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

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Food system innovations will be instrumental to achieving 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 facilitate the implementation of the SDGs. Emerging trade-offs need to be intentionally addressed to achieve 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 consequences are manageable through the development of well planned transition pathways, careful monitoring of key indicators, and through the implementation of transparent science targets at the local level.

Introduction

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, the Global Burden of Diseases, Injuries, and Risk Factors Study 2019, estimates that 8 million deaths were attributable to dietary risk factors.[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]

Simply producing a larger volume of food and healthier food more sustainably will not ensure human wellbeing. Other crucial challenges must also be addressed, such as poverty reduction; social inclusion; increased equity, education, and health care; 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 UN member states in 2015 and built around the 17 Sustainable Development Goals (SDGs).[4,5] There is an explicit interdependence of the goals within the SDGs. Although this feature of the design of the SDGs points to the synergies between goals, it also highlights the trade-offs that need to be reduced to achieve food systems sustainability.[6–8]

Previously, we explored new technology and system-shifting solutions that can help humanity meet the grand challenges it faces.[5] In this Personal View, we identify the potential consequences of, and interactions between, food system innovations in relation to the SDGs. This information is crucial for guiding investment and policy formulation, and for coordinating action throughout the food system to enhance human wellbeing while safeguarding our planet. In doing so, we make five key points. First, even the most attractive technologies face long, complex pathways to affect the SDGs.[9] A so-called impact pathway describes the process by which a technology creates change. Complex intermediate factors can accelerate and magnify these effects, or alternatively, slow and disrupt them. These dissimilar outcomes can occur because innovation in food systems can come in many different forms (eg, social and institutional change, and technology), might emerge from different origins (eg, grassroots movements and 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 (eg, environmental externalities or distributional effects). Technologies aimed at addressing one SDG commonly also affect others, potentially having a positive (ie, a co-benefit) or negative (ie, a trade-off) influence;[6,11,12] hence it is important to plan their deployment according to responsible scaling principles.[13] Third, impact pathways 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 focused on so-called silver bullet solutions 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. Lastly, 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

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the net societal benefit of a technology is high. Standalone technical solutions are in many instances unlikely to result in exclusively positive effects, and they are unlikely to be implemented quickly because of pushbacks from players wanting to maintain the status quo.[5]

Sociotechnical innovation bundles (ie, 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), combined with policy and institutional reforms, which are guided by an overall mission or intentionality[16] might be able to address these challenges and mitigate any unintended adverse outcomes.[17] Only then can truly sustainable food systems be achieved.

Identifying the impact pathways 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 might operate when deployed at scale, and their potential effects on multiple SDGs. This issue has been the subject of considerable research in sustainability transitions in multiple sectors.[18–20] Recognising that the impact pathways could be complex and multifaceted, here, we use four case studies to show potentially far-reaching platform technologies. We highlight the effects on the SDGs that these technologies could deliver, and the potential trade-offs and unintended spatiotemporal consequences that will need to be considered and potentially mitigated by other measures. These examples, built in workshops between the authors, are intended to show possible effects, 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.[21] Animal-source foods will continue to fill a crucial micronutrient gap in the diets of young and vulnerable populations in many low-income countries.[22] Nevertheless, novel and previously untapped non-agricultural based protein production pathways could be increasingly important to meet the growing demand both directly (ie, food for human consumption) and indirectly (ie, as inputs to animal production systems), while reducing the negative effects 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, and includes algae, yeast, bacteria, and fungi.[26] Microbial protein for animal feed, slow-release organic fertiliser, and human food can be produced from waste streams that are 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 the 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 could also soon become increasingly attractive options under conditions in which energy costs decline, conventional feed costs increase, or environmental pollution is taxed. Unlike some plant-based proteins that are capturing a rapidly growing market among high-income consumers, circular feeds and foods might be slower to gain public acceptance.[25,27]

Circular feed technology could substantially affect several SDGs, both positively and negatively (figure 1A). For example, microbial protein could reduce the demand for soybean meal that is currently mainly used for animal feed, reduce the profitability of the soybean sector, reduce the expansion of soybean cultivating areas (a recent driver of land-use change), and have positive effects on goals relating to biodiversity (SDG 15) and greenhouse gas emissions (SDG 13). However, soybean produces more than protein. Consequently, reduced soybean oil supply could result in an increase of palm oil production and consumption, with possible knock-on deforestation effects (SDG 15) and lead to 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 partly 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 consequence might result in increased greenhouse gas emissions and potentially to increased obesity[32,33] and NCDs[34–38] in communities that already have high levels of meat consumption (SDG 2). However, increased livestock product consumption in undernourished subpopulations, especially in children and in women who are pregnant or lactating, could help improve their nutritional status and health.[39–41] Lower feed prices could affect the livelihoods of small-scale livestock farmers (SDG 1).

Circular feed could also increase the economic value of waste (SDG 12). This consequence 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 effects, such as reduced availability of animal manures as a source of organic soil nutrients in mixed crop–livestock systems.

Case study 2: personalised nutrition

Personalised nutrition encompasses several individual technologies that can be combined or used in isolation to apply detailed and multidimensional metabolic data and health data to better understand human metabolic responses to diet. These technologies include the use of

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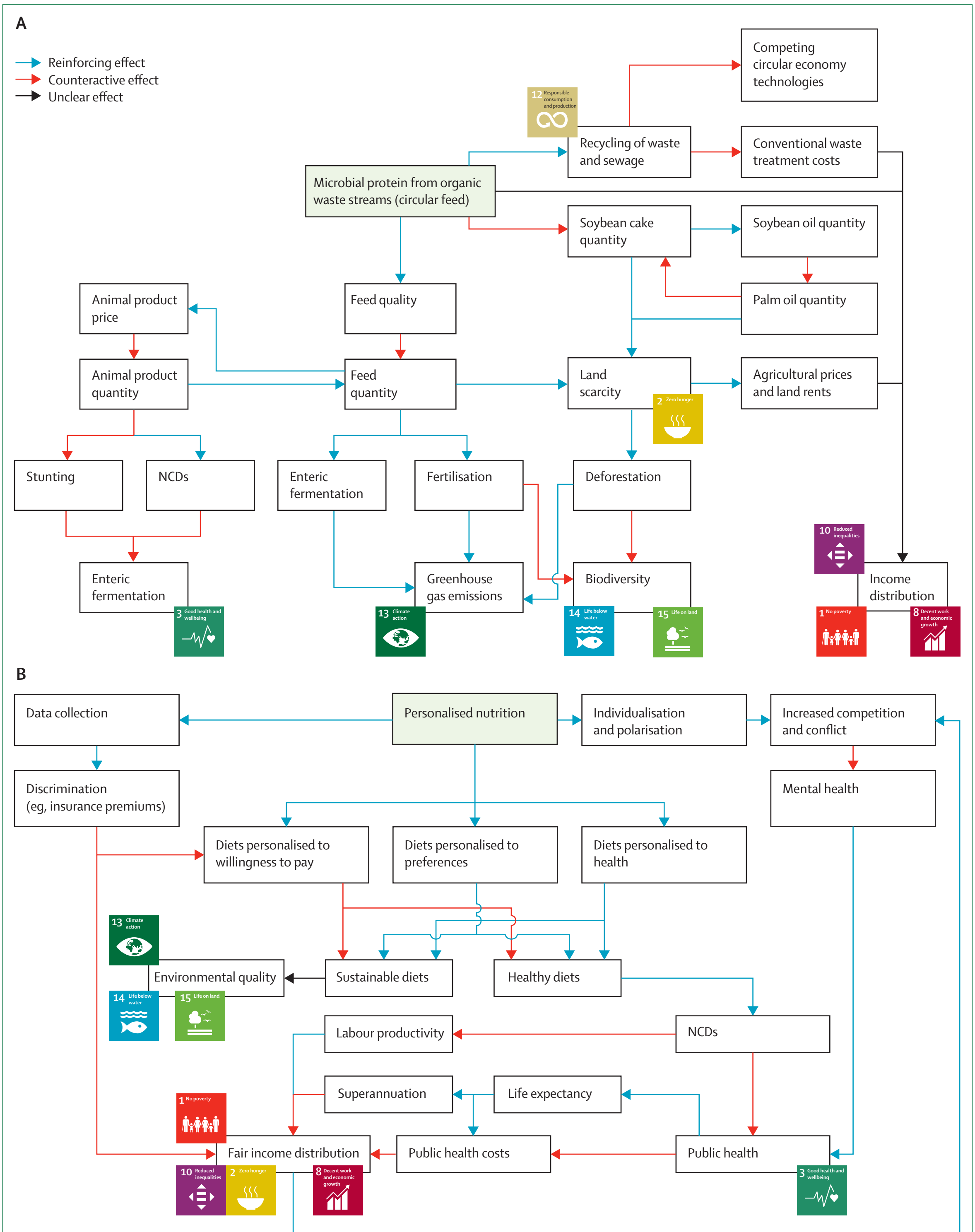

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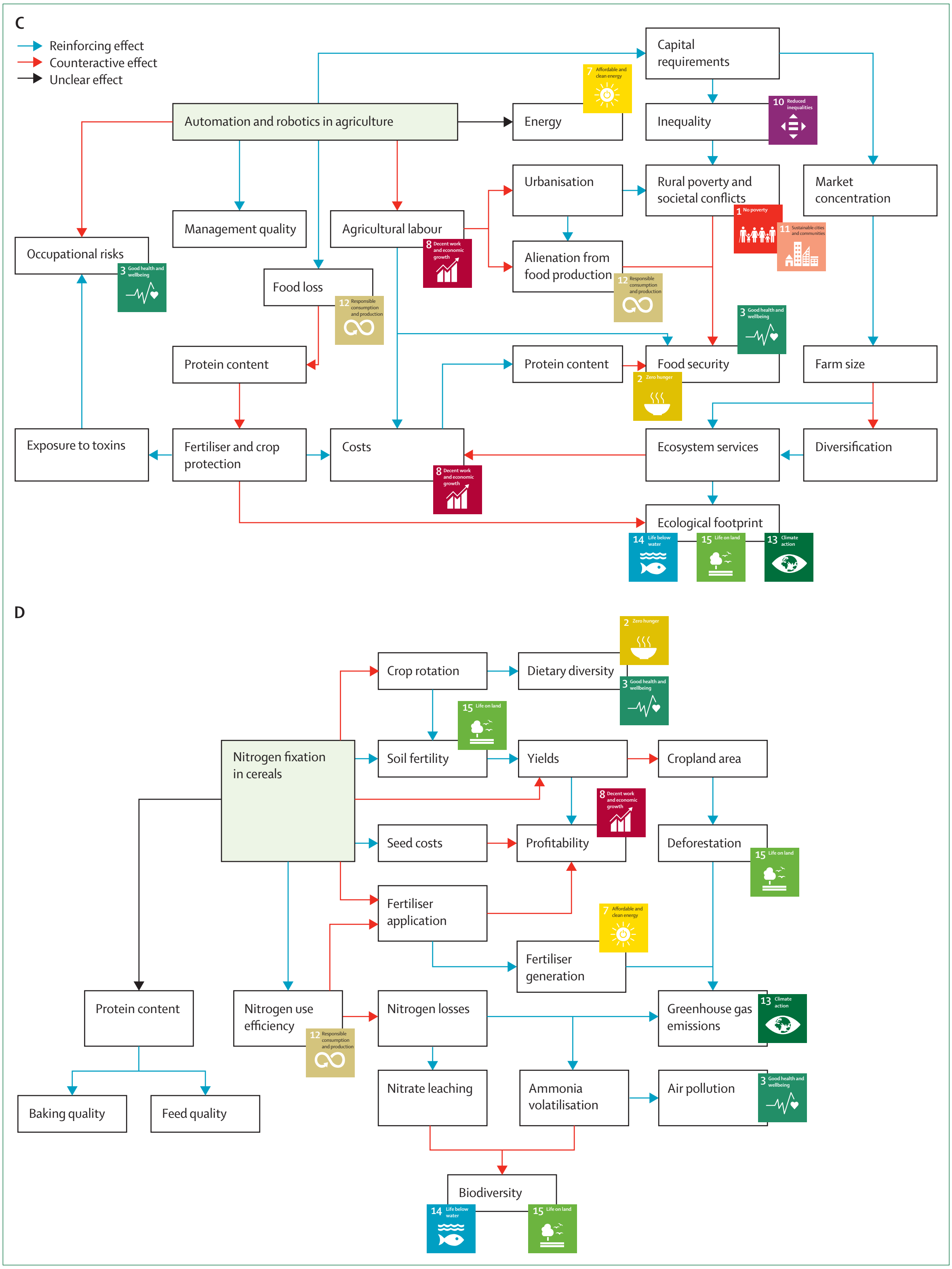

Figure 1: **Potential impact pathways of four case study technological innovations towards the food-related SDGs**
(A) Production of microbial protein from organic waste streams (circular feed). (B) Personalised nutrition. (C) Automation and robotics in agriculture. (D) Nitrogen fixation in cereals. NCDs=non-communicable diseases. SDG=Sustainable Development Goal.

dietary recommendations tailored to individual genetic profiles to maximise health and wellbeing and reduce risk of future disease; microbiome composition mapping aimed at optimising individual gut bacteria; food-on-demand (ie, food purchased with a specific composition personalised to individual requirements); and diet guidance based on personal and group preferences and automatic diet recommendations based on personal nutritional status sensors and genomics.[42–45] Personalised nutrition 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 personalised nutrition 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 personalised nutrition would encourage the increased adoption of healthy diets is unclear. If personalised nutrition increases the demand for healthy foods, this could stimulate greater supply of these foods, creating 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, thereby making healthy diets less accessible for poorer consumers (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, the 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 knock-on effects to other SDGs. Without changes in retirement ages, increased life expectancy could also increase dependency ratios, putting financial stress on social welfare programmes (SDG 1).

Personalised nutrition might result in 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. Personalised nutrition might increase the consumer'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). Conversely, an increasingly individualised diet could disconnect consumers from food systems, potentially reducing social cohesion and consumer responsibility (SDG 11, 12).

Personalised nutrition at scale would result in vast quantities of personal data available for either positive uses (eg, monitoring food safety) or negative ones (eg, encroaching on privacy), which is likely to raise concerns among consumers.[49] Personalised nutrition 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 a major driver of the global burden of diet-related disease is 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 (eg, planting, 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.[51,55–57] Many large food processing plants, primarily supplying food to urban environments, are highly optimised and automation and robotics improve food safety in many instances. There are specific requirements for the hygienic design of special surfaces between the product and machine interface (eg, hygienic grippers for fresh meats that are easy to clean and sterilise).

All these potential uses could reduce the labour and agrochemical costs of food production and processing, but could also increase energy costs. Automation could have important benefits to human safety by reducing exposure to harmful agrochemicals and dangerous equipment, reducing human injuries (SDG 3, 8), as well as by potentially improving managerial decision making by reducing cognitive biases. Automation could also improve resource-use efficiency by 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). Moreover, automation could boost the resilience of supply chains by reducing their vulnerability to labour supply disruption resulting from pandemics, ageing, or lower population growth rates.[54] All of 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 of share of production, processing, and income within subsectors is expected due to economies of scale, and declining diversity as automation works best in more homogeneous production systems (eg, cereal, vegetable, and fruit monocultures). Landscapes could be considerably affected via changes in the size distribution and diversity of farms, which could have knock-on effects on society, particularly on small-scale farmers (SDG 10) and ecosystem services (SDG 14, 15). Automation would decrease the number of unskilled jobs in agricultural production (SDG 8), possibly resulting in more urbanisation due to migration to cities, lower wage rates, greater urban unemployment and poverty, and, ultimately, possible increases in social conflict in the absence of adequate social support. Nevertheless, automation could ease labour shortages in some areas where increasing urbanisation and ageing agricultural labour restrict production. Furthermore, widespread use of robotics could 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 sociocultural 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 faults, or hacking. Thus, automation might simply trade the vulnerability of labour to disruption for the vulnerability of machinery to other disruptive mechanisms.

Case study 4: nitrogen fixation in cereals

The large expansion of cereal production over the past century is partly attributable to the sharp expansion in the availability of, 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 (eg, water pollution) costs, and is not sustainable.[59–62] Substantial advances towards enabling nitrogen fixation by crops, in which nitrogen 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.[63–67]

If consumer, environmental, and regulatory concerns about particular methods of genetic engineering can be addressed, nitrogen-fixing crops could reduce the need for inorganic nitrogen fertilisers and their associated input costs, lower food and feed prices (SDG 2), and help to mitigate water pollution (SDGs 6, 14) and emissions from nitrous oxide, a potent greenhouse gas (SDG 13). To capture the benefit of less nitrogen loss from the use of inorganic fertiliser, the system needs to use any residual nitrogen in roots and residues remaining after harvest.[68] Lower prices could, however, also increase the 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 could offset some of the protein dilution that is expected to occur due to increased atmospheric carbon dioxide concentrations.[69] The increased protein could also increase cereal use as a livestock feed. Lower prices for cereals and animal-source 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).

Socioeconomic factors mediate the effect of novel technologies

The key mediators between the introduction of a new technology and its consequences 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.[18,70] 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, as well as complementary technological adaptations. Crucially, innovation arises not through stand-alone breakthroughs by individual inventors or firms, but instead through multiple incremental contributions across private, public, and civil sectors.[71,72] No innovation leads to exclusively positive outcomes, and the ends to which innovation is deployed involve choices.[16] These choices frame the direction of innovation activity and reflect the political economy surrounding those choices, with winners benefiting 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.[54,73] 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.[5]

Food transformations are often erroneously solely attributed to the emblematic technology that was central to their realisation, while the crucial enabling social and political conditions get overlooked. For example, the so-called Asian green revolution, which genuinely transformed food systems in the region, with both positive and negative consequences,[74] was not only a result of the development of input-responsive high yielding crop varieties, the emblematic technology of the era. The transformation also required a system of public investments in irrigation, transportation and communications infrastructure, input supply arrangements, public pricing, and procurement systems. Furthermore, 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 programmes worldwide, and a cadre of skilled scientists and extension agents to both develop and extend the new technology in distinct social and biophysical contexts. In 2020, 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 the widespread consequences of 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, and compressed refrigeration and cold chain logistics. All of these examples reinforce the point that to achieve impacts at scale, emblematic technologies require a complex supporting set of what has been termed transformation accelerators.[5]

Eight essential sociocultural, behavioural, economic, and political factors affect whether technologies emerge, are able to be scaled, and drive the effect that they were originally intended to have on society, the environment, and thus the SDGs.[5] The elements that most effectively combine with each technology depend fundamentally on the context, on human agency,[17] and on the opportunities for reflective learning.[54,75] Food transformations are likely to have the right enabling conditions in regions doing well across many of the SDGs, resulting in a technology trap that can lead to exacerbation of inequalities. The key point is the need for sociotechnical bundles.[17] The task of discovering, adapting, and scaling transformational innovation is as much one for social scientists as it is for natural scientists.[54,75]

Figure 2 draws on the framework developed by Herrero and colleagues[5] to show the essential elements for advancing beneficial effects from the four example technologies discussed earlier. The building trust element 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. The transforming mindsets element 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.[76] The enabling social licence element 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. The changing policies and regulations element is about fulfilling expectations of support for the technology—whether for the innovator (eg, ensuring that health and safety standards for the technology are in place, are appropriate, and are enforceable), the consumer (eg, clear labelling), or other food system actors. The designing market incentives element recognises that there could be very large start-up costs and risks associated with deploying new technology at scale, and that these costs and risks might 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. The safeguarding against undesirable effects element 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. The ensuring stable finance element 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 of these elements are brought together in the developing transition pathways element, which addresses the specific sequence and timing of actions that might be needed for a specific technology to contribute to a food system that is better aligned with society's objectives.

Interactions among the SDGs and the role of technological innovations

Technologies inevitably vary in their extent and focus of effect across food system-related SDGs. But, as we have emphasised, no technology touches only one SDG. The SDGs overlap and might not all be mutually reinforcing; on the contrary, trade-offs can and do exist.[77–79] Currently, there are 232 indicators for the 17 SDGs at country level. Studies have analysed these data for synergies and trade-offs between the SDGs.[6,80] 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 might 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-application and over-application of nitrogen fertiliser.[4,60]

For more on **country-level SDG indicators** see unstats.un.org/sdgs/indicators/indicators-list/

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 their study,[5] we used an expert elicitation process to map the potential effects of technologies in eight groups of food system technological innovations against the eight SDGs most directly associated with the food system (appendix pp 3–5). Experts offered quite varied assessments of the

See **Online** for appendix

Elements for food system transformation	Examples
Building trust among actors in the food system Vision and values	For all case studies • Build trust of so-called profit with a purpose or so-called system positive benefits • Foster transparent production, distribution, and management processes • Build trust in regulatory bodies that define and enforce environmental, health, and safety standards Specific to the personalised nutrition case study • Develop a health-centric technology platform that balances short-term 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 streams case study • Recognise waste of all types as byproducts that can serve as valuable inputs to other processes • Accept feed production from organic waste streams, including animal and human waste
Enabling social licence and stakeholder dialogue Responsibility	For all case studies • Engage with stakeholders across society (including among consumers, labourers, 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 • Show 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 and robotics 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 programmes 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 streams case study • Increase the cost of waste to encourage alternative use (eg, 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 for large investors Specific to the nitrogen fixation in cereals case study • Monitor land use, to ensure technology adoption helps reduce the footprint of food systems • Monitor more broadly adverse effects (eg, biodiversity) of increased adoption of novel crops • Monitor soil nitrogen concentrations 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 people who are 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 and robotics in agriculture case study • Promote healthy, safe, and productive employment to achieve equitable and responsible production

Figure 2: **Essential elements for developing and scaling beneficial effects, with examples from the four case-study technologies**
Data derived from Herrero and colleagues.[5] ESG=environmental, social, and corporate governance standards. SDG=Sustainable Development Goal.

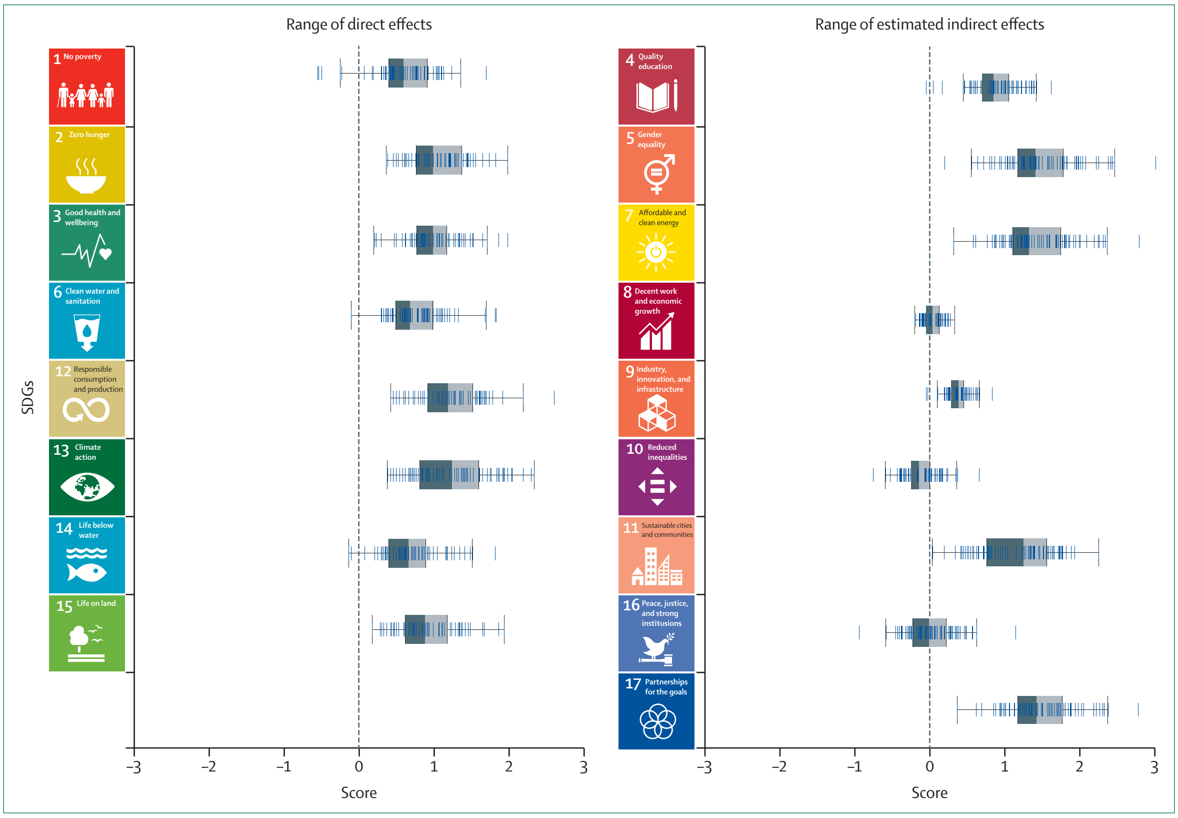

Figure 3: **Range of potential effects of anticipated technologies across SDGs**
Direct effects are those that occur on the SDGs that directly relate to food systems. Indirect effects are those mediated through the effect of food systems technologies on non-food-system-related SDGs. The small blue bars represent an average score of all respondents for an individual technology. The box plots show the median score of all technologies for each SDG, together with the range of the 25th percentile in dark grey and the 75th percentile in light grey. SDG=Sustainable Development Goal.

likely effects of different food system technologies on those eight SDGs (figure 3). For SDG 1 (no poverty), SDG 6 (clean water and sanitation), and SDG 14 (life under water), in particular, there was some diversity of opinion as to whether some technologies would have negative or positive consequences. This uncertainty highlights the necessity of broader civil society dialogue to identify and avert predictable, negative, and unintended consequences of technologies that aim to advance key SDGs, and the need for sociotechnical bundling.

We used updated data from Pradhan and colleagues[6] to estimate potential secondary consequences on the other nine SDGs that the technologies were not scored against, on the basis of the probability of a synergistic, neutral, or antagonistic effect between each pair of SDGs (appendix p 6). Results for the various technology groups are shown in figure 4. There were broadly synergistic secondary consequences on SDG 5 (gender equality) and SDG 7 (affordable and clean energy). There were more varied effects on SDG 8 (decent work and economic growth) and SDG 10 (reduced inequalities). Technologies related to inputs and waste reduction, in particular, might have had antagonistic effects on equity considerations, also mirrored in SDG 16 (peace, justice, and strong institutions). Technological innovations could help to advance SDG 2 (zero hunger), SDG 3 (good health and wellbeing), SDG 15 (life on land), and 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 consequences 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 multisectoral interlinkages that could arise from optimised portfolios of new and old technologies. These insights would be a prerequisite for understanding the possible negative consequences of different technologies and for examining alternative actions that could help to offset them. Although envisaging the consequences of as-yet undeveloped technologies is challenging, this type of framework might assist in evaluating their broader consequences. Developing such a framework calls to the integration of economics and natural sciences with a rich array of social sciences that study different

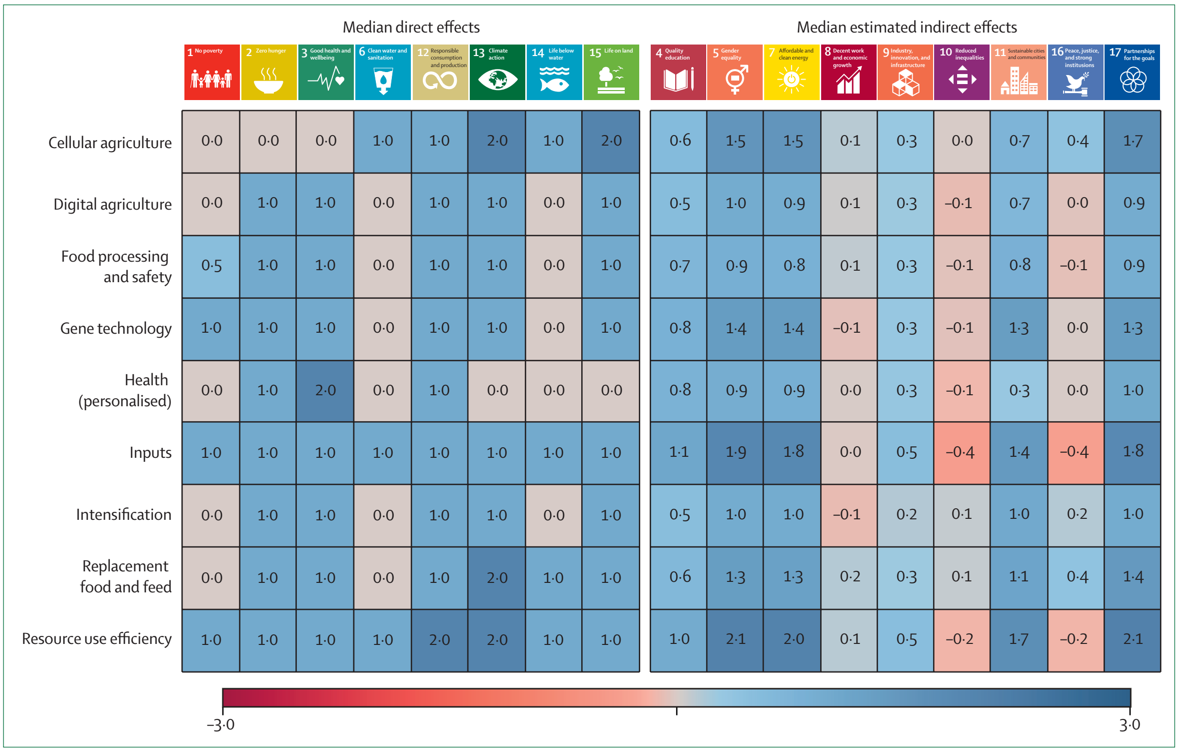

***Figure 4:* Direct effects of different technology domains on the food systems-related SDGs (left) and their indirect effects on the rest of the SDGs (right)**
Indirect effects are mediated via the interactions between SDGs as quantified by Pradhan and colleagues.[6] Dark blue squares represent strong positive effects and interactions. Mid blue squares represent moderate positive effects and interactions. Light blue squares represent weak positive effects and interactions. Grey squares represent neutral effects and interactions. Red squares represent negative effects and interactions. Numbers represent median scores for each effect. SDG=Sustainable Development Goal.

facets of transformation in multiple sectors, including transition management,[81,82] responsible research and innovation thinking,[54,75,83] interactive design,[84] responsible scaling and scaling readiness,[13] complexity awareness evaluation,[85,86] and transdisciplinary sustainability science for food systems transformation.[14,87]

Conclusion

> "Nothing vast enters the life of mortals without a curse"
>
> *Sophocles 497–406 BCE*

Progress on achieving the SDGs is imperative, but also difficult. A vast array of promising agricultural and food system technologies are 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 of the temptation of so-called win–win technological solutions and commit to the discipline of exploring and addressing possible perverse incentives, human decision making patterns, unintended and indirect effects, and resulting trade-offs. The long, complex impact pathways that result from the release of exciting new technologies necessarily involve a host of sociocultural, economic, ethical, and political mediators that can accelerate or impede progress. The complexity of these impact pathways inevitably influences the trade-offs or synergies across different SDGs. Managing those accelerators thoughtfully will require dialogue and cooperation from a wide range of public, private, and civil society sector actors.[88] Steiner and colleagues[88] 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 to, for example, energy, health, and the deployment of platform technologies (eg, 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 consequences of innovation in agri-food systems will require a clear examination of the complex pathways, from technology development to its deployment and consequences, as well as being alert to unintended consequences to ensure that 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 socioeconomic support mechanisms and environmental, social, and corporate governance standards[89] to harness these new technological capabilities towards delivering improved human and planetary development outcomes. This aim will also require the further development of modelling and analytical techniques to better quantify and understand the multiple consequences and trade-offs between desired objectives and the innovations we hope will help us to achieve them.

As Sophocles noted, change and innovation come with trade-offs, but we now have methods, the science, the targets, and the socioeconomic 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 sociotechnical innovation and immense human ingenuity to use to secure the future of our planet and the next generations.

Contributors

MH, PKT, DM-D, and JP designed the research. MH, PKT, DM-D, JP, BLB, PP, CBB, TGB, AH, and IP wrote the manuscript. MH, PKT, DM-D, JP, BLB, PP, CBB, TGB, AH, and IP analysed the data. All authors contributed data and edited the paper.

Declaration of interests

We declare no competing interests.

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