Socio-Technical Innovation Bundles Tailored to Distinct Agri-Food Systems

Scientific discovery is neither linear nor predictable. The time it takes to develop breakthrough technologies varies enormously among application domains. Some basic scientific discoveries remain elusive and will need continued, concerted funding and attention in the years and decades ahead. In some cases, the stumbling block is the scientific advancement per se, when important discoveries along the path towards technological readiness have not yet been made. This has been the case, for example, with numerous vaccines, both for humans (e.g., malaria, HIV) and for livestock (e.g., East Coast fever, trypanosomiasis, African swine fever). Research teams must sometimes work for several decades on the science necessary for a breakthrough discovery that can lead to a demonstrably effective, scalable product or impact. Similarly, several emerging options that could revolutionize crop yields (e.g., reconfiguring photosynthetic pathways for greater efficiency, nitrogenase in cereals) have remained elusive but continue to show sufficient promise to merit generous R&D investment. But even when breakthroughs occur, the time to market may be long, often decades.

Promising innovations often do not gain traction, not because the underlying science has proved too difficult but, rather, because the enabling environment

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essential to development and diffusion is lacking. Most breakthrough science requires financial, institutional, and sociopolitical support in order to advance through pilot stages to achieve impact at scale. It is therefore essential to identify the socio-technical bundles that combine social and scientific elements to unlock the transformative potential of emergent technologies.

Indeed, throughout history **all dramatic new technological inventions and impactful innovations have been combinatorial**, brought about through the intentional combination of different prior discoveries with the express intent of solving a human need (Arthur 2009). Transformative innovation therefore necessarily involves bundles of (1) scientific and engineering advances that improve the attributes of goods and processes; (2) public policies that induce appropriate behaviors by private actors, both internalizing externalities and advancing coordination that might otherwise fail to emerge spontaneously; and (3) informal private behaviors—the culture of food, if you will—that incentivize and help diffuse innovations as well as pressure public policymakers. Transformation thus requires multiple transitions at once.

One thread that runs through the preceding, lengthy discussion of scores of exciting emergent innovations is **that the scientific challenges, while formidable in many cases, may be the least of the obstacles to bringing promising innovations to impactful scale**. The "best" or most scientifically elegant technologies only occasionally prevail, often floundering due to cultural, economic, ethical, or political counter-pressures. The agri-food transformations that capture attention are often too narrowly associated with a particular emblematic technology that was central to their success. **The sociocultural, policy, and/or institutional changes that enable that new science to turn into transformative technologies are commonly overlooked but are equally important. Hence the importance of bundling**.

INDEED, THROUGHOUT HISTORY ALL DRAMATIC NEW TECHNOLOGICAL INVENTIONS AND IMPACTFUL INNOVATIONS HAVE BEEN COMBINATORIAL, BROUGHT ABOUT THROUGH THE INTENTIONAL COMBINATION OF DIFFERENT PRIOR DISCOVERIES WITH THE EXPRESS INTENT OF SOLVING A HUMAN NEED.

For example, the Asian Green Revolution, which genuinely transformed Asia's AFSs, was not just a result of the development of input-responsive high-yielding crop varieties, although these are the emblematic technology of the era. The transformation required a whole ecosystem of structures and institutions to make it work, and this took considerable time to emerge and develop, at least a decade. In the case of the Asian Green Revolution, the ecosystem included public investment in irrigation, transportation and communications infrastructure, input supply arrangements, public pricing, and procurement systems; a set of shared values among a group of philanthropic agencies, government bureaucrats, and international and local scientists to both develop and promote the new technology; and commitments to making the technology an international public good freely available to breeding programs worldwide. Nearly half a century later, these same technologies have failed to transform the AFSs of sub-Saharan Africa precisely because this wider enabling environment has yet to emerge.

Other examples reinforce this point. For example, the 2011 declaration of the eradication of rinderpest (cattle plague)—an animal disease with enormous adverse impact over centuries, especially in sub-Saharan Africa—featured a new vaccine as an emblematic technology but relied equally on a complex ecosystem of global scientific cooperation, cold chain distribution infrastructure, national policy and regulatory changes, awareness campaigns, and internationally coordinated vaccination programs. Like the Green Revolution, it also depended on generous, non-commercial financing and unencumbered intellectual property rights on the vaccine.

As was clear in our earlier example of the simple comparison between rice genetics discoveries—the IR8, IR36, and IR64 varieties of the Green Revolution versus contemporary golden rice—"novel technologies alone are not sufficient to drive agri-food system transformations; instead, they must be accompanied by a wide range of social and institutional factors that enable their deployment" (Herrero et al. 2020, p. 267). Despite having viable transgenic rice varieties containing high levels of beta carotene for more than a decade, these varieties are yet to be produced by farmers independent of scientific trials, let alone consumed by the vitamin A–deficient populations for whom they were developed. A critical missing part of the ecosystem was social license, with major political and ethical opposition emerging in several target countries (Regis 2019).

These successes and failures led Herrero et al. (2020) to describe eight essential elements for accelerating systematic transformation in AFSs (left panel of Fig. 1). These actions complete the socio-cultural fabric of the enabling environment for increasing the chances that promising technologies get adapted to fit a given context, adopted by many, and ultimately scale to achieve the desired societal impacts. Which elements most impactfully combine with which technology

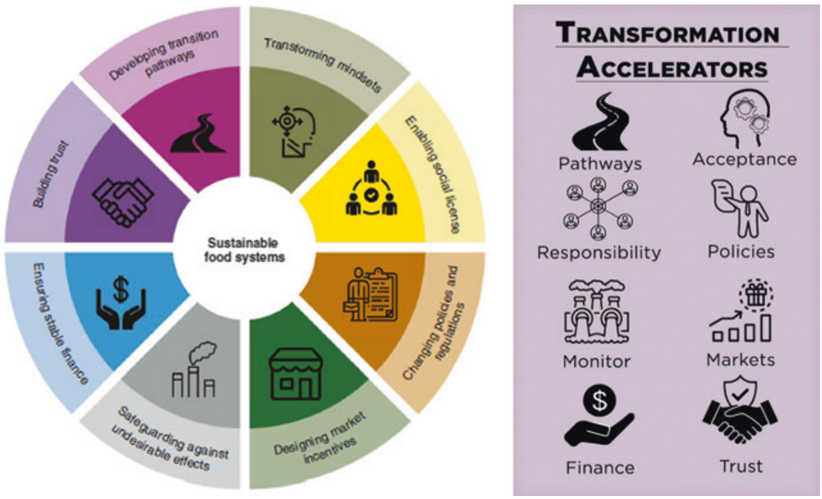

Fig. 1 Essential elements for accelerating the systemic transformation of agri-food systems (Lefthand figure reproduced from Herrero et al. 2020)

depends fundamentally on the context and the technology. But those combinations do not occur without human agency. The eight "transformation accelerators" depicted in Fig. 1 and Herrero et al. (2020) are all human actions: building trust, transforming mindsets, designing market incentives, etc.

We therefore emphasize socio-technical innovation bundles as appropriately contextualized combinations of science and technology advances that, when combined with specific, appropriate institutional or policy adaptations, exhibit particular promise for advancing one or more design objectives in a particular setting. **The task of discovering, adapting, and scaling beneficial innovations is as much one for humanists and social scientists as it is for engineers and natural scientists**. Agents throughout AVCs play an active role. Innovation is not just the business of engineers and scientists who think of R&D as their bread-and-butter activities. Table 1 works out a stylized example of the articulation of the need for these accelerators for two promising new upstream technologies described earlier: nitrogen-fixing cereals and circular (livestock) feeds.[1]

[1] The specifics of these cases are described in detail in Herrero et al. (2021).

Table 1 Accelerators for two promising agri-food technologies

Elements for AFS Transformation	INNOVATIONS	
	Circular Feeds (Microbial Protein from Organic Waste Streams)	Nitrogen Fixation in Cereals
Building Trust amongst Actors in the Food System  Vision and Values	**True for all Case Studies** • Trust building of "profit with a purpose" or "system positive benefits" • Transparent production, distribution, and management processes • Trust in regulatory enforcement of environmental, health, and safety standards	
	Specific to Case Study Technology	
	• Developing bio-safe production processes that ensure products are clean and safe to use/consume throughout the value chain (e.g. animals, operators, and consumers)	• Developing and confirming reliable nitrogen fixation and protein content in cereals • Ensuring the products are cost-effective for farmers and of high food safety and quality for consumers
Transforming Mindsets  Acceptance	**True for all Case Studies** • Acceptance of highly technological production and handling of food and feeds • Investment in education to increase awareness and appropriate use of new tech	
	Specific to Case Study Technology	
	• New by-product paradigm: waste of all types becomes input to other processes • Acceptance that feed can be produced from a range of organic waste streams, including animal and human waste	• Increased acceptance of applications of genetic modification/ gene transfer • Adjusted agricultural management practices to account for new bio-chemical requirements of advanced crops

(continued)

Table 1 (continued)

<table>
<tr><td rowspan="2">Elements for AFS Transformation</td><td colspan="2">INNOVATIONS</td></tr>
<tr><td>Circular Feeds (Microbial Protein
from Organic Waste Streams)</td><td>Nitrogen Fixation in Cereals</td></tr>
<tr><td rowspan="3">ENABLING SOCIAL LICENSE/STAKEHOLDER DIALOGUE

Responsibility</td><td colspan="2">True for all Case Studies
• Engage with stakeholders, including consumers, workers, and producers, to ensure technologies are developed and implemented transparently</td></tr>
<tr><td colspan="2">Specific to Case Study Technology</td></tr>
<tr><td>• Deepen collaboration and cooperation between agriculture, and sanitation and waste management sectors to better understand each other's needs and social obligations</td><td>• Ensure quality of new crops as good as, or better than, alternatives
• Demonstrate improved environmental profile that reduces input use/waste
• Avoid vertical integration models that overly concentrate market power</td></tr>
<tr><td rowspan="3">ENSURING STABLE FINANCE

Explore and Pilot</td><td colspan="2">True for all Case Studies
• Clear and stable medium- to long-term goals adopted to signal to stakeholders the direction of change to reorient investment portfolios
• Government soft loans, guarantees, and tax breaks linked to SDG/ESG performance
• ESG public and private financing encouraged
• New infrastructure investments based on long-term financing carried out
• Given that early adopters are typically better off, financing that does not reinforce existing inequalities
• Alternative funding mechanisms (e.g., AMCs, prizes) piloted to promote innovations that advance social and environmental objectives</td></tr>
<tr><td colspan="2">Specific to Case Study Technology</td></tr>
<tr><td>• Prioritize funding to develop waste processing in diverse locations
• Coordinate investments in sanitation and hygiene compatible w/ emerging waste processing technologies</td><td>• Promote open-access IP to increase access to novel crops for varied applications and business models</td></tr>
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(continued)

Table 1 (continued)

Elements for AFS Transformation	INNOVATIONS	
	Circular Feeds (Microbial Protein from Organic Waste Streams)	Nitrogen Fixation in Cereals
DESIGNING MARKET INCENTIVES  Spread Cost and Risk	**True for all Case Studies** • Targeted fiscal and trade policies to ensure a viable, scalable initial market • Improved cost of externalities (environmental, social, health, etc.) at source to facilitate the competitiveness of new approaches	
	Specific to Case Study Technology	
	• Increase the cost of waste to encourage alternative use (e.g. increase waste handling fees) • Provide price supports for key inputs to reduce production costs • Target support to conventional feed sectors to transition to alternative production and land use	• Tax nitrogen leaching per the polluter pays principle to encourage uptake • Incentivize seed distribution networks to promote equitable farmer access • Develop mechanisms to repurpose N-fertilizer capital towards other economically and socially viable uses
CHANGING POLICIES AND REGULATIONS  Expectations Of Support	**True for all Case Studies** • Revised policies ensure effective oversight of new technologies and industries • Streamlined/coherent environmental, health, and safety regulations enacted throughout AFS • Policies targeted at reducing economic and bureaucratic constraints to technological adoption and diffusion	
	Specific to Case Study Technology	
	• Create circular feed targets for domestic animal diets • Improve coordination of waste processing and transport • Waste and agriculture authorities coordinate by-product disposal	• Optimize IP rights to facilitate diffusion of new technologies • Co-develop input supply markets with private industry

(continued)

Table 1 (continued)

Elements for AFS Transformation	INNOVATIONS	
	Circular Feeds (Microbial Protein from Organic Waste Streams)	Nitrogen Fixation in Cereals
Safeguarding Against Undesirable Effects  Monitor and Correct	**True for all Case Studies** • Capable, independent regulatory bodies transparently enforcing standards/rules • Inter-governmental agreements on environmental and labor standards for technology transfer and trade • Requirements for impact assessment, free prior informed consent, and other safeguarding principles for foreign direct investment • Enhanced mandatory ESG disclosure and SDG/SBT reporting • Increased ESG screening/reporting by financial institutions	
	Specific to Case Study Technology	
	• Identify potential zoonoses and chemical contamination sources • Disincentivize excess waste output • Monitor for downstream environmental and social impacts (e.g., increased production and consumption of livestock products)	• Monitor land use to ensure improving environmental footprint of the AFS • Monitor adverse impacts on biodiversity (pollinators, etc.) and agro-biodiversity (local varieties) to boost adoption of novel crops • Monitor soil nitrogen levels and tax surplus nitrogen to avoid over-fixation
Developing Transition Pathways  How and When	**True for all Case Studies** • Integrate the previous elements into an integrated implementation plan • Design transition pathways that not only promote winners, but ensure that those disadvantaged by change can also benefit from the fruits of innovation • Recognize there are no perfect solutions (let not perfection be the enemy of the good); prepare to course correct as unexpected consequences are identified • Focus not on specific technologies but on achieving AFS outcomes • Make local, national, and international commitment with appropriate resource allocation	

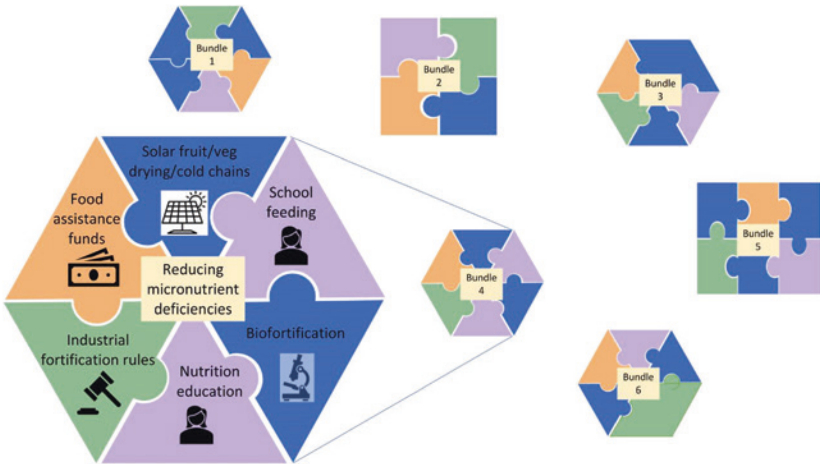

Fig. 2 Socio-technical bundles fit for purpose to an objective and context

Even with appropriately contextualized use of accelerators to enhance uptake of a given technology, many objectives require multiple, complementary interventions and the environment to support those multiple interventions. These often originate in different scientific spheres. A distinct set of multiple, mutually reinforcing innovations may be needed to achieve meaningful results at scale for a given design objective in a particular context. This, too, implies a need for contextualized socio-technical bundling of innovations, albeit for a slightly different purpose than for fostering and accelerating uptake of a given technology.

Figure 2 illustrates the case. Puzzle pieces represent innovations, which draw on different (natural or social) science-based methods (represented by different colors) to generate products, processes, or policies with distinct designs and purposes (represented by different shapes). These combine into different composite shapes to fit the people, place, and time. In this stylized figure, six distinct bundles are developed for half a dozen different objectives and AFS application domains. The right combination for one specific objective—in the enlarged case of bundle 4, reducing micronutrient (i.e., mineral and vitamin) deficiencies in a remote rural and traditional AFS—will differ from the bundle needed in other cases. Progress may require some combination of scientific advances (e.g., genetic improvement of crops through biofortification or inexpensive off-grid solar-powered fruit and vegetable drying and refrigeration technologies), financing (e.g., food assistance funding to enable poor consumers to afford a more diverse, nutrient-rich diet), legislation or regulation (e.g., required iodization of manufactured salt or folate fortification of flour and pasta), and policies (e.g., school feeding programs that feature nutrient-rich foods, and nutrition education to promote food culture, dietary diversity, and healthful food preparation and storage). The key point is that **science and engineering can design and adapt the raw materials, but ultimately stakeholders must work together to assemble the right bits into fit-for-purpose combinatorial innovations**.

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