Perspective
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# Innovation can accelerate the transition towards a sustainable food system

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**Future technologies and systemic innovation are critical for the profound transformation the food system needs. These inno-vations 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 licence. These, in turn, require constructive stakeholder dialogue and clear tran-sition pathways.**

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. 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[1–6]. Yet, as studies have shown, even with wide adoption of existing agricultural technologies, full implemen-tation of flexitarian diets and food waste reduction by half, it will be challenging to feed a growing world population while ensuring planetary well-being[1,7–11].

So far, few studies have explored the boundaries of what would be feasible if the world adopted more disruptive, 'wild', game-changing options[10,12,13] that could accelerate progress in many desired dimen-sions 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 fea-sible across different sectors[14]. Data on investment in agricultural start-ups suggest an increasing portfolio of companies focusing on these technologies[15].

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. The transformational power of a technology depends on the economic and political context, the needs of the society and its socio-economic conditions[16]. Yet, the elements that could catalyse the transformation of the food system through sys-temic 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.

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## Technological innovations

Since Neolithic times, technology has played a considerable role in improving many metrics of human well-being, including pov-erty, life expectancy and disease control[17]. Supplementary Table 1 presents a detailed list of many past technological innovations in the food system. Despite the benefits to humanity of these innova-tions in food and agriculture, deterioration has also been observed of some environmental and health metrics, 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[18–20]. Noncommunicable diseases and inequali-ties are also growing in many societies[11,21] despite rapid technologi-cal advances. The development of inexpensive, fast or discretionary foods has also contributed to significant malnutrition in many parts of the world[21].

Food systems technologies are being developed at an unprec-edented rate, some of which could be deployed in the next decade and significantly transform the food system. We present an inven-tory of near-ready and future technologies that could accelerate progress towards achieving food system sustainability, from exten-sive literature reviews. We classified each technology according to its position in the value chain (that is, production, processing, packaging, distribution, consumption and waste) and its 'readiness score'. The latter, developed by NASA, is a systematic measurement that supports assessments of the maturity of a particular technology (see Supplementary Information for full details)[22–24]. 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[22–24].

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 manage-ment (Fig. 1). Hence, an arsenal of technological options can be tai-lormade 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.

Second, technologies vary widely in their readiness for imple-mentation (Fig. 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 sur-prising 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 pro-viding alternative protein sources, and to reduce its environmental impact by decoupling animal production from land via alterna-tive, 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%[25].

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 dis-ruption, 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 tech-nologies and the need to establish regulatory frameworks and mar-ket 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 becomes clearer, and the manufacturing processes and supply chains are better established.

Fourth, the simultaneous implementation of several of these technologies could significantly accelerate progress towards achiev-ing 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 busi-ness 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[26–32].

## Transformation accelerators

The transformation of the food system will not be purely technolog-ical[16]. At the heart of this process is a form of innovation involving deep changes in the component parts of the food system (technolo-gies, infrastructure, and skills and capability) and a fundamental reformatting of the values, regulations, policies, markets and gov-ernance 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 compro-mise about new directions and pathways. Powerful players within food systems have strong incentives to maintain the status quo and their current market share. By 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 tech-nology. 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 ambig-uous and diverse. Technology may catalyse transformation by triggering regulator shifts (for example, circularity, drones), new market demands (for example, seaweed) and other system inno-vations (for example, personalized nutrition, molecular printing, biodegradable coatings). Alternatively, it may change/evolve in response to system innovations arising from broader societal and political shifts driving transformation[16,32] (for example, growing demand for sustainably sourced produce). Technology may also enhance undesirable lock-ins (for example, a farmer specialized and heavily invested in grain production cannot easily switch to diversified agriculture[33]) . Identifying pathways of change for pre-venting these lock-ins is essential.

Based on this broader understanding of transformation, we propose eight key, largely interconnected action points to acceler-ate technological change and systemic innovation in food systems (Fig. 3).

**Building trust amongst the actors of the food system.** Transform-ation 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— for example, sustainability, provenance and socioeconomic benefit. Building trust sits centre stage in this process. All the actors within


**Fig. 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 Supplementary Table 2.

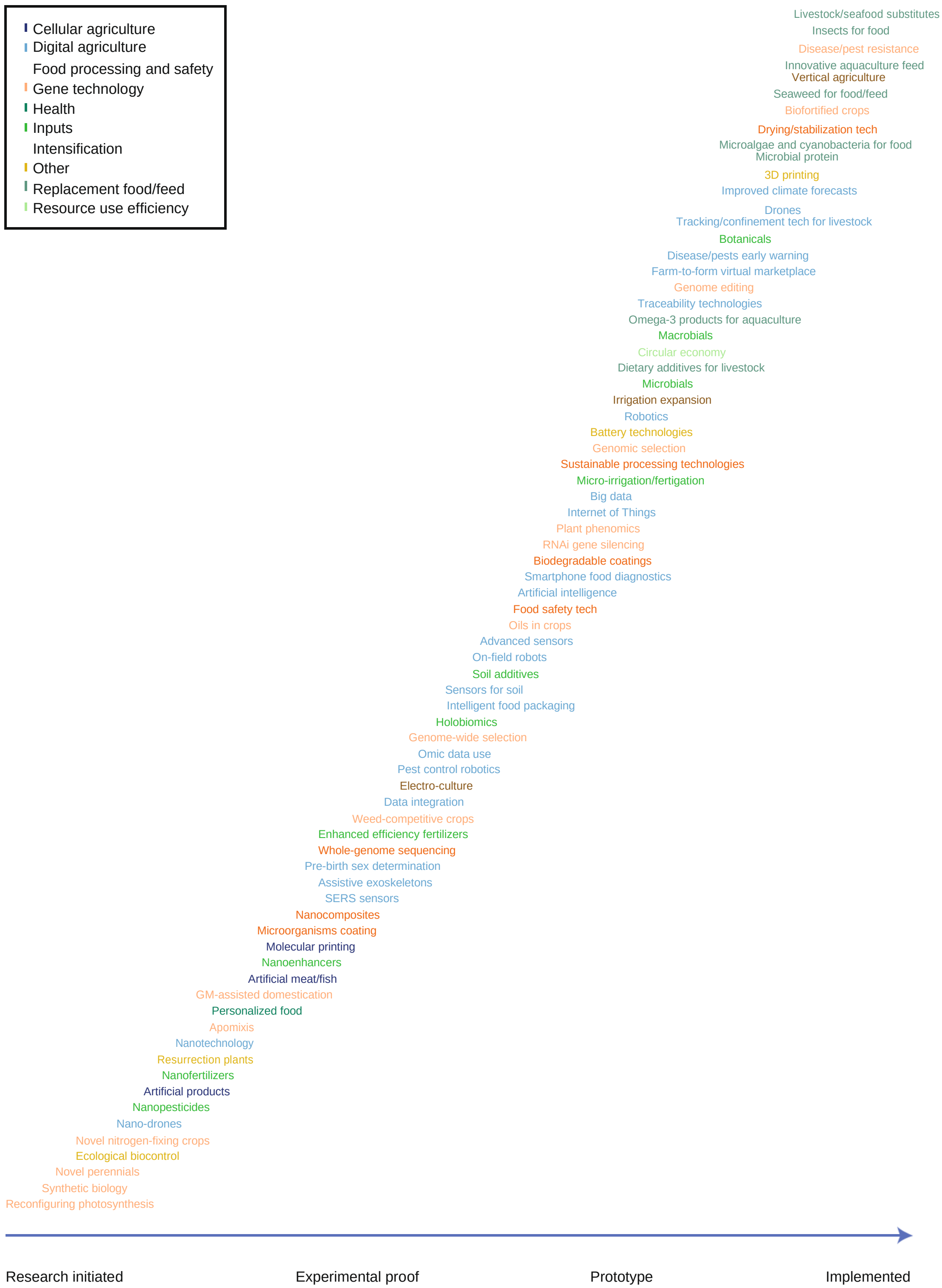


**Fig. 2 | Technological readiness of future food system technologies.** The technological readiness score is a nine-stage systematic measurement system that supports the assessment of the maturity of a particular technology. Details on each stage, score calculation and technology groups are shown in Supplementary Table 2.

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[16,34]. The Green Revolution in Asia provides a good example of these systemic changes at play: it enabled crop yields to increase rapidly, consump-tion to increase and undernutrition to diminish in a bit more than a decade[16].

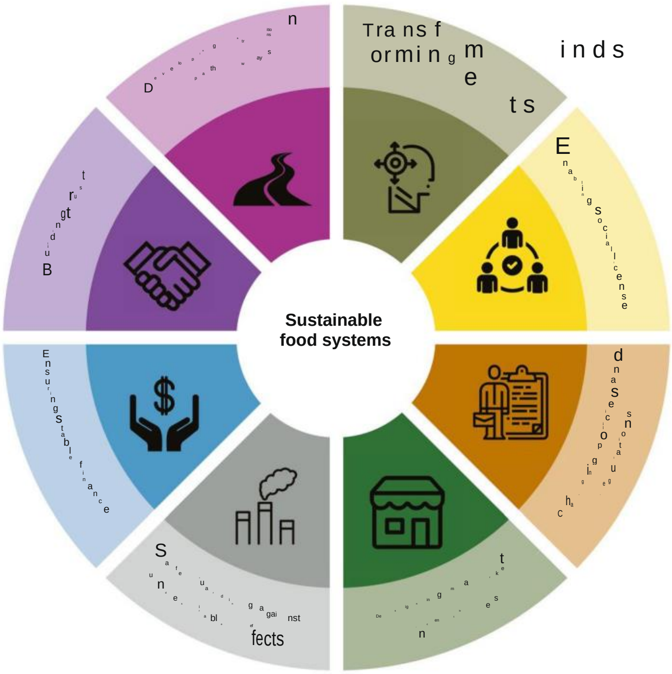


**Fig. 3 | Essential elements for accelerating the systemic transformation of food systems.** These accelerators help achieve healthy and sustainable diets, productive agrifood systems and improved waste management— three outcomes necessary to attain sustainable food systems.

Given that governments may need to play a leading role in facil-itating 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 legitimize 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 green-house emissions targets, which are at the centre of the strategies of many national and international public sector departments and pri-vate companies.

Managing expectations of different stakeholders can be essen-tial 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 (for example, using and/or investing in a specific technology) is per-ceived as a function of that behaviour's popularity among others, vicious or virtuous cycles of self-fulfilling expectations may arise[35], 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[36].

**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'[37]) and cultural relationships to food[33], 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 mar-ket 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 disad-vantages are still largely unknown (for example, gene editing, recon-figuring photosynthesis, novel nitrogen-fixing crops).

**Enabling social licence and stakeholder dialogue.** Public invest-ment 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[38]. Rising public awareness of the issues may create pressure from consumers, employees, investors, and government itself, to push innovation in different directions (for example, meat substitutes, nanopesticides). Without engaging these actors in responsible innovation, potentially powerful tech-nologies may not be adopted (for example, 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'[39,40] and might disadvantage food systems actors with less education such as smallholders or vendors in low-income countries.

**Guaranteeing changes in policies and regulations.** Expectations about future policies are essential for both public and private invest-ments 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 the first action point, vicious or virtuous cycles of self-fulfilling expectations may arise[35], in which case, policies can help steer expectations in a desired direction[41]—particularly through subsidies or direct investment in low-carbon technologies[42,43].

**Designing market incentives.** The appropriateness of measures and incentives and the factors that 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, gov-ernments have sought to correct this market failure by rewarding innovative efforts, including 'market pull' measures, like granting innovators (temporary) monopoly rents through patent protec-tion, complemented by other inducements and subsidies for under-funded priorities (for example, orphan diseases); and 'market push' incentives, for example, 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[44]. Innovation incubators and accelerators often play a key role in bringing novel solutions to market[45]. 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, personalized food). Incentives that drive innovation also differ from those that encour-age diffusion.

**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[15,46–48]. 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 dis-eases outbreaks[49]). A broader public dialogue and consultation is likely to legitimize 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 licence 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[33,37,39].

**Ensuring stable finance.** Technologies associated with food and agriculture often involve a physical product that 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 restart/iterate" model (designed to stop flawed operations and then restart differ-ently). Nonetheless, transformative change is likely to be unpredict-able 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 (for example, reconfiguring photosynthesis, novel nitrogen-fixing plants and/or perennials, new vaccines, GM-assisted breeding technologies). Nevertheless, the digitalization 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.

**Developing transition pathways.** Most analyses of the future of food systems anticipate the impacts of alternative scenarios and the roles of different strategies (for example, diet changes, waste reduction, increased food production)[1,4–11,25]. However, these studies rarely shed light on how to implement the desired changes. The 'how' of achiev-ing planned and actionable change is critical towards realizing 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 minimize adverse effects (socially, economically and environmentally), gradual steps to be taken by dif-ferent 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.

## 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 organizations. 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, espe-cially 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.

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## Author contributions

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

## Competing interests

The authors declare no competing interests.

## Additional information


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