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Innovation can accelerate the transition towards a sustainable food system

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Abstract

Future technologies and systemic innovation are critical for the profound transformation the food system needs. These innovations range from food production, land use and emissions, all the way to improved diets and waste management. Here, we identify these technologies, assess their readiness and propose eight action points that could accelerate the transition towards a more sustainable food system. We argue that the speed of innovation could be significantly increased with the appropriate incentives, regulations and social license. These, in turn, require constructive stakeholder dialogue and clear transition pathways.

Main

To date, the future sustainability of food systems, the role of changing diets, reducing waste and increasing agricultural productivity have been mainly studied through the lens of existing technologies. Regarding the latter, for example, a common research question concerns what level of yield gain could be achieved through new crop varieties, livestock breeds, animal feeds, or changes in farming practices and the diffusion of technologies such as irrigation and improved management[7–13]. Yet, as studies have shown, even with wide adoption of existing agricultural technologies, full implementation of flexitarian diets and food waste reduction by half, it will be challenging to feed a growing world population while ensuring planetary wellbeing[14,15].

So far, few studies have explored the boundaries of what would be feasible if the world adopted more disruptive, ‘wild’, game-changing options[16–18] that could accelerate progress in many desired dimensions of food systems simultaneously. Some of these game-changers are no longer in the realms of imagination; they are already being developed at considerable pace, reshaping what is feasible across different sectors[19]. Data on investment in agricultural startups suggests an increasing portfolio of companies focusing on these technologies[20].

Technologies by themselves are not always transformative, but are often crucial for innovation in an environment with a multitude of actors, political economy dynamics, patterns of supply and demand, as well as regulations. How transformational a technology will be depends on the economic and political context, the needs of the society and its socio-economic conditions[21]. Yet, the elements that could catalyse the transformation of the food system through systemic innovations are rarely examined. This Perspective contributes to the discussion on how to achieve positive transformation in food systems by providing insights on emerging technologies and what is needed to accelerate systemic change for sustainability.

Technological innovations

Since Neolithic times, technology has played a considerable role in achieving progress in many metrics of human well-being, including poverty, life expectancy and disease control[22]. Table S1 in the supplementary information presents a detailed list of many past technological innovations in the food system. Despite the benefits to humanity of these innovations in food and agriculture, deterioration of some environmental and health metrics has also been observed, especially in recent times. For example, land conversion into cropland or pastures, increasing agricultural greenhouse gas emissions and water use, and application of reactive nitrogen and phosphorus have increased several-fold even as their intensities per unit of product have tended to decrease over time[23–25]. Noncommunicable diseases and inequalities are also growing in many societies[26,27] despite rapid technological advances. The development of inexpensive, fast or discretionary foods has also contributed to significant malnutrition in many parts of the world[26].

Food systems technologies are being developed at an unprecedented rate, some of which could be deployed in the next decade and significantly transform the food system. We present an inventory of near-ready and future technologies that could accelerate progress towards achieving food system sustainability from extensive literature reviews. We classified each technology according to its position in the value chain (i.e. production, processing, distribution, consumption and waste) and its 'readiness score'. The latter, developed by the US National Aeronautics and Space Administration (NASA), is a systematic measurement system that supports assessments of the maturity of a particular technology (see the supplementary information for full details)[54-56]. It consists of nine levels, from basic research, principles observed and technology prototypes deployed, all the way to the proven implementation of a technology under real-world conditions[54-56].

A few conclusions emerge from this exercise. The first is that technological innovations span the entire food system, from food production, processing and consumption to waste stream management (Figure 1). Hence, an arsenal of technological options can be tailor-made to address different food system challenges in a range of institutional and political contexts. This diverse pipeline, including consumer-ready artificial meat, intelligent packaging, nano-drones, 3D printing and vertical agriculture, to name a few, presents a real opportunity for systemic change. Depending on the level of socio-economic development of a country or region and other institutional and political constraints, the mix of technologies could vary widely.

Figure 1 about here

Second, technologies vary widely in their readiness for implementation (Figure 2). Despite considerable spread across technology groups, those related to digital agriculture and replacement of food and feed for livestock and fish are associated with a relatively large number of near-ready and mature technologies. This is not surprising considering the speed of innovation and cost reduction of digital technologies, followed by their widespread adoption across low, middle and high-income countries alike. Similarly, efforts are under way to reduce the demand for livestock products by providing alternative protein sources, and to reduce its environmental impact by decoupling animal production from land via alternative, circular feeds. Meeting a growing demand for fish depends on reducing the share of total fish capture used as feed for livestock, currently around 12%[5].

Third, a number of near-ready technologies have high potential to be adopted, rendering investments in their dissemination and implementation strategic. Research is urgently needed on how to make options available in current food systems with minimal disruption, as well as better understanding of what might affect their uptake to scales that transform. This also highlights the potential contribution of the private sector in driving the uptake of these technologies and the need to establish regulatory frameworks and market structures to ensure that these advances are well aligned with the aims of public policy. It is essential that, at least in the medium term, affordability of these novel options increases, which is more likely to happen as demand size becomes clearer, and the manufacturing processes and supply chains are better established.

Figure 2 about here

Fourth, the simultaneous implementation of several of these technologies could significantly accelerate progress towards achieving more sustainable food systems. This could lead to simultaneous improvements in sustainable food production and waste reduction while improving human well-being and creating new local business opportunities as resources are revalued as part of the process. Moreover, this is in line with current local efforts for energising the bioeconomy in many parts of the world[28–34]

Transformation accelerators

The transformation of the food system will not be purely technological[21]. At the heart of this process is a form of innovation involving deep changes in the component parts of the food system (technologies, infrastructure and skills and capability) and a fundamental reformatting of the values, regulations, policies, markets and governance surrounding it. This view of transformation as a complex and systemic process implies that novel technologies alone are not sufficient to drive food system transformations; instead, they must be accompanied by a wide range of social and institutional factors that enable their deployment.

Transformation is also a deeply political process with winners and losers, which involves choices, consensus as well as compromise about new directions and pathways. Powerful players within food systems have strong incentives to maintain the status quo and their current market share. In contrast, new entrants have much greater potential to act as disrupters of the system and to use this as a way of creating new products and/or value (meat substitutes, are an example). As a result, efforts to accelerate desirable technical change and transformation need to be in line with the social and political processes that either impede or catalyse system innovation. In practice, this means building alliances, dialogue and trust around food systems development pathways and ensuring governance and regulator regimes to safeguard desired food system outcomes – all of which are essential conditions for the deployment of new technology. Examples of emerging technologies that have benefited from such changes are insect-based food/feed, plant-based meat alternatives, circularity in food systems, and vertical agriculture.

In addition, the role of technology in transformation is ambiguous and diverse. Technology may catalyse transformation by triggering regulator shifts (e.g. circularity, drones), new market demands (e.g. seaweed) and other system innovations (e.g. personalised nutrition, molecular printing, biodegradable coatings). Alternatively, it may change/evolve in response to system innovations arising from broader societal and political shifts driving transformation[21,34] (e.g. growing demand for sustainably-sourced produce). Technology may also enhance undesirable lock-ins (e.g. a farmer specialised and heavily invested in grain production cannot easily switch to diversified agriculture[40]). Identifying pathways of change for preventing these lock-ins is essential.

Based on this broader understanding of transformation, we propose eight key, largely interconnected action points to accelerate technological change and systemic innovation in food systems (Figure 3):

1. Building trust amongst the actors of the food system: Transformation requires consensus and support for the new development pathways being pursued. This involves not only technological choices but also broad-based collaboration and a set of shared values about the desirability of different food system outcomes – e.g. sustainability, provenance, and socioeconomic benefit. Building trust sits centre-stage in this process. All the actors within the food system (whether farmers, consumers or food companies) are highly interconnected through economic and social networks. For systemic change and technological uptake to occur, there often needs to be an iterative process: private industries identify a business opportunity; governments identify the need for systemic change to achieve prosperity and well-being; a dialogue is initiated with citizens to enable attitudinal change; and finally innovations in policy, institutions and public investment encourage market shifts[21,36]. The Green Revolution in Asia provides a good example of these systemic changes at play, as it enabled crop yields to increase rapidly, consumption to increase and undernutrition to diminish in a bit more than a decade[21].

Given that governments may need to play a leading role in facilitating and communicating "why" and "how" to innovate to citizens, high-level agreement about new directions is key. For future food systems, this agreement is critical because of the environmental and ethical concerns around food production and consumption. Such agreement, based on solid and transparent science targets, and dialogue and consensus between public and/or private actors, can legitimise efforts to develop transition pathways, new products, business plans, policies and incentives. Good examples of these are the Sustainable Development Goals and the Paris Agreement greenhouse emissions targets, which are at the centre of the strategies of many national and international public sector departments and private companies.

Managing expectations of different stakeholders can be essential to gain legitimacy and trust. The optimal behaviour from an individual's point of view may strongly depend on the behaviour expected from others. If the benefit of adopting a certain behaviour (e.g., using and/or investing in a specific technology) is perceived as a function of that behaviour's popularity among others, vicious or virtuous cycles of self-fulfilling expectations may arise[37], ultimately accelerating or retarding change. Once again, the Green Revolution of the 1960s provides a good example: the success of a technology depends on its adoption at scale; if an individual does not expect others to adopt it, then this individual's response may be not to do it either. In cases like this, temporary subsidies and other incentives may help tip the system[38].

2. Transforming mindsets: The transformation of agriculture requires a learning mindset by the actors of the food system. A similar attitude to monitoring, review and knowledge generation is needed amongst the various levels of decision-makers. People have deeply engrained biological, psychological (particularly around "naturalness"[39]) and cultural relationships to food[40], so development of an effective technology is no guarantee of social acceptance, as this is not purely determined by factors like price and safety. There is a tripartite relationship between people's attitudes to technology, regulation that can change the structure of the market, and market actors that play out within a regulatory framework. The need to better understand a technology and to transform mindsets arises particularly in the case of technologies whose advantages and disadvantages are still largely unknown (e.g. gene editing, reconfiguring photosynthesis, novel nitrogen-fixing crops).

3. Enabling social license and stakeholder dialogue: Public investment in technology development and uptake should be tied to social licence and technology acceptability. These, in turn, require greater consideration of responsible innovation principles and extensive public dialogue[51]. Rising public awareness of the issues may create pressure from consumers, employees, investors, and government itself, to push innovation in different directions (e.g. meat substitutes, nanopesticides). Without engaging these actors in responsible innovation, potentially powerful technologies may not be adopted (e.g. genome editing). The transformation necessary to tackle society's grand challenges as embodied in global food systems might be constrained by those who trade on a business-as-usual basis. Technological uptake also involves the know-how to use a technology effectively. Higher knowledge-intensive systems often involve more 'learning by doing'[41],[42] and might disadvantage food systems actors with less education such as smallholders or vendors in low-income countries.

4. Guaranteeing changes in policies and regulations: Expectations about future policies are essential for both public and private investments in technological change. For example, investing in research and development of low-carbon technologies is more attractive for private investors if they believe that carbon emissions will have a somewhat stable and attractive price in the future. Once new low-carbon technologies are in place, carbon policies (including pricing) may involve lower social costs, thus being more likely to be implemented. However, if no one expects this to happen, it will probably not happen since few people will find it worthwhile to invest in the technology. As with action point 1, vicious or virtuous cycles of self-fulfilling expectations may arise[37], in which case, policies can help steer expectations in a desired direction[53] –particularly through subsidies or direct investment in low-carbon technologies[43,44].

5. Designing market incentives: The appropriateness of measures and incentives and the factors which are critical to the success of transformational innovations are often context- and technology-specific. The barriers to innovation and diffusion also differ. In competitive markets (such as food and energy), companies often underspend on research and development relative to what would be the optimal expenditure level from a society's perspective, since they typically cover all the costs but are not the sole beneficiaries of the knowledge generated along the process. Historically, governments have sought to correct this market failure by rewarding innovative efforts, including 'market pull' measures – like granting innovators (temporary) monopoly rents through patent protection, complemented by other inducements and subsidies for under-funded priorities (e.g., orphan diseases) – and 'market push' incentives – e.g. tax credits, public procurement, or pricing of externalities. Making these incentives accessible to new entrants is critical, as it is unclear whether transformative innovation will emerge from established industry players[45]. Innovation incubators and accelerators often play a key role in bringing novel solutions to market[52]. This has been the case with many technologies on our list (Fig. 1) across all technology groups (drones, algae for feed, plant-based meat substitutes, nanoenhancers, personalised food). Incentives that drive innovation also differ from those that encourage diffusion.

6. Safeguarding against indirect, undesirable effects: There are real challenges in designing policy and investment frameworks to harness the transformational potential of new technology. Unintended consequences may be overlooked, especially where public acceptance and the regulatory landscape remains to be determined [20,46–48]. For instance, circular economy strategies in the food system must comply with strict regulations from Europe and North America concerning the re-use of organic waste as animal feed (adopted after bovine spongiform encephalopathy and foot-and-mouth diseases outbreaks[49]). A broader public dialogue and consultation is likely to legitimise wider support and/or identify the potential for unexpected impacts. Such broader dialogue can also highlight the complexity behind the science and the trade-offs between adoption/non-adoption, and avoid the lack of social license simply because relevant issues are not sufficiently understood. Yet, as noted above, even when these issues are well understood, a technology may not be socially acceptable if it is thought to go against "naturalness" or existing cultural biases[39-41].

7. Ensuring stable finance: Technologies associated with food and agriculture often involve a physical product which is subject to production seasonality and complex regulations. This poses an additional challenge to their diffusion, especially because the financial environment does not reward the "fail fast and re-start/iterate" model (designed to stop flawed operations and then restart differently). Nonetheless, transformative change is likely to be unpredictable and its impacts variable, so technology exploration and piloting under real world conditions are important to test effectiveness. More creative investment solutions like increased deployment of accelerators or special finance for diffusion, and more steady and longer-term finance for technology development may be needed to drive transformational shifts[50], as the research, development and implementation cycles can be long for a broad range of technologies (e.g. reconfiguring photosynthesis, novel nitrogen-fixing plants and/or perennials, new vaccines, GM-assisted breeding technologies, etc.). Nevertheless, the digitalisation of agriculture and some other technologies could provide ample opportunities to spread and scale transformative solutions, just as mobile banking did on the back of the mobile phone revolution in the 2000s.

8. Developing transition pathways: Most analyses of the future of food systems anticipate the impacts of alternative scenarios and the roles of different strategies (e.g.

diet changes, waste reduction, increased food production)[5, 7, 10-16, 27]. However, these studies rarely shed light on how to implement the desired changes. The 'how' of achieving planned and actionable change is critical towards realising these transformations and is what we call 'transition pathways'. Transition pathways include the necessary understanding of technologies and their impact, desired science targets, transition costs, identification of winners and losers, strategies to minimise adverse effects (socially, economically and environmentally), gradual steps to be taken by different actors, major aspects of institutional reframing (public and private), as well as the systemic innovation required to achieve the expected transformation. In essence, the accelerators proposed here provide critical information for building these pathways.

Figure 3 about here

Conclusions

Food systems currently pose enormous challenges. Technological innovation will surely have a major role to play in the future of food systems, just as society is undergoing immense, transformative advances in telecommunications and renewable energy use. The list of potential food system-related technologies is long. Nevertheless, more robust analyses of the feasibility of technological innovations and their potential impacts are urgently needed. Such studies are technically complex, particularly with respect to uncertainty and the identification of options to pilot new investment streams for funding and research organisations. It is crucial that these studies are designed with a multicultural and socio-political lens to ensure rapid innovation where it matters most, with equity and embracing diversity of thought.

Food system innovations will depend on adequate investment in basic research and development to keep the pipeline flowing, given that many of the technologies identified here may contribute little to the global food system over the next two decades. We also see a great need to bypass the bottlenecks of the enabling environment, especially in lower-income countries where the potential impacts (both positive and negative) of technological innovation may be relatively larger. History shows clearly that innovation produces winners and losers. We need to ensure that social sustainability becomes a higher agenda item, in the short and long term, to address the sectors of society at risk of being left behind.

Finally, and perhaps most importantly, accelerating food systems transitions towards positive, desired states will have to involve societal dialogue. Of the eight elements identified in Fig. 3 for accelerating the systemic transformation of food systems, at least five revolve around building trust, changing mindsets, enabling social licence, developing transition pathways and safeguarding against undesirable effects. Success in all these actions will result in better health, wealth and environmental outcomes; failure will result in much more than a lack of food.

Author contributions

M.H., P.K.T., D.M.C., J.P., J.B. designed the research.
M.H., P.K.T., D.M.C., J.P., A.H., B.L., K.N. wrote the manuscript.
M.H., P.K.T., D.M.C. J.P., J.B., C.G., K.D., J.N. analysed data.
All authors contributed data and edited the paper.

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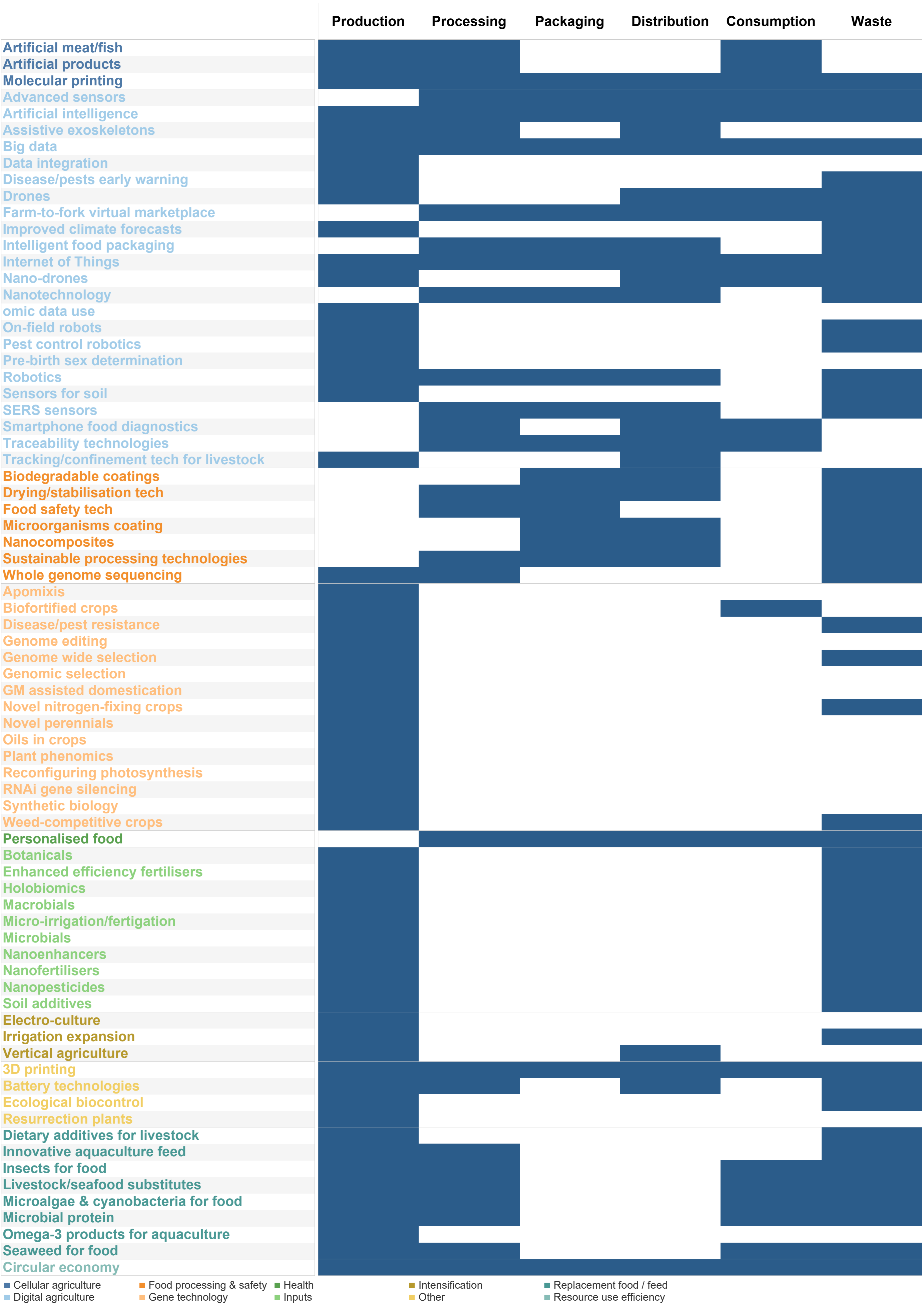
Figure captions.

Figure 1. Future technologies with transformation potential. The technologies are classified under ten groups and span the entire food system. A complete description of each technology is presented in Table S2 of the supplementary information.

Figure 2. Technological readiness of future food system technologies. The technological readiness score is a 9-stage systematic measurement system that supports the assessment of the maturity of a particular technology. Details on each stage, score calculation and technology groups are shown in Table S2 of the supplementary information.

Figure 3. Essential elements for accelerating the systemic transformation of food systems. These accelerators help achieve healthy and sustainable diets, productive agri-food systems and improved waste management - three outcomes necessary to attain sustainable food systems.


Production
Processing
Packaging
Distribution
Consumption
Waste
Artificial meat/fish
Artificial products
Molecular printing
Advanced sensors
Artificial intelligence
Assistive exoskeletons
Big data
Data integration
Disease/pests early warning
Drones
Farm-to-fork virtual marketplace
Improved climate forecasts
Intelligent food packaging
Internet of Things
Nano-drones
Nanotechnology
omic data use
On-field robots
Pest control robotics
Pre-birth sex determination
Robotics
Sensors for soil
SERS sensors
Smartphone food diagnostics
Traceability technologies
Tracking/confinement tech for livestock
Biodegradable coatings
Drying/stabilisation tech
Food safety tech
Microorganisms coating
Nanocomposites
Sustainable processing technologies
Whole genome sequencing
Apomixis
Biofortified crops
Disease/pest resistance
Genome editing
Genome wide selection
Genomic selection
GM assisted domestication
Novel nitrogen-fixing crops
Novel perennials
Oils in crops
Plant phenomics
Reconfiguring photosynthesis
RNAi gene silencing
Synthetic biology
Weed-competitive crops
Personalised food
Botanicals
Enhanced efficiency fertilisers
Holobiomics
Macrobials
Micro-irrigation/fertigation
Microbials
Nanoenhancers
Nanofertilisers
Nanopesticides
Soil additives
Electro-culture
Irrigation expansion
Vertical agriculture
3D printing
Battery technologies
Ecological biocontrol
Resurrection plants
Dietary additives for livestock
Innovative aquaculture feed
Insects for food
Livestock/seafood substitutes
Microalgae & cyanobacteria for food
Microbial protein
Omega-3 products for aquaculture
Seaweed for food
Circular economy
Cellular agriculture
Digital agriculture
Food processing & safety
Gene technology
Health
Inputs
Intensification
Other
Replacement food / feed
Resource use efficiency

Technology Group
Cellular agriculture
Digital agriculture
Food processing and safety
Gene technology
Health
Inputs
Intensification
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Disease/pest resistance
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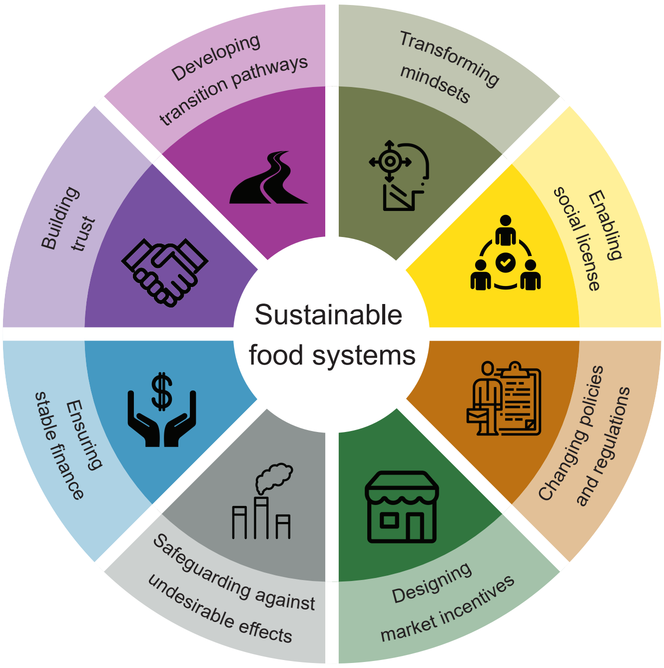
Ecological biocontrol
Novel perennials
Synthetic biology
Reconfiguring photosynthesis
Research Initiated
Experimental Proof
Prototype
Implemented


Sustainable food systems
Transforming mindsets
Enabling social license
Changing policies and regulations
Designing market incentives
Safeguarding against undesirable effects
Ensuring stable finance
Building trust
Developing transition pathways