods such as cheese and yoghurt requires control of the phosphorylation of the milk proteins, a cellular process that is not well understood for milk caseins (Antuma et al., 2023).

One response to the perceived environmental issues associated with the food chain that has emerged over the past few years is the move towards a greater use (or reuse) of food processing materials that were previously considered waste. For many years, large proportions of organic food waste (whether domestic or from food processing) were sent to landfill. This leads to increased methane emissions as the organic matter decomposes, and potential environmental contamination of water courses. It is now realized that this "waste" (now more appropriately termed a co- or by-product stream) has potential value for agri-food manufacturers. This has led to an increase in research on how to use these streams for direct extraction of useful nutrients (a biorefinery approach) that could be fed back into the food or feed chain, or whether they can be used as a feedstock to produce other high-value chemicals through fermentation. Using microbial fermentation to produce functional food ingredients is a possible solution to consumer demands for less synthetic chemicals in their foods (so-called clean label foods). Biobased chemicals are claimed to be more sustainable, environmentally friendly (less toxic and more biodegradable) and with equivalent functionality to current alternatives that are often produced from petrochemical feedstock. There is also a shift towards circular value chains, with byproducts of industry redirected to be used as ingredients for another product (e.g. bread waste to produce beer).

Ultimately, whether the UK moves towards a greater emphasis on a biobased model for the economy will depend largely on government policy and investment from both the state and private sector. Of concern is the fact that although the UK released a roadmap outlining a path towards a bioeconomy for 2030, the document was criticized by many in the biobased industries for containing little information on the policy changes required to achieve this, nor of the funding intended to support it (Jasi, 2018). Of greater concern is the apparent abandonment or deferral of some green pledges by the government because they have a cost to the consumer or industry stakeholders, which could signal a wider backlash against bioeconomy principles. The presumption here is that the cost-of-living crisis experienced since the COVID-19 pandemic has made it more difficult to persuade the populace that changes to the food system that will make it more environmentally sustainable are beneficial. Food inflation has increased faster than core inflation over the past year, increasing food poverty in many parts of the UK. This is not always borne out by surveys, where a significant proportion of respondents think the government is too weak on green policy (Holder, 2023; Allegretti, 2023).

At best policy can currently be described as ambiguous. The sooner clarity is provided the sooner a better picture will emerge of how Net Zero policy will impact the food system. This is critically important as it will determine how we handle issues such as the environmental impact of animal farming vs alternative plant foods. Currently, farmers are under scrutiny for the effect intensive animal rearing has on the environment. If, because of either consumer rejection of meat for plant-based diets or the development of cultured meat, animal farming becomes unsustainable, the policy will need to evolve to recognize this and manage the transition towards a more sustainable model for animal farmers.

Another potential concern for the food system is if there is a push for the use of crops in the production of biofuel, or as feedstock for other fermentation processes. This could take up valuable productive land for feedstock crop production, thus aggravating the food vs fuel dilemma (ETIP Bioenergy, 2024).

3. Summary of recent literature

In the Global Bioeconomy Summit Communiqué (2020) it was stated that there are three overarching bioeconomy contribution areas to help people and the planet. These are:

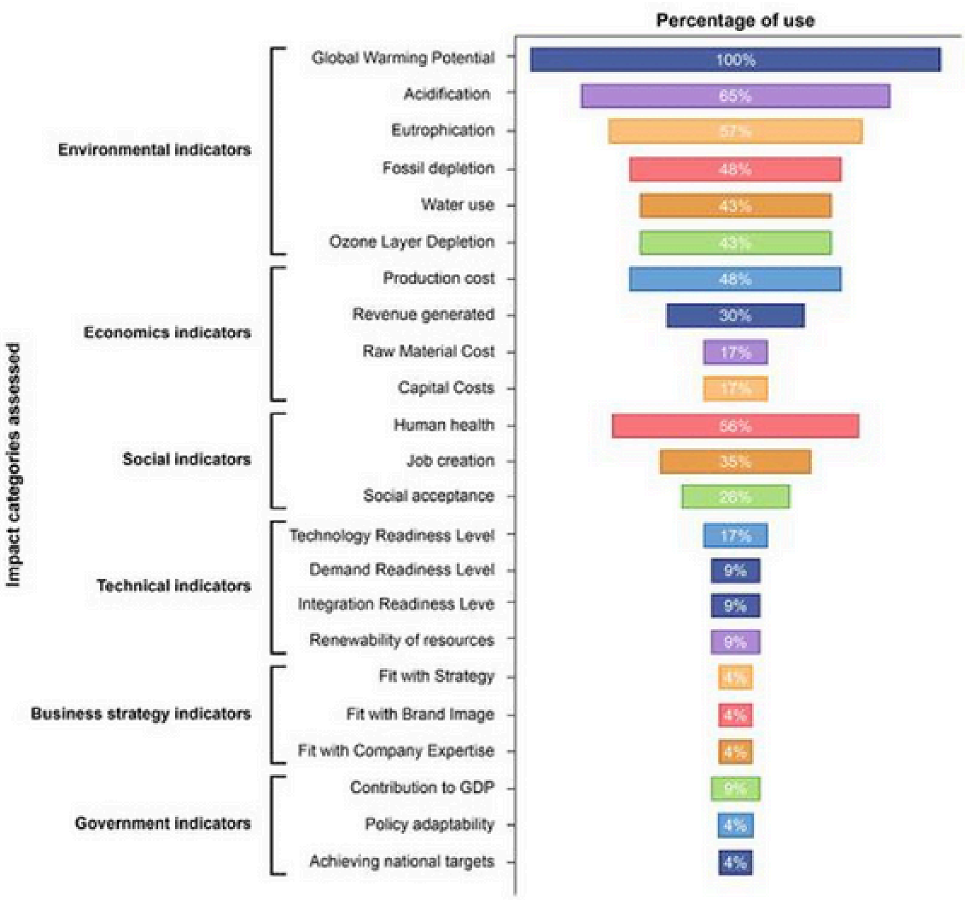
- Bioeconomy for health and wellbeing.
- Science and technology breakthroughs advancing the sustainable bioeconomy.
- Climate action, ecosystems and biodiversity protection with and for sustainable bioeconomy.

3.1 Waste

Considering food waste, the primary aim would be to reduce this as much as possible and methods are increasingly in place to achieve this. Inevitably there will always be some food waste, especially at the farm gate or retail/hospitality end. Utilising residual food waste to generate biofuels, certain chemicals and bio-based materials (food waste biorefinery) is increasing. A useful review of this is given by Tsegeye et al (2021). The authors give data on food waste country by country and conclude that this potentially valuable contribution to the bioeconomy is at a very early stage and research is needed to make it a more valuable contribution to the bioeconomy.

Using a different approach, Romero-Perdomo and Gonzales-Curbelo (2023) reviewed the approach to using agri-food waste biomass for the bioeconomy by considering the novel integration of multi-criteria decision analysis (MCDA) into life cycle assessment (LCA) tools and whether this approach would be helpful in the transition of agri-food waste to the circular bioeconomy. The use of such relatively new uses of MCDA to complex food systems could bring advancement in social and political areas. Figure 1 summarizes current applications of this approach.

Figure 1 - Impact categories most reported in the literature on the use of the MCDA/LCA framework in AWB's circular bioeconomy transition (Adapted from Romero-Perdomo and Gonzáles-Curbelo, page 12).



3.2 Sustainability

The Food and Agricultural Organisation (FAO) of the United Nations in a recently published paper summarized the best approaches to using the bioeconomy for climate change as described by the Intergovernmental Panel on Climate Change (IPCC), with case study examples examples (Gomez San Juan et al., 2022). The IPCC identified mitigation options for each of three macro sectors, and the FAO paper has suggested bioeconomy innovation examples for each of these options. These are summarized in the Table 1:

Table 1 - Nine IPCC mitigation options and the corresponding bioeconomy innovations (Adapted from Gomez San Juan et al., 2022, page 13).

Macro Sectors	IPCC Mitigation Options	Bioeconomy Innovations
Primary production	Shift to balanced, sustainable healthy diets	New food sources
	Carbon sequestration in agriculture	Microbiome innovations
	Reduce methane and nitrous oxide emissions	Biofertilisers
Circularity and by-product use	Ecosystem restoration, afforestation, reforestation	Biopesticides
	Enhance recycling	Bio-based biodegradable plastics
	Reduce food loss and waste	Residue management and cascading use
Bio-based industries	Enhance use of wood products	Enhance use of wood products
	Feedstock decarbonization, process change	Natural organisms and enzymes in food production and processing
	Fuel switching (bioenergy)	Sustainable bioenergy from waste

Key: Green = primary production; Blue = circularity & by-product use; Amber = bio-based industries.

In conclusion, the FAO (Gomez San Juan et al., 2022) advised that to achieve net zero carbon emissions, society should use a combination of three mechanisms within the circular bioeconomy, namely:

- Use new renewable biological resources.
- Improve efficiency of biomass already used by current activities (through enhanced lifetimes of products, cascading use of biomass, recycling)
- Rescue atmospheric carbon and store it in soils, forests, aquatic environments, and bioproducts.

3.3 Smart Agriculture

In a paper on the increasing use of smart agriculture to address global food security , Whitfield et al. (2018) discuss that the livestock contribution to global greenhouse gases of approximately 14.5% has led to a focus on reducing this, but more needs to be done. Specifically, they argue that as well as reducing livestock emissions, strong efforts in the area of novel thinking and new technologies are also needed to achieve ambitious climate mitigation goals. The authors argue that setting out a research agenda to combat global challenges requires a plan that answers several key questions. These include:

- Understanding the social and economic impact of climate-smart agriculture (and a clear definition of what this is);
- which climate-smart actions are feasible and what are the trade-offs;
- how can consumer diet choices contribute to the climate smartness of the food system in the long term.

4. Landscape of current funded projects/research

A search of the Gateway to Research (GtR) database (UKRI) using various keywords has been used to map the number of funded (current and closed) projects in the bioeconomy and smart food systems research area. Primary keywords have been searched with additional secondary keywords and used to generate a heat map (Appendix Table A1 and Table A2) that highlights projects that link the two keywords. This allows a diagrammatic representation of specific research area in terms of how highly they are funded. The heat map can be used to give a preliminary indication of areas of research that we have identified as important in supporting a move towards a sustainable food system but are currently not highly funded. It should be noted that the GtR database was searched on 24/8/23 and may not include all projects funded under more recent calls. It should also be noted that the database does not include individual projects funded by larger networks such as SFN/SFN+ and various BBSRC NIBBS (Networks in Industrial Biotechnology and Bioenergy) that are known to fund relevant research.

Table A1 (see page 22) shows results for a search for keywords associated with bioeconomy. Highly funded areas are mainly associated with three research areas, namely synthetic biology/microbial & genetic engineering, industrial biotechnology and recycling/renewables. Waste valorization projects are being funded, but to a lower level than recycling. Surprisingly, the bioeconomy keyword is hardly mentioned in association with secondary keywords in the database.

Research areas that are currently sparsely funded include plant-based foods, alternative proteins and cellular agriculture. For food systems keywords (Appendix Table A2 see page 20), highly funded areas include sensors, digital, digitalisation, big data, AI/machine learning. Less heavily funded areas are hydroponics, aquaponics, controlled environment, and food safety. Most of the projects are funded by EPSRC, BBSRC, NERC and Innovate UK (20-25% each, with approximately a total of 90% for these four funders) (Appendix Table A3 and Table A4).

5. Food strategy

As several scientists and policy experts have emphasized, the identification of key challenges is difficult because of the complexity of the food system and its interdisciplinary nature. However, this does not mean that producing a robust sustainable food system that meets net-zero targets and delivers improved diets for the consumer that are affordable for both consumers and producers, is impossible. In 2018, the UK government commissioned a study of the food system as part of producing a National Food Strategy for England (DEFRA, 2020). In this two-part review, part one contained urgent recommendations for food policy following the pandemic and Brexit.

Part two is an in-depth look at the fundamental strengths and weaknesses of the food system from farm to fork. This review summarized the global food system as a huge success, producing a huge quantity of food, and also a big disaster. To quote from the executive summary, “The global food system is the single biggest contributor to biodiversity loss, deforestation, drought, freshwater pollution and the collapse of aquatic wildlife. It is the second-biggest contributor to climate change, after the energy industry.”

Current food habits threaten food security through climate change and damage human health through poor diets. The report states that reducing emissions, restoring biodiversity in the environment, and producing enough sustainable affordable food needs a fundamental change in the agrifood system. This change will need diverse methods of agriculture, investment in the latest science and exploration of new protein sources and different ways to produce food more sustainably.

Using examples from nature, the review considers the food system in terms of feedback mechanisms and identified two feedback loops that needed changing: namely the junk food (HFSS) cycle and the invisibility of nature (the complex interactions that take place to keep ecosystems in balance). The junk food cycle has produced an obesity crisis in the UK putting huge strain on the NHS. The invisibility of nature means that it has not been given a financial value and this has allowed food production and distribution to damage the ecology and exacerbated the climate and biodiversity crisis. The report details examples of how these are thought to have come about.

The review considers what a food system needs to be to make nature more visible (give the ecosystems value), produce enough food to feed everyone and simultaneously restore nature and sequester carbon. The review stated four objectives and suggested recommendations for achieving these. The objectives were:

1. Escape the junk food cycle to protect the NHS.
2. Reduce diet-related inequality.
3. Make the best use of our land.
4. Create a long-term shift in our food culture.

The recommendations listed that will achieve these objectives are given in the report. Many of these are related to government decisions, but those that relate directly to the research agenda for bioeconomy and smart systems are:

- Introduce a Sugar and Salt Reformulation Tax. Use some of the revenue to help get fresh fruit and vegetables to low-income families. Although this is a government decision, it will fall to the food industry to innovate to reduce sugar and salt in many foods.
- Create a Rural Land Use Framework based on the three-compartment model. This is an agricultural system based on wild land and low and high-intensity farming. Success for this will rely on traditional farming methods as well as cutting-edge science.
- Introduce mandatory reporting for large food companies (on sales of HFSS foods; fruit and vegetables; protein by type, and major nutrients including fiber. Also, waste food. This should lead to the development of new products based on healthier and reduced-carbon ingredients.
- Invest £1 billion in innovation to create a better food system. This recommendation includes better farming and biodiversity systems; alternative proteins based on a new hub merging businesses with science; and new ways of growing food including vertical farming and fermentation.
- Create a National Food System Data Programme covering land, transport, manufacture, retail, to human health and diet. This will enable large and small businesses to identify weaknesses or gaps in the system and plan new products or systems.

This review was published before the war in Ukraine so additional pressures on energy supply and food security caused by this will impact the need for research calls in these areas.

The government food strategy published in June 2022 responded to the review above (DEFRA, 2022) and does take into consideration these more recent issues. The food strategy emphasizes the key importance of innovation to “sustainably boost production and profitability across the supply chain”. Examples of areas at the agricultural end include automation and increased industrial horticulture as well as continued development of alternative proteins. To help combat the consumer health crisis, the government strategy has announced the provision of a Diet & Health Open Innovation Research Club which will support research in furthering understanding of the relationship between diet and health.

6. Main challenges and priorities

When assessing future research needs, both gaps in current and past funding and government and national policy strategies need consideration.

- The main challenge for the world is food security, with clean water available. A priority should be to research to improve food security. This could be aligned with any of the drivers that would impact food security, such as new ingredients or waste utilization, or improvements to food supply.
- A second important challenge is to improve consumer health through food.
- A third overarching challenge is to address climate / environment issues directly relating to food.

In considering these challenges, the areas that address these challenges directly and are receiving a low level of funded research are:

- Refining plant and other organic waste/side-streams into energy or alternative-use materials.
- Alternative proteins and plant-based protein foods to reduce the need for animal protein.
- Combined crop and forestry research.
- Alternative food cultivation, notably hydroponics and controlled environment growth.

7. Recommendations for research to address main challenges.

Food security: to reduce reliance on imported crops (particularly soy) alternative protein sources should be investigated. This should include not only novel plant sources but also algae, insects, microbial, and fungal, as well as fish and seafood (although there remain questions over the sustainability of fishing and sourcing of some products). For alternative production systems such as vertical farming, precision agriculture and cellular meat and dairy a priority should be to demonstrate whether these are both technically and economically feasible, as well as environmentally advantageous.

Improved nutrition: Diet-related health issues continue to be a drain on NHS resources in the UK. Efforts to reduce salt, fat and carbohydrate content of foods have seen some success but there remain issues with the taste and texture of these foods. This is also an issue for plant-based foods where how to remove saturated fats is a priority whilst maintaining taste and texture. In general, the quality of plant-based foods is perceived as sub-optimal and improving the quality (taste, texture, nutritional) and overall acceptability of plant-based foods could lead to higher uptake as healthier alternatives to animal foods.

Increased human lifespan creates additional nutritional issues. The elderly people require higher protein intake which is not always met by current diets. Improvements in the nutritional status of an ageing population through the development of palatable high-protein foods could help ease the burden on the NHS.

Ultra-processed foods: Whether you believe ultra-processing of foods is hype or an existential threat to health, research in the removal of e-number ingredients could help to improve the image of processed foods. Biobased alternatives for surfactants, emulsifiers, sweeteners, flavours etc. produced either through microbial fermentation or extraction from natural sources would support this. These could replace current ingredients that are largely produced synthetically from petrochemical feedstock. A successful example of this is the replacement of synthetic colours such as tartrazine in the 1990's using natural alternatives.

Climate/environmental aspects of the food system

Climate: Any increase in mean temperatures in the UK will increase stress on current crop options as well as a shift in those that can be grown. Developing ways to improve crop tolerance to drought (or flooding), increased temperature, salinity, and other soil conditions will be key to protecting the UK crop food system. This could include research on applications of genetic engineering for climate tolerance, or bioaugmentation of soil with bacteria that, for example, polysaccharides to improve water holding in soil, or produce other biostimulants.

Emerging crop (and animal) diseases due to climate change: Due to climate change, plant and animal pathogens not normally seen in the UK may emerge. This will require research on novel insecticides, pesticides, antimicrobials and fungicides, that are safer and more friendly environmentally. Fungicides are a priority as there have been few new fungicides developed in the past decades.

Food safety: In addition to threats from emerging plant and animal pathogens, we would also expect food-borne illnesses to increase as temperatures increase. This will require investment in new technologies for the detection of pathogen growth in foods as well as investment in research on prevention. We would expect to see the emergence of new technologies for the storage of raw materials, as well as renewed interest in old approaches such as fermentation (and precision fermentation).

Environmental: Better valorization of "waste" or co/by-product streams will not only improve environmental outcomes for food producers but may also allow the development of additional product/value lines, thus increasing economic returns. The UK lags behind Europe in research into biorefining and boosting this area by aiming to build integrated pilot UK food co/by-product biorefineries within the next few years would be a welcome challenge. To support this, additional research on green extraction technologies for agri-food waste (for example natural deep eutectic solvents, and supercritical extraction) would give a further enhancement of environmental sustainability in this area. There is also a pressing need for more research in assessing the decarbonization opportunities of technology like cultivated meat. This would ensure a validated pathway to maximise the benefit of bioeconomy-driven technology platforms.

8. Conclusions

In summary, the food system is complex and covers areas of production, processing, transportation, importation, health and social behaviour and these need to be integrated into the global geopolitical scenario. The development of the bioeconomy and smart food systems is essential to combat the stresses of climate change and social demands and provide a secure food system. This position paper has given insights into current thinking and research. Research gaps that directly address the areas that will provide solutions have been identified.

References

Allegretti, A. (2023). 'I realise how serious it is': voters in England support action on climate crisis. The Guardian [Online]. 29 July 2023. Available at: https://www.theguardian.com/environment/2023/jul/29/i-realise-how-serious-it-is-voters-in-england-support-action-on-climate-crisis. [Accessed on 23rd April 2024].

Antuma, L.J., Steiner, I., Garamus, V.M., Boom, R.M. and Keppler, J.K. (2023). Engineering artificial casein micelles for future food: Is case in phosphorylation necessary? Food Research International, 173, p.113315. Available at: https://edepot.wur.nl/636992.

Bohrer, B.M. (2019). An investigation of the formulation and nutritional composition of modern meat analogue products. Food Science and Human Wellness, 8, 320–329.

Clegg, M.E., Tarrado Ribes, A., Reynolds, R., Kliem, K. and Stergiadis, S. (2021). A comparative assessment of the nutritional composition of dairy and plant-based dairy alternatives available for sale in the UK and the implications for consumers' dietary intakes. Food Research International, 148, p.110586. Available at: https://pubmed.ncbi.nlm.nih.gov/34507731/.

DEFRA (2020). National Food Strategy for England [Online]. Available at: https://www.gov.uk/government/publications/national-food-strategy-for-england. [Accessed on 23rd April 2024].

DEFRA (2022). Policy paper: Government Food Strategy [Online]. Available at: https://www.gov.uk/government/publications/government-food-strategy/government-food-strategy. [Accessed on 23rd April 2024].

ETIP Bioenergy (2024). Food versus Fuel [Online]. Available at: https://www.etipbioenergy.eu/sustainability/food-vs-fuel-debate. [Accessed on 23rd April 2024].

European Commission (2024). Bioeconomy [Online]. Available at: https://research-and-innovation.ec.europa.eu/research-area/environment/bioeconomy_en#:~:text=The%20bioeconomy%20means%20using%20renewable,produce%20food%2C%20materials%20and%20energy. [Accessed on 23rd April 2024].

Falloon, P., Bebber, D.P., Dalin, C., Ingram, J., Mitchell, D., Hartley, T.N., Johnes, P.J., Newbold, T., Challinor, A.J., Finch, J., Galdos, M.V., Petty, C., Cornforth, R., Bhunnoo, R., Pope, E., Enow, A., Borrion, A., Waterson, A., McNeill, K. and Houldcroft, A. (2022). What do changing weather and climate shocks and stresses mean for the UK food system? Environmental Research Letters, 17(5), p.051001. Available at: https://iopscience.iop.org/article/10.1088/1748-9326/ac68f9.

FAO (2023). The State of Food and Agriculture 2023: Revealing the true cost of food to transform agrifood systems [Online]. Available at: https://www.fao.org/documents/card/en/c/cc7724en. [Accessed on 23rd April 2024].

Flood, E. (2023). Plant-based meat alternatives continue decline in sales [Online]. Available at: https://www.fooddive.com/news/plant-based-meat-alternatives-continue-decline-sales/689470/. [Accessed on 23rd April 2024].

Global Bioeconomy Summit Communiqué (2020). Expanding the Sustainable Bioeconomy: Vision and way forward [Online]. Available at: https://knowledge4policy.ec.europa.eu/publication/expanding-sustainable-bioeconomy-%E2%80%93-vision-way-forward-communiqu%C3%A9-global-bioeconomy_en. [Accessed on 23rd April 2024].

Gomez San Juan, M., Harnett, S., and Albinelli, I. (2022). Sustainable and circular bioeconomy in the climate agenda: Opportunities to transform agrifood systems [Online]. Rome, FAO. Available at: https://doi.org/10.4060/cc2668en.

Good Food Institute (2023a). Alternative protein in the United Kingdom: an ecosystem review [Online]. Available at: https://gfieurope.org/sustainable-proteins-in-the-united-kingdom-an-ecosystem-review/#:~:text=Alternative%20protein%20in%20the%20United,meat%20flourish%20in%20the%20UK. [Accessed on 23rd April 2024].

References

Good Food Institute (2023b). US retail market insights for the plant-based industry [Online]. Available at: https://gfi.org/marketresearch/.[Accessed on 23rd April 2024].
Good Food Institute (2024). The costs and environmental impacts of cultivated meat [Online]. Available at: https://gfi.org/resource/cultivated-meat-lca-tea-report-analysis/. [Accessed on 23rd April 2024].
Holder, G. (2023). Poll: UK swing voters fear Conservative party is too weak on green policy [Online]. Available at: https://www.businessgreen.com/news/4120991/poll-uk-swing-voters-fear-conservative-party-weak-green-policy. [Accessed on 23rd April 2024].
Humbird, D. (2021). Scale-Up Economics for Cultured Meat, Biotechnology & Bioengineering. 118, 3239. Available at: https://analyticalsciencejournals.onlinelibrary.wiley.com/doi/10.1002/bit.27848.
International Crops Research Institute for the Semi-Arid Tropics (2020). The initiative [Online]. Available at: https://www.smartfood.org/the-initiative/#:~:text=Smart%20Food%20is%20food%20that,increase%20yields%2C%20multiple%20uses. [Accessed on 23rd April 2024].
Jasi, A. (2018). Scepticism over the UK Bioeconomy strategy [Online]. Available at: https://www.thechemicalengineer.com/news/scepticism-over-the-uk-bioeconomy-strategy/. [Accessed on 23rd April 2024].
Nguyen, H. (2016). Sustainable food systems: Concept and framework [Online]. FAO. Available at: https://www.fao.org/3/ca2079en/CA2079EN.pdf. [Accessed on 23rd April 2024].
Pilkinton, A. (2019). UK meat-free foods market report 2019 [Online]. Available at: https://store.mintel.com/report/uk-meat-free-foods-market-report?_ga=2.78824221.826312273.1619103702-326598597.1619103702. [Accessed on 23rd April 2024].
Romero-Perdomo, F., and González-Curbelo, M.A. (2023). Integrating Multi-Criteria Techniques in Life-Cycle Tools for the Circular Bioeconomy Transition of Agri-Food Waste Biomass: A Systematic Review. Sustainability, 15(6), 5026, Available at: https://doi.org/10.3390/su15065026.
Southey, F. (2023). A sign of investor delusion? Or just an unfortunate casualty? What meatless farms fall might signal about plant-based meat [Online]. Available at: https://www.foodnavigator.com/Article/2023/06/16/What-does-Meatless-Farm-s-falls-into-administration-signal-about-plant-based-meat-market. [Accessed on 23rd April 2024].
Tsegaye, B., Jaiswal, S., and Jaiswal, A.K. (2021). Food Waste Biorefinery: Pathway towards Circular Bioeconomy. Foods, 10(6), 1174, Available at: https://pubmed.ncbi.nlm.nih.gov/34073698/.
UKRI (2023). Cellular Agriculture Manufacturing Hub [Online]. Available at: https://gtr.ukri.org/projects?ref=EP%2FX038114%2F1. [Accessed on 23rd April 2024].
UN Environment Programme (2016). World Food Day: Resource-smart food systems are a must for sustainable development [Online]. Available at: https://www.unep.org/news-and-stories/story/world-food-day-resource-smart-food-systems-are-must-sustainable-development#:~:text=A%20resource%2Dsmart%20or%20environmentally,future%20generations%20is%20not%20compromised. [Accessed on 23rd April 2024].
Webber, J. (2023). Beyond meat sales fall by 30%, reigniting 'Plant-based fad' debate [Online].Available at: https://plantbasednews.org/news/economics/vegan-protein-alternatives-market-fad-beyond-meat/. [Accessed on 23rd April 2024].
Whitfield, S., Challinor, A. J., and Rees, R. M. (2018). Frontiers in Climate Smart Food Systems: Outlining the Research space. Frontiers in Sustainable Food Systems, 2. Available at: https://www.frontiersin.org/articles/10.3389/fsufs.2018.00002.

Appendices

Table A1- Heat map of funded project in the bioeconomy category by combined keyword. Data is from a Boolean search (primary keyword AND secondary keyword). The numbers in each cell represent active & closed projects. The colours correspond to green = less than 6 active or closed projects; amber = 6-19 active or closed projects; red = > 20 active or closed projects. The column on the far-left hand side of the table gives the total number of funded grants for the individual primary keywords, and the topmost row the total number of funded grants for the individual secondary keywords. The data was downloaded on 24/8/23 and was correct at this time.

		21&59	29&17	141&393	120&164	302&740	34&73	99&224	103&304	346&687	55&103	1162&2333	1052&2225	16&9	12&15	11&2	18&3
	seconday keywords primary key words	biorefinery	agroforestry	algae	carbon sequestration	ecosystem services	green chemistry	industrial biotechnology	microbial or genetic engineering	synthetic biology	waste reduction, organic waste, waste valorisation	renewable	recycling, recycled, recyclable	plant-based food	alternative proteins	cellular agriculture	cellular meat, cultivated meat
395&1041	biomass	11&28	0&4	22&45	15&26	14&54	4&8	4&24	3&7	17&39	7&13	76&264	58&120	1&1	1&2	1&0	2&0
62&275	bioenergy	0&5	0&0	0&6	1&13	1&36	0&0	15&39	1&9	3&37	1&3	13&68	5&12	0&0	0&0	0&0	0&0
455&1071	biotechnology	4&5	2&8	18&27	1&0	1&1	3&7	98&223	20&39	80&158	5&6	30&79	30&40	2&0	0&1	2&0	2&0
87&110	bio-based	11&33	14&5	59&128	50&61	133&326	13&43	45&110	39&101	178&313	25&36	515&974	516&856	16&9	4&4	5&1	5&3
296&234	circular economy	4&4	2&2	5&2	5&1	1&1	7&2	2&0	3&0	7&2	9&7	47&27	208&183	0&1	0&0	0&0	0&0
57&149	bioprocessing	1&4	0&2	1&2	0&0	0&0	0&1	3&6	2&8	7&15	1&0	6&5	4&3	7&5	6&7	7&1	10&1
40&235	biofuel	2&0	0&0	5&27	0&1	0&23	1&0	3&5	1&8	5&25	2&0	15&74	1&13	0&0	0&1	0&0	0&0
12&24	bioplastic	2&6	0&0	1&1	0&0	0&0	0&0	1&4	0&1	1&2	0&0	1&8	8&5	0&0	0&0	0&0	0&0
42&48	bioeconomy	1&8	0&0	0&1	0&0	0&3	0&1	4&6	2&0	11&9	1&1	10&8	5&8	0&0	0&0	0&0	0&1

Table A2 - Heat map of funded projects in the smart food systems category by combined keyword. Data is from a Boolean search (primary keyword AND secondary keyword). The numbers in each cell represent active & closed projects. The colours correspond to green = less than 6 active or closed projects; amber = 6-19 active or closed projects; red = > 20 active or closed projects. The column on the far left hand side of the table gives the total number of funded grants for the individual primary keywords, and the topmost row the total number of funded grants for the individual secondary keywords. The data was downloaded on 24/8/23 and was correct at this time.

		1919&4222	198&243	329&624	3185&5893	1912&5386	18&36	2&10	81&173	62&183	2624&1800	50&89	4979&13028
	secondary keywords / primary keywords	sensors	drones	remote sensing	digital, digitalisation, big data	software	hydroponics	aquaponics	controlled environment	food safety	machine learning	agri-food	innovation
22&62	precision agriculture	6&24	3&3	2&9	3&8	0&11	0&0	0&0	0&0	0&0	3&2	1&0	2&18
30&22	vertical farming	5&4	0&0	1&0	3&2	1&2	6&5	0&0	8&2	1&1	1&0	21&13	9&13
10&60	agri-tech	28&87	3&9	3&6	84&137	56&103	5&3	1&0	5&2	3&5	43&28	136&317	161&367
226&437	internet of things	72&161	5&5	3&5	67&138	38&89	1&0	1&0	1&1	1&0	43&36	6&10	61&143
51&101	traceability	10&14	0&0	0&3	25&24	10&15	0&0	0&0	0&0	2&2	8&3	18&27	19&33
1452&992	artificial intelligence	123&122	19&17	27&6	247&179	176&223	0&0	0&0	3&3	2&3	529&300	47&43	291&277
840&1183	robotics	186&245	29&38	5&12	114&106	100&184	0&0	0&0	7&7	1&1	156&104	42&73	166&285
58&133	blockchain	7&9	1&1	0&0	30&55	12&22	1&1	0&0	0&0	1&3	8&15	7&16	28&45
597&468	data-driven	70&48	4&2	7&5	132&86	58&64	0&0	0&0	1&2	0&2	203 &93	27&44	121&139
5&14	supply chain optimisati	1&1	0&0	0&0	1&5	1&1	0&0	0&0	0&0	0&0	1&0	1&3	2&6
16&9	plant-based food	0&0	0&0	0&0	0&0	0&0	0&0	0&0	0&0	1&1	0&0	16&9	4&2
12&15	alternative proteins	1&2	0&0	0&1	0&0	0&1	1&1	0&0	0&0	3&2	0&1	9&6	4&3
11&2	cellular agriculture	1&0	0&0	0&0	3&0	0&0	0&0	0&0	0&0	0&0	0&0	6&1	6&1
18&3	cellular meat, cultivated meat	0&0	0&0	0&0	0&0	0&0	0&0	0&0	2&0	1&0	0&0	22&6	14&3

Table A3 – Who is funding this research? Bioeconomy Keywords. The data was downloaded from Gateway to Research on 24/8/23 and was correct at this time.

	AHRC	BBSRC	EPSRC	ESRC	Horizon Europe Guarantee	Innovate UK	MRC	NC3Rs	NERC	STFC	UKRI
biomass	1	322	415	12	9	221	12	0	435	7	2
bioenergy	0	166	69	2	0	26	1	0	70	0	3
biotechnology	11	919	290	22	12	175	45	2	36	2	12
bio-based	1	55	56	2	10	69	0	0	2	0	2
circular economy	16	31	174	9	18	256	0	0	20	1	5
bioprocessing	0	103	46	0	0	33	3	0	19	0	2
biofuel	0	122	74	2	1	33	2	0	41	0	0
bioplastic	0	9	6	1	0	18	0	0	1	0	1
bioeconomy	1	39	20	5	6	12	0	0	7	0	0
biorefinery	0	35	25	0	3	17	0	0	0	0	0
agroforestry	0	7	1	3	3	4	1	0	27	0	0
algae	1	161	70	1	1	50	1	0	246	1	2
carbon sequestration	2	27	41	2	2	28	0	0	178	3	1
ecosystem services	13	108	38	39	14	17	0	0	799	10	4
green chemistry	0	15	67	0	0	19	0	0	6	0	0
industrial biotechnology	1	238	44	0	3	34	0	0	0	0	3
microbial or genetic engineering	0	235	48	1	1	20	84	10	8	0	0
synthetic biology	1	576	327	11	6	80	20	0	4	0	8
waste reduction, organic waste, waste valorisation	1	28	28	5	1	84	0	0	11	0	0
renewable	173	350	1473	128	25	884	69	5	329	38	21
recycling, recycled, recyclable	68	322	765	53	31	952	92	2	940	31	21
plant-based food	0	13	0	5	0	6	0	0	1	0	0
alternative proteins	0	7	2	1	2	11	1	1	0	2	0
cellular agriculture	1	3	3	1	0	5	0	0	0	0	0
cellular meat, cultivated meat	0	3	5	0	1	12	0	0	0	0	0
Total	**291**	**3894**	**4087**	**305**	**149**	**3066**	**331**	**20**	**3180**	**95**	**87**

Table A4 - Who is funding this research? Food systems keywords. The data was downloaded from Gateway to Research on 24/8/23 and was correct at this time.

	AHRC	BBSRC	EPSRC	ESRC	Horizon Europe Guarantee	Innovate UK	MRC	NC3Rs	NERC	STFC	UKRI
biorefinery	0	35	25	0	3	17	0	0	0	0	0
agroforestry	0	7	1	3	3	4	1	0	27	0	0
algae	1	161	70	1	1	50	1	0	246	1	2
carbon sequestration	2	27	41	2	2	28	0	0	178	3	1
ecosystem services	13	108	38	39	14	17	0	0	799	10	4
green chemistry	0	15	67	0	0	19	0	0	6	0	0
industrial biotechnology	1	238	44	0	3	34	0	0	0	0	3
microbial or genetic engineering	0	235	48	1	1	20	84	10	8	0	0
synthetic biology	1	576	327	11	6	80	20	0	4	0	8
waste reduction, organic waste, waste valorisation	1	28	28	5	1	84	0	0	11	0	0
renewable	173	350	1473	128	25	884	69	0	329	38	21
recycling, recycled, recyclable	68	322	763	53	31	952	92	0	940	31	21
plant-based food	0	13	0	5	0	6	0	0	1	0	0
alternative proteins	0	7	2	1	2	11	1	1	0	2	0
cellular agriculture	1	3	3	1	0	5	0	0	0	0	0
cellular meat, cultivated meat	0	3	5	0	1	12	0	0	0	0	0
Total	261	2128	2935	250	93	2223	268	11	2549	85	60

STFC Food Network+

UKRI Science and Technology Facilities Council

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