Articulating the impact of food systems innovation on the Sustainable Development Goals

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Abstract

Food system innovations will be instrumental to reaching multiple Sustainable Development Goals (SDGs). However, major innovation breakthroughs can trigger profound and disruptive changes, leading to simultaneous and interlinked reconfigurations of multiple parts of the global food system. The emergence of new technologies or social solutions therefore have very different impact profiles, with favourable consequences for some SDGs and unintended adverse side-effects for others. Stand-alone innovations seldom achieve positive outcomes over multiple sustainability dimensions. Instead, they should be embedded as part of systemic changes that deliver towards the SDGs. Emerging trade-offs need to be intentionally addressed for achieving true sustainability, particularly those involving social aspects like inequality in its many forms, social justice and strong institutions, which remain challenging. Trade-offs with undesirable impacts are manageable through the development of well-planned transition pathways, careful monitoring of key indicators and supported by transparent science targets actionable at local level.

Main body

Humanity faces the grand challenge of reconfiguring food systems to deliver healthy diets that are accessible to all people while safeguarding planetary health. The latest assessment suggests that 11 million deaths annually were attributable to dietary risk factors with the top three being high sodium, low whole grains intake, and low fruit intake [1]. The adoption of healthy diets can reduce the number of premature deaths considerably, while remaining within the safe operating space of a stable Earth system [2,3].

On its own, producing more and healthier food more sustainably will not ensure human well-being. Other crucial challenges must also be addressed such as poverty reduction, social inclusion, increased equity, education and healthcare, biodiversity conservation, sustainable energy, water security, and climate change adaptation and mitigation. These interlinked challenges are embodied in the 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015 and built around the 17 Sustainable Development Goals (SDGs) [4,5]. There is an explicit interdependence of the goals in the framing of the

SDGs. While this points to the synergies between the different goals, it also highlights the trade-offs that need to be reduced to achieve food systems sustainability [6–8].

Herrero *et al.* (2020) recently explored new technology and system-shifting solutions that can help humanity meet the grand challenges we face. In this paper, we identify the potential impacts and interactions of food system innovations in relation to the SDGs. This information is crucial for guiding investment, for policy formulation and for coordinating action throughout the food system to enhance human well-being while safeguarding our planet. In doing so, we make five key points. First, even the most attractive technologies face long, complex pathways to impact the SDGs [9]. An 'impact pathway' articulates the process by which a technology creates change. Complex intermediate factors can accelerate and magnify these impacts, or alternatively, slow and disrupt them. This occurs because innovation in food systems can come in many different forms (social and institutional change, technology), may emerge from different origins (grassroots movements, start-ups) and can be inspired by different values [10]. Second, those complex impact pathways and the closely coupled nature of food systems mean that unforeseen outcomes abound, e.g., environmental externalities or distributional effects. Technologies aimed at addressing one SDG commonly also affect others, potentially having a positive (i.e., a co-benefit) or negative (i.e., trade-off) influence [6,11,12], hence it is important to plan their deployment according to responsible scaling principles [13]. Third, those impact pathways will vary across technologies, SDGs, and distinct food system types, ranging from the rural and traditional systems of many low-income settings to the types supporting industrialised and consolidated settings of high-income, predominantly urban societies [14]. Fourth, the development community has traditionally focussed on silver bullets that often solve one problem and create others. Innovation for system transformation involves disruption, including the intentional and unintentional creation of winners and losers [15]. Policy makers and institutions require both evidence and courage to articulate known trade-offs. Only a combination of measures can reach multiple SDGs simultaneously. Fifth, the disruptive effects of innovation often prompt vigorous political efforts to try to block or delay the deployment of a particular technological breakthrough when it is seen as threatening, even when the net societal benefit of a technology is high. Stand-alone technical solutions are in many cases unlikely to result in exclusively positive impacts, and they are unlikely to be implemented quickly due to pushbacks from veto-players [5]. Socio-technical innovation bundles, combined with policy and institutional reforms, and guided by an overall mission or intentionality [16], may be able to address these challenges and mitigate any unintended adverse outcomes. Only then can we achieve truly sustainable food systems.

Identifying the pathways to impact of technology towards the SDGs

We must strive to understand, project and manage the impact pathways - including the human decision-making processes - through which different technological innovations may operate when deployed at scale, and their potential effects on multiple SDGs. This has been the subject of considerable research in sustainability transitions in multiple sectors [17–19]. Recognising that the pathways to impact may be complex and multi-faceted, here we use four case studies to illustrate potentially far-reaching platform technologies. We highlight the SDG impact that these technologies could deliver, and the potential trade-offs and unintended consequences across time and space that will need to be considered and potentially mitigated by other measures. These examples, built in workshops between some of the authors, are intended as illustrations of possible impacts, rather than a comprehensive analysis of these technologies in a dynamic market setting.

Case study 1. Production of microbial protein from organic waste streams (circular feed)

In the face of population growth and rising income levels demand for animal-source foods, especially in emerging economies, is projected to rise rapidly in coming decades [20,21]. This growing demand relates not simply to consumer preferences for animal-source foods although protein supply is estimated to be more than adequate from a nutrition and health perspective into the future [22], animal source foods will continue to fill a critical micronutrient gap in the diets of the young and vulnerable in many lower-income countries. Nevertheless, novel and previously untapped non-agricultural based protein production pathways could be increasingly important to meet the growing demand both directly (food for human consumption) and indirectly (as inputs to animal production systems) while reducing the negative impact on the environment. In this context, the potential of microbial protein as an alternative protein production pathway has gained widespread attention [23–25]. The term microbial protein is used broadly, including algae, yeast, bacteria and fungi [26]. Microbial protein for animal feed, slow-release organic fertiliser, and human food can be produced from waste streams rich in organics as well as gaseous substrates such as methane, carbon dioxide, and hydrogen [24,25,27]. Microbial protein production is not yet economically competitive as a replacement for conventional soybean but is already a viable alternative for fish meal in aquaculture [28] and human food as a substitute for meat in the form of mycoprotein [29]. Moreover, other microbial protein production processes may also soon become increasingly attractive options under conditions where energy costs decline, conventional feed costs increase, or environmental pollution is taxed. Unlike some plant-based proteins which are capturing a rapidly growing market among high-income consumers, circular feeds and foods may be slower to gain public acceptance [25,27].

Circular feed technology could substantially impact several SDGs both positively and negatively (Figure 1A). For example, microbial protein could reduce the demand for soybean meal currently primarily used for animal feed, it could reduce the profitability of the soybean sector, reducing the expansion of soybean area a recent driver of land-use change, with positive impacts on biodiversity (SDG 15) and greenhouse gas emissions (SDG13). However, soybean produces more than protein. Consequently, reduced soybean oil supply, on the other hand, could result in an increase of palm oil production and consumption, with possible knock-on deforestation effects (SDG 15) and potential increases in non-communicable diseases (NCDs) (SDG 3) [30,31]. Microbial protein could also reduce the demand for fish used for animal feed, which could lead to improved outcomes for fish stocks (SDG 14).

If widely adopted, circular feed could partially decouple the production of protein-rich animal feed from land use, offering a second pathway by which greenhouse gas emissions might be reduced with unclear implications for consolidation of feed supplies, and thus pricing, and market power within the food system. Conversely, cheap feed supply could drive down livestock prices and lead to an increase of livestock product consumption. This might result in increased greenhouse gas emissions and potentially to increased obesity [32,33] and NCDs [34–38] in already high consuming communities (SDG 2). However, increased livestock product consumption in undernourished sub-populations, especially children and pregnant or lactating women, could however help improve their nutritional status and health [39–41]. Lower feed prices may affect the livelihoods and incomes of poor and small livestock farmers (SDG 1).

Circular feed could increase the economic value of waste (SDG 12). This could provide new sources of income from waste collection, distribution, and processing, as well as potential trade-offs with existing livelihood alternatives and their environmental impacts, such as reduced availability of animal manures as a source of organic soil nutrients in mixed crop-livestock systems.

Figure 1 about here

Case study 2. Personalised nutrition

Personalised nutrition (PN) encompasses several individual technologies that can be combined or used in isolation to apply detailed and multidimensional metabolic and health data to better understand human metabolic responses to diet. These include the use of dietary recommendations tailored to individual genetic profiles to maximise health and wellbeing while reducing risk of future disease; microbiome composition mapping aimed at optimising individual gut bacteria; food-on-demand; diet guidance based on personal and group preferences and automatic diet recommendations based on personal nutritional status sensors and genomics, for example [42–45]. PN relies on a wide range of tools, including genomics and phenotyping to arrive at a highly personalised and targeted dietary guidance and interventions [46].

If PN could improve diet, then it could substantially reduce NCDs, increase life expectancy (SDG 3), and generate health care cost savings through reductions in chronic disease, with economic and social co-benefits (Figure 1B). However, whether, how and to what extent PN would encourage the increased adoption of healthy diets is unclear. If PN increased demand for healthy foods, this could stimulate greater supply making a stronger market for fruit and vegetables, which could drive down prices and increase accessibility (SDG 2, 10) [47]. Conversely, a shift in food demand towards healthier dietary alternatives could drive up prices for food rich in essential nutrients and bioactive compounds, making healthy diets less affordable for poorer consumers, thereby aggravating healthy food access and affordability (SDG 2, 10). In addition, a large growth in demand for a particular product could lead to increased agricultural expansion that results in land-use change and biodiversity loss (SDG 15), for example, avocado orchard expansion in Mexico [48]. Increased life expectancy (SDG 3) could also increase population size thereby increasing pressure on food systems and resources in general with flow-on effects to other SDGs. Without changes in retirement ages, increased life expectancy could also increase dependency ratios, putting financial stress on social welfare programs (SDG 1).

PN may allow for market power with personalised price discrimination according to individuals' ability and willingness to pay, leading to increased health and economic inequality within society (SDG 2, 3, 10). Algorithms produced by companies are typically designed to increase revenue (rather than deliver products for public health benefit) and so might persuade consumers to pay for high-priced superfoods that do not necessarily improve their health. PN might increase people's connection to the food system, creating greater consumer demand for ethically sourced food products (SDG 14, 15) and potentially reducing food waste (SDG 12). On the other hand, an increasingly individualised food system may disconnect consumers from food systems potentially reducing social cohesion and consumer responsibility (SDG 11, 12).

PN at scale would result in vast quantities of personal data available for either positive uses (e.g., monitoring food safety) or negative ones (e.g., encroaching on privacy) likely raising concerns amongst consumers [49]. PN is also no substitute for public health infrastructure addressing underlying social, political and economic inequities that are known drivers of dietary patterns and population health outcomes [50]. The extent to which individual differences in responses to diets are really a significant driver of the global burden of diet-related disease remains unclear. Personalised diets also raise a raft of ethical questions with potentially perverse effects: for example, individuals with genetic predisposition to a specific disease (that would otherwise be undisclosed) could face costlier health insurance premiums or exclusion from health insurance.

Case study 3. Automation and robotics in agriculture

Automation and robotics, building on previous advances in mechanisation and precision agriculture, are already in use throughout the food system (e.g., planting and harvesting and environmental monitoring) [51], and have many more prospective uses in the food system [52–54]. Applications include autonomous cropping implements for planting, surveying, nursing, harvesting and handling, robotics for animal husbandry, crop and livestock monitoring, pest control, slaughterhouse operations, and food delivery [51,55–59]. Many large food processing plants, primarily supplying food to urban environments, are highly optimized and automation and robotics improve food safety in many cases. There are very special requirements in terms of hygienic design and special surfaces between product/machine interface; e.g. hygienic grippers for fresh meats; easy to clean and sterilize designs and others.

All these potential uses may reduce the labour and agrochemical costs of food production and processing, but may increase energy costs. Automation could have important human safety impacts, reducing exposure to harmful agrochemicals and dangerous equipment and reducing human injuries (SDG 3, 8) and potentially improve managerial decision-making by reducing cognitive biases. It could improve resource-use efficiency, decreasing harmful agrochemical input use and their ecological footprint (SDG 12, 14, 15). Input waste, through more controlled dosages could also be reduced (SDG 12). Automation could boost the resilience of supply chains by reducing vulnerability to labour supply disruption resulting from pandemics, aging, or lower population growth rates [54]. All these factors could increase and stabilise production and reduce food prices for consumers, thereby reducing hunger (SDG 2) (Figure 1C).

Automation would substantially increase the amount of capital in agriculture, resulting in potential increases in economic and social inequality (SDG 10) as available jobs and income opportunities in commercial agriculture substantially decrease (SDG 8) [53,54]. Greater concentration within subsectors is expected due to economies of scale, and declining diversity as automation works best in more homogeneous production systems. Landscapes could be considerably affected via changes in the size distribution and diversity of farms, having knock-on effects on society, particularly small-scale farmers (SDG 10), and ecosystem services (SDG 14, 15). Automation would decrease the number of relatively unskilled jobs in agricultural production (SDG 8), possibly resulting in more urbanisation due to migration to cities, lower wage rates and greater urban unemployment and poverty, and ultimately in social conflict in the absence of adequate social support. Nevertheless, automation may ease labour shortages in some areas where increasing urbanisation, and aging agricultural labour constrain production. Furthermore, widespread use of robotics would increase the need for skills related to the design, construction and repair of robotic devices. Overall, there could be increased spatial separation of consumption and production, further eroding socio-cultural ties to land and the natural environment for an increasingly urban population [53]. In addition, robotics are vulnerable to disruptions due to breakdown, power supply or hacking. Thus, this innovation may simply trade vulnerability of labour to disruption for vulnerability of machinery to other disruptive mechanisms.

Case study 4. Nitrogen fixation in cereals

The dramatic expansion of cereal production over the past century is partly attributable to sharp expansion in the availability (and reduction in the cost) of synthetic nitrogen fertiliser enabled since the discovery of the Haber-Bosch process. Inefficient use of inorganic fertilisers has both economic and environmental (e.g., water pollution) costs, and is not sustainable [60–63]. Significant advances towards enabling N fixation by crops in which N-fixation does not naturally occur or occurs at low levels have been made. There are several candidate mechanisms, including: transferring the genes that control the development of root nodule symbiosis from legumes to cereals; creating nodule-independent nitrogen-fixing cereals with endophytes that fix nitrogen; gene editing of associative nitrogen-fixing bacteria; and directly introducing nitrogenase into the plant [64–68].

If consumer, environmental, and regulatory concerns about certain methods of genetic engineering can be addressed, nitrogen-fixing crops could reduce the need for inorganic nitrogen fertilisers and the associated input costs, lower food and feed prices (SDG 2), mitigate water pollution (SDGs 6, 14) and emissions of nitrous oxide, a potent greenhouse gas (SDG 13). In order to capture the benefit of less N loss from the use of inorganic fertiliser, the system needs to utilise any residual nitrogen in roots and residues remaining after harvest [69]. Lower prices could, however, also increase demand for both food and feed leading to increased livestock production, reducing (potentially even entirely offsetting) the direct environmental savings (Figure 1D).

The increased protein content of nitrogen-fixing cereals may offset some of the protein dilution that is expected to occur due to increased atmospheric carbon dioxide concentrations [70]. The increased protein may also increase cereal use as a livestock feed. Lower prices for cereals and animal sourced foods might increase their consumption and reduce dietary diversity and potentially result in more NCDs (SDG 3). By enabling substantial reductions in inorganic fertiliser use, nitrogen-fixing cereals in a well-managed system would decrease the energy and pollution footprint of crop production and increase soil fertility, generating benefits for biodiversity (SDG 12, 14, 15).

Socio-economic factors mediate the impact of novel technologies

The key mediators between the introduction of a new technology and its impacts are wide ranging. They involve a cascade of responses across multiple parts of the food system to enable the deployment of new technology and direct its use in socially and environmentally responsible ways [17,71]. These adaptations include social dimensions such as practices, capabilities, preferences and values, policy and regulatory dimensions, adaptation in business models and the development of new value propositions, but also complementary technological adaptations. Crucially, innovation arises not through standalone breakthroughs by individual inventors or firms, but rather through multiple incremental contributions by across private, public and civil sector sectors [72,73]. No innovation leads to exclusively positive outcomes, and the ends to which innovation is deployed involves choices [16]. These choices frame the direction of innovation activity and reflect the political economy surrounding those choices, with winners benefitting from creative destruction while losers suffer harm to health, wellbeing, environment and economic opportunities. Food system innovation is therefore far more than merely a scientific, commercial, or technological matter and requires the incorporation of aspects of social justice and different transition pathways for different actors to be truly sustainable [54,74]. These transition pathways must include all the activities designed for achieving planned, intentional, and actionable change towards the attainment of key goals, in this case the SDGs (Herrero et al 2020).

Food transformations are often erroneously attributed solely to an emblematic technology that was central to their realisation, while the critical enabling social and political conditions get overlooked. For example, the Asian Green Revolution, which genuinely transformed food systems in the region, with both positive and negative impacts [75], was not just a result of the development of input-responsive high yielding crop varieties, the emblematic technology of the era. The transformation required a system of public investments in irrigation, transportation and communications infrastructure, input supply arrangements, public pricing and procurement systems. It also required a set of shared values among a group of philanthropic and government agencies committed to financing an international public good made freely available to breeding programs worldwide, and a cadre of skilled scientists and extension agents to both develop and extend the new technology in distinct social and biophysical contexts. Half a century later, these same technologies have failed to transform sub-Saharan African food systems precisely because these enabling factors have not yet emerged. Other examples of widespread impact from technological innovations are similarly multidimensional: the diffusion of hybrid maize varieties in North America in the 1930s-50s, the eradication of Rinderpest (cattle plague), improved nutrition from biofortified orange-fleshed sweet potato and golden rice, compressed refrigeration and cold chain logistics. All these examples reinforce the point that in order to achieve impacts at scale, emblematic technologies require a complex supporting set of what Herrero et al., (2020) termed 'transformation accelerators'.

Eight essential socio-cultural, behavioural, economic, and political factors affect whether technologies emerge and scale and drives the impact that they have on society, the environment and thus the SDGs [5]. Which of these elements most impactfully combines with which technology depends fundamentally on the context, on human agency [76] and on opportunities for reflective learning [54,77]. Food transformations are likely to have the right enabling conditions in regions performing well across many of the SDGs, resulting in a technology trap which can lead to exacerbation of inequalities. The key point is the need for "socio-technical bundles": appropriately contextualised combinations of science and technology advances that when combined with specific institutional or policy adaptations show particular promise for advancing one or more SDGs in that setting [76]. The task of discovering, adapting, and scaling transformational innovation is as much one for social scientists as it is for natural scientists [54,77].

Table 1 draws on the Herrero *et al.* (2020) framework to illustrate some essential elements for advancing beneficial impacts from the four example technologies discussed earlier. "Building trust" is largely about working towards a high-level consensus on what future food systems might look like and the outcomes they might produce. Trust in the ability of the technology to help deliver on these outcomes is key, particularly with respect to the processes that might be needed to deal with intermittent problems or failure. "Transforming mindsets" recognises the deeply engrained cultural relationship that many people have with food. All four technologies above have characteristics that challenge people to modify the way they think about food and the values that shape their choices [78]. "Enabling social licence" accepts that public trust in genuinely responsible innovation must be built and maintained, and a large part of that is fostering and maintaining a social contract between researchers and the other actors in the food system. "Changing policies and regulations" is about fulfilling expectations of support for the technology – whether for the innovator (e.g., ensuring that health and safety standards for the technology are in place, appropriate and enforceable), the consumer (e.g., clear labelling), or other food system actors. “Designing market incentives” recognises that there may be massive start-up costs and risks in deploying new technology at scale, and that these costs and risks may need to be spread well beyond the innovators themselves, and that there is a public policy responsibility to ensure that new innovative directions and opportunities are aligned to sustainability. “Safeguarding against undesirable effects” has implications for the monitoring and analysis of the early stages of upscaling highly innovative technology, as well as agreed-upon plans for taking corrective or redistributive action when necessary. “Ensuring stable finance” can help to address the challenges of diffusing innovations that, in the food system, are more often akin to a “fail slowly and iterate with difficulty” model rather than a “fail fast and re-iterate quickly” model that is better suited to an environment characterised by very rapid change. All these elements are brought together in “developing transition pathways”, which address the specific sequence and timing of actions that may be needed for a specific technology to contribute to a food system that is better aligned with society’s objectives.

Interactions amongst the SDGs and the role of technological innovations

Technologies inevitably vary in their extent and focus of impact across food system-related SDGs. But as our prior discussion emphasised, no technology touches just one SDG. The SDGs overlap and may not all be mutually reinforcing; on the contrary, trade-offs can and do exist [79–81]. Currently there are 232 indicators for the 17 SDGs at country level (see unstats.un.org/sdgs/indicators/indicators-list/). Studies have analysed these data for synergies and trade-offs between the SDGs [6,82]. There are many synergies between different SDGs at a country level, although some trade-offs too. There can also be trade-offs between the different indicators within a single SDG. There may be interactions at other scales as well; for example, there are trade-offs between different SDGs at the farm household, with respect to both the under- and over-application of nitrogen fertiliser [4,61].

Herrero and colleagues [5] collated an inventory of anticipated technologies that could accelerate progress towards achieving the food-systems SDGs . Using the technologies and scoring approach from Herrero and colleagues [5], we utilised an expert elicitation process to map the potential impacts of technologies in eight groups of food system technological innovations against the eight SDGs most directly associated with the food system (See SI). Experts offered quite varied assessments of the likely impacts of different food system technologies on those eight SDGs (Figure 2). For SDGs 1 (No poverty), 6 (Clean water and sanitation) and 14 (Life under water), in particular, there was some diversity of opinion as to the whether some technologies may have negative or positive impacts. This highlights the necessity of broader civil society dialogue to identify and avert predictable, negative, unintended consequences of technologies that aim to advance key SDGs, and the need for socio-technical bundling.

Figure 2 about here

We used updated data from Pradhan and colleagues [6] to estimate potential secondary impacts on the other nine SDGs that the technologies were not scored against, based on the probability of a synergistic, neutral or antagonistic effect between each pair of SDGs (see SI). Results for the various technology groups are shown in Figure 3. There are broadly synergistic "secondary effects" on SDGs 5 (Gender equality) and 7 (Affordable and clean energy). There are more varied effects on SDG 8 (Decent work and economic growth) and SDG 10 (Reduced inequalities). Technologies related to inputs and waste reduction, particularly, may have antagonistic effects on equity considerations, also mirrored in SDG 16 (Peace, justice and strong institutions). Technological innovations may help advance SDGs 2 (Zero hunger), 3 (Good health and wellbeing), 15 (Life on land) or others closely connected to the food system within which they are developed and evaluated. But ignoring prospective unintended indirect effects does not avoid them, and the potential for unintended negative impacts is great in the absence of concerted efforts to ensure safety net protections for prospective losers from technological change.

These results are indicative only, but they highlight the need to investigate the potential multi-sectoral interlinkages that may arise from optimised portfolios of new and old technologies. This would be a prerequisite for understanding the possible negative consequences of different technologies and examining alternative actions that could help to offset them. Although envisaging the consequences of as-yet undeveloped technologies is challenging, this type of framework may assist in evaluating their broader impacts. This calls to the integration of economics and natural sciences with a rich array of social sciences studying different facets of transformation in multiple sectors, including transition management [83,84], responsible research and innovation thinking [54,77,85], interactive design [86], responsible scaling and scaling readiness [13], complexity aware evaluation [87,88] and transdisciplinary sustainability science for (food systems) transformation [14,89].

Figure 3 about here

Conclusions

'Nothing vast enters the life of mortals without a curse' Sophocles 497-406 BC.

Progress on achieving the SDGs is imperative, but also difficult. A vast array of scientifically promising agricultural and food system technologies is poised to enter common use in the coming years in a wide range of contexts. These innovations can help advance multiple policy objectives in the context of sustainable development. But we must all beware the Sirens' call of 'win-win' technological solutions and commit to the discipline of exploring and addressing likely perverse incentives, human decision-making patterns, unintended and indirect effects, and resulting trade-offs. The long, complex impact pathways from the release of exciting new technologies to societal impacts necessarily run through a host of socio-cultural, economic, ethical, and political mediators that can accelerate or impede progress and that inevitably influence the trade-offs or synergies across different SDGs. Managing those accelerators thoughtfully will require dialogue and cooperation from a wide array of public, private and civil society sector actors; [90] go as far as suggesting that one of the 11 levers of transforming food systems is engaging with, and instilling science in, social movements.

Innovation in the agri-food system cannot, therefore, be understood without recognising the influence of wider processes of technological change relating, for example, to energy, health, and the deployment of platform technologies such as artificial intelligence that have pervasive effects across multiple economic and social sectors. The way that different technologies interact produces powerful new possibilities, but also unpredictable outcomes and predictable but easily overlooked collateral benefits or damages. Careful thinking about the likely impacts of innovation in agri-food systems will require a clear examination of the complex pathways from technology development to its deployment and impacts, and being alert to unintended consequences to ensure they do not create unacceptable damage or conflict with approaches to ensure social justice. These are essential aspects for achieving the human and planetary health that we aspire to. It is imperative to co-develop regulatory and socio-economic support mechanisms and environmental, social and corporate governance standards [91] in order to harness these new technological capabilities towards delivering superior human and planetary development outcomes. This will also require the further development of modelling and analytical techniques to better quantify and understand the multiple impacts and trade-offs between desired objectives and the innovations we hope will help us achieve them.

As Sophocles reminds us, change and innovation come with trade-offs, but we now have methods, the science, the targets and the socio-economic mechanisms in place to ensure that the trade-offs of our actions do not become unsurmountable. Now is the time to put our arsenal of socio-technical innovation and immense human ingenuity to use, to secure the future of our planet and the next generations.

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Contributions

M.H., D.M-D., J.P and P.K.T. planned the paper; M.H., DM-D, J.P., P.K.T., B.B., C.B.B., and P.P. wrote the manuscript, all authors contributed data and edited the paper.

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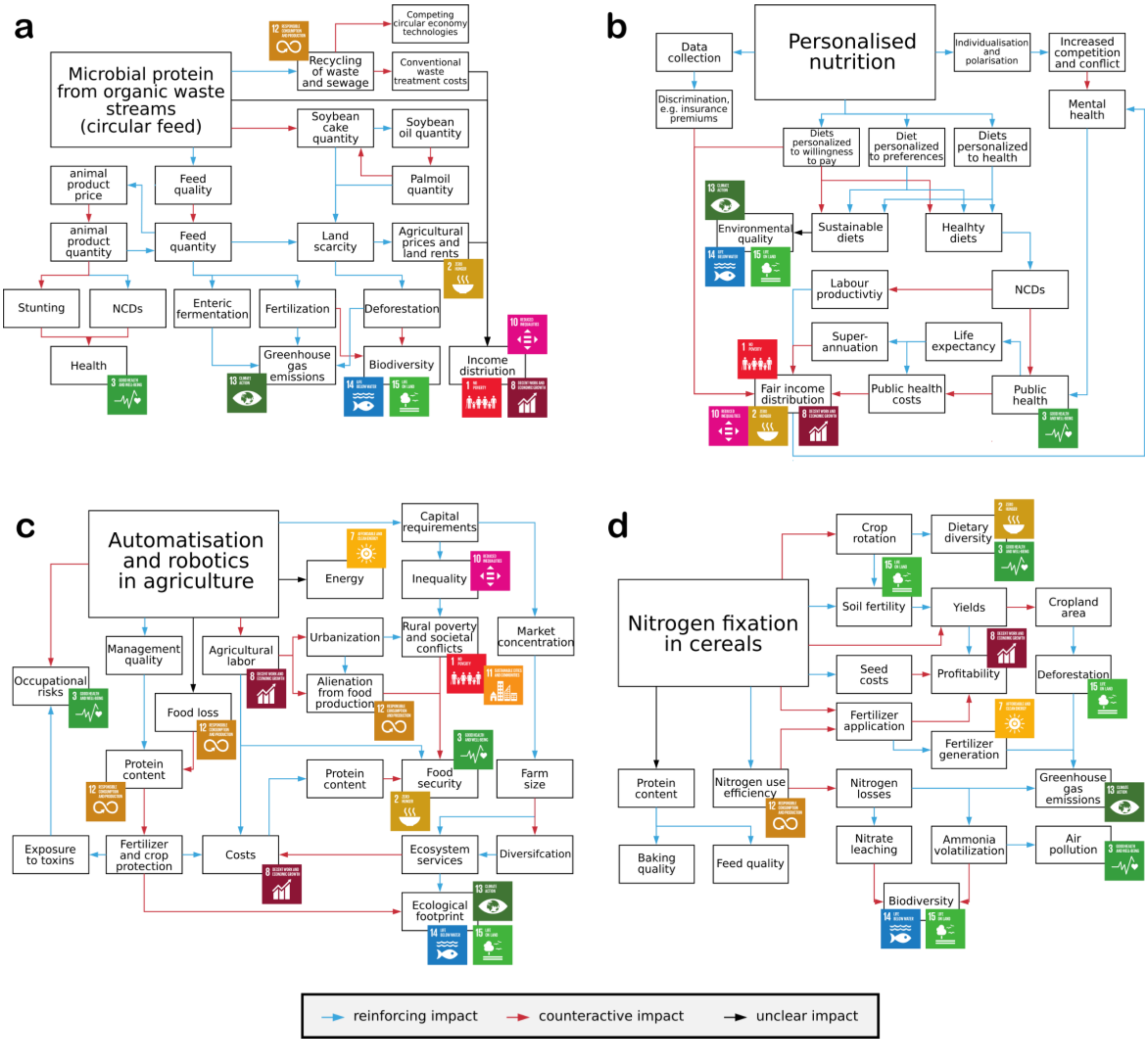

Figure 1. Potential impact pathways of four case study technological innovations towards the food-related SDGs: (A) Production of microbial protein from organic waste streams ('circular feed'); (B) Personalised nutrition (C) Automation and robotics in agriculture (D) Nitrogen fixation in cereals. Blue (red) arrows depict positive (negative) expected net impacts.

Table 1. Essential elements for developing and scaling beneficial impacts, with illustrations from the four case-study technologies (microbial protein from organic waste streams; personalised nutrition; automation in agriculture; nitrogen fixation in cereals).

Elements for Food System Transformation	Examples
Building Trust amongst Actors in the Food System Vision and Values	**For all Case Studies** • Build trust of “profit with a purpose” or “system positive benefits” • Foster transparent production, distribution, and management processes • Build trust in regulatory bodies that define/enforce environmental, health, and safety standards **Specific to the Personalised Nutrition Case Study** • Develop a health-centric technology platform that balances short- and long- term objectives • Provide clear recommendations that recognise individual autonomy and diversity of choices
Transforming Mindsets Acceptance	**For all Case Studies** • Encourage acceptance of highly technological production and handling of food and feeds **Specific to the Microbial Protein from Organic Waste Steams Case Study** • Recognise waste of all types as by-products that can serve as valuable inputs to other processes • Accept feed production from organic waste streams, including animal and human waste
Enabling Social License and Stakeholder Dialogue Responsibility	**For all Case Studies** • Engage with stakeholders across society, including amongst consumers, labour, and producers, to ensure technologies are developed and implemented transparently **Specific to the Nitrogen Fixation in Cereals Case Study** • Focus on food quality to ensure new crops are as good if not better than alternatives • Demonstrate improved environmental footprint, that reduces input use and waste • Avoid vertical integration models that would raise concerns around industry collusion
Ensuring Stable Finance Explore and Pilot	**For all Case Studies** • Clear commitment to long-term goals to encourage stakeholders to reorient investment • Government soft loans, guarantees and tax breaks linked to SDGs and ESG criteria • Encourage alternative funding mechanisms to promote responsible innovations • Encourage long-term financing recognising extended timelines for full returns on investment • Ensure financing does not reinforce existing inequalities **Specific to the Automation in Agriculture Case Study** • Encourage the application of proven automation technologies in new agricultural settings to increase visibility and perceived viability in agri-food systems
Designing Market Incentives Spread Cost and Risk	**For all Case Studies** • Target fiscal and trade policies to foster initial markets to achieve economies of scale • Invest in programs to increase awareness of new technologies and their appropriate use • Improve costing of externalities at source to facilitate the competitiveness of new approaches **Specific to the Microbial Protein from Organic Waste Steams Case Study** • Increase the cost of waste to encourage alternative use (e.g. increase waste handling fees) • Provide price support for key inputs to reduce production costs • Target support to conventional feed sectors to transition to alternative production
Changing Policies and Regulations Expectations of Support	**For all Case Studies** • Revise and streamline coherent policies and regulations to ensure appropriate supervision and enforcement of environmental, social, health, and safety standards throughout food systems • Reduce economic and bureaucratic constraints to technological adoption and diffusion **Specific to the Personalised Nutrition Case Study** • Implement clear standards on nutritional and health labelling • Ensure independent oversight of health and nutritional claims • Improve regulation of the food environment, which shapes personal consumption choices
Safeguarding Against Undesirable Effects Monitor and Correct	**For all Case Studies** • Independent, transparent, and capable regulatory bodies to supervise and enforce standards • Develop global environmental, labour, and trade standards to avoid offshoring of externalities • Require investments to increase use of impact assessments and other safeguarding principles • Require mandatory ESG disclosure and SDG reporting, particularly among large investors **Specific to the Nitrogen Fixation Case Study** • Monitor land use, to ensure technology adoption helps reduce the footprint of food systems • Monitor more broadly adverse impacts (e.g. biodiversity) of increased adoption of novel crops • Monitor soil nitrogen levels to inform nitrogen surplus taxation to avoid over-fixation
Developing Transition Pathways How and When	**For all Case Studies** • Build transition pathways on a foundation of all the elements above • Ensure that everyone, including those disadvantaged, can benefit from innovation • Apply adaptive approaches that adjust to changing circumstances and unexpected consequences • Focus on achieving big-picture outcomes rather than on specific technologies • Local, national, and international commitment with appropriate resource allocation **Specific to the Automation in Agriculture Case Study** • Promote healthy, safe, productive employment to achieve equitable and responsible production

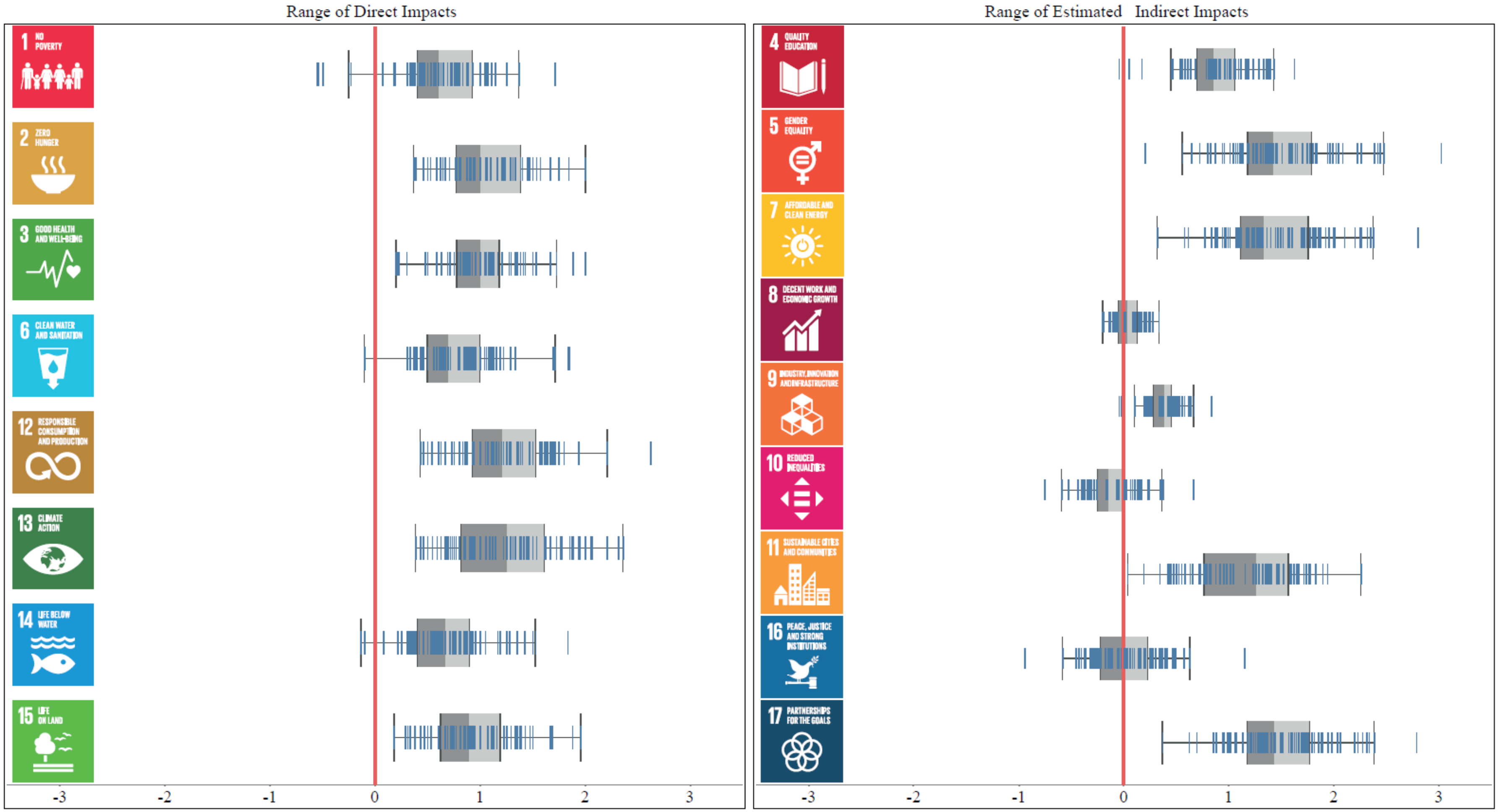

Figure 2: Range of potential impacts of anticipated technologies across SDGs. Direct impacts are those that occur on the SDGs that directly relate to food systems. Indirect impacts are those mediated through the impacts of food systems technologies on non-food system related SGDs. The small blue bars represent an average score of all respondents for an individual technology.

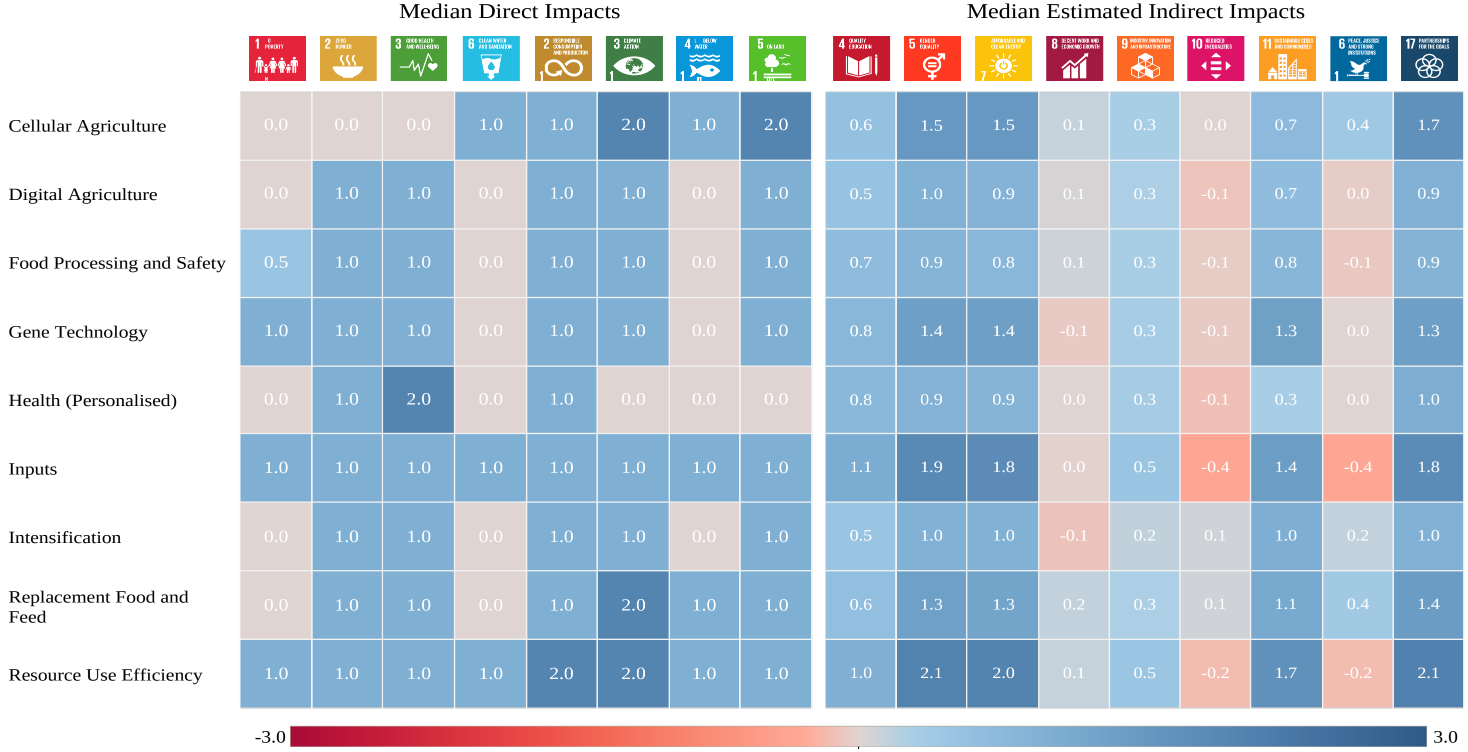

Figure 3. Direct impacts of different technology domains on the food systems-related SDGs (left) and their indirect effects on the rest of the SDGs (right). Indirect effects are mediated via the interactions between SDGs as quantified by Pradhan et al. (2017). Dark, mid and light blue squares represent strong, moderate or weak positive impacts and/or interactions, respectively. Grey and red squares represent neutral or negative interactions and/or impacts, respectively. Numbers represent median scores for each impact.

10