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Bio-Innovation Dialogue Initiative

Bio-Innovation in the Food System
Towards a New Chapter in Multistakeholder Collaboration

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Executive summary

Food is not only a central part of our daily lives; how food is produced, distributed and consumed is also at the centre of important nutrition, environmental and social challenges the world faces today. Our food system is under stress and in need of profound transformation if it is to provide the broadest possible access to healthier, more diverse and environmentally sustainable nutrition moving forward.

Innovation – technology-enabled or otherwise – is required across many areas of the food system and beyond to bring about holistic change. Mindful of the systemic nature of the challenge, the present discussion paper focuses more specifically on the future role of bio-innovation. The paper defines bio-innovation as the interplay between emerging biotechnologies and the fast-evolving social context (business and governance models) in which they are developed and applied.

The foundation for shaping the future role of bio-innovation in food system transformation needs to be a holistic and inclusive conversation among all relevant stakeholders willing to engage to build shared understanding and a shared vision. This paper serves as an invitation to open dialogue. It offers some preliminary ideas for further discussion on how to enable a new chapter in multistakeholder collaboration.

Bio-innovation in food and agriculture directly concerns the health and well-being of consumers, living organisms, and our shared natural resources and ecosystems. The stakes are therefore high, and questions of affordability, sustainability, ethics and safety carry particular weight. Moreover, food plays a special role in our lives, linking issues of science and technology closely to questions of culture and identity; the voices of citizens and consumers are therefore crucial to shaping the future of bio-innovation and determining the conditions under which it can best contribute to desired nutrition, social and environmental outcomes. Incorporating farmers' perspectives is equally important. They are responsible for feeding the world and they themselves depend on the food system to secure their livelihoods, with many smallholders in a particularly precarious position. The economic welfare implications of bio-innovation are therefore equally crucial.

Bio-innovation, let alone specific biotechnologies, are not a silver bullet for advancing the food system. At the same time, bio-innovation will continue to contribute in fundamental ways to an ever-evolving food system. It also merits its own space for conversation, given the distinctive opportunities and challenges it brings to the table.

Considering the polarized debate of recent decades around food applications of biotechnologies involving genetically modified organisms (GMOs), the capacity for a more holistic and constructive conversation on bio-innovation has been lacking. At the same time, the challenging GMO experience serves as a rich pool of lessons that offer the community of stakeholders in the food system a unique occasion – and indeed a responsibility – to develop new and improved ways of collaborating and shaping a shared vision for navigating innovation and change. Ensuring transparency and engaging with different perspectives – including from diverse types of farmers and consumers – are crucial for building broader public trust.

The fast-paced structural transformation of today's bio-innovation space offers a powerful opportunity for a new kind of conversation. Fuelled by digitalization, growing connectivity and falling costs, important advances in biotechnology are intertwined with more systemic shifts in how bio-innovation is undertaken and who is involved. Microbiome technologies, advanced genomics, gene editing and synthetic biology are among key enabling technologies that have the potential to change the face of bio-innovation. This broader redefinition of bio-innovation creates new prospects to help address important nutrition, environmental and development needs. Stakeholders recognize in particular the potential for a more accessible, diverse and participatory bio-innovation ecosystem to emerge. At the same time, the new context for bio-innovation also raises important challenges and potential risks that all parties need to jointly acknowledge and address. By recognizing both opportunities and challenges, a new chapter in multistakeholder collaboration will have to shift away from a binary, zero-sum approach – labelling bio-innovation as either good or bad – towards a common interest agenda, anchored in the United Nations Sustainable Development Goals and the Universal Declaration of Human Rights. This will allow relevant parties to address real-world issues and trade-offs, establishing the conditions under which bio-innovation can help to advance shared objectives.

To establish these conditions – or, put differently, to develop effective governance frameworks – stakeholders recognize the systemic nature of the task at hand. Systemic challenges require systemic solutions.

This White Paper recommends that stakeholders consider working together to build a holistic governance framework for bio-innovation in the food system that aims to:

- Provide a comprehensive and dynamic overview of relevant actors and activities in bio-innovation
- Ensure connectivity and, where possible, consistency and coordination among existing governance efforts
- Build broad public and multistakeholder engagement and earn trust in bio-innovation governance
- Facilitate the development of new governance concepts and prototypes, at the global, national and local levels.

To advance this agenda, relevant parties will need to converge on a shared journey. In the absence of a commitment to work together across diverse perspectives and interests, stakeholders will risk a repeat of the GMO experience. More profoundly, through inaction or maintaining a binary stance, stakeholders will weaken their ability to effectively manage important risks inherent in bio-innovation that will surface and grow regardless – and at ever greater speeds. Finally, they will limit their possibilities to improve on the existing system or to leverage the area of bio-innovation in new ways to create the technologies, business models and governance solutions of the future that can contribute to the transformation of the food system.

1. Introduction and back-ground

In 2016, the World Economic Forum was asked by a number of stakeholders to provide a space for an informal dialogue on the topic of bio-innovation in the food system. Following consultations with over 50 organizations from different parts of society and across geographies, the Forum hosted and curated a series of global, regional and thematic roundtables and workshops in 2017 and 2018 to help relevant actors find a new approach to engage with each other.

A wide range of organizations and individuals have participated in these dialogues, including social and environmental non-governmental organizations, religious groups, food and beverage brands, food ingredient manufacturers, consumer advocacy groups, farmers, agribusinesses and input companies, commodity traders, small and established biotech companies, retailers, scientists and research organizations, foundations, science and agricultural ministries, international organizations, as well as independent academics specializing in food systems, environmental studies, technology governance, ethics and other relevant disciplines.

An important anchor for this effort has been a shared mindset of mutual listening and learning, as well as the recognition that shared desired societal outcomes have to be the starting point of any conversation – in particular the overarching goals of providing access to healthy and nutritious diets and protecting our resources and environment.

Following an initial dialogue at the World Economic Forum Annual Meeting 2017 in Davos-Klosters, stakeholders engaged in conversations with a regional focus in Buenos Aires (April 2017), New Delhi (October 2017) and São Paulo (March 2018), as well as in a full-day workshop on the topic of biotechnology democratization in San Francisco (July 2017).

At the World Economic Forum Annual Meeting 2018, senior leaders across stakeholder groups reconvened to take stock of conversations to date. In light of the rapid evolution of bio-innovation, they urged to move beyond dialogue towards jointly articulating an emerging shared understanding of the opportunities and challenges related to bio-innovation. They also urged to move towards building an action agenda for navigating these opportunities and challenges.

This White Paper serves as a first step in that direction.

2. A food system under stress

Agricultural food production more than tripled since 1960, in large part due to productivity-enhancing Green Revolution technologies and significant expansion in the use of natural resources for agriculture. Food supply chains have become highly complex and the consumption of processed, packaged and prepared foods has increased virtually everywhere.[1] More broadly, the efficiency gains achieved through modern agriculture have liberated social and economic resources that have fuelled the global expansion of the production and services sectors.

Increased yield and efficiency gains have allowed global food production to keep up with global population growth. In recent decades, undernutrition has been declining globally. Between 2000 and 2017, the prevalence of stunting among small children declined from 32.6% to 22.2%, and the number of stunted children fell from 198 million to 151 million.[2] Even more progress may have been achieved with full stakeholder engagement into a system of solutions.

Despite progress made, today's food system falls short of meeting people's nutrition, environmental and socio-economic needs. In terms of health and nutrition, approximately 800 million people are chronically undernourished and 2 billion people are micronutrient deficient.[3] At the same time, 2 billion people are overweight or obese,[4] a key contributor to the worldwide rise of non-communicable diseases. Nearly one-third of global food production – 1.3 billion tonnes of food[5] – is lost along the supply chain or wasted by consumers and retailers. This represents a waste of resources used in food production, including labour, water, energy and other inputs. The food system accounts for 20% to 30% of global greenhouse gas emissions,[6;7] 70% of freshwater withdrawals[8] and 70% of biodiversity loss.[9] In turn, climate change is threatening agricultural production, which disproportionately burdens smallholder farmers. Many people who work in agriculture live below the poverty line and are themselves food insecure. Global population growth is fastest in regions where food insecurity threats are most acute.[10] Yet, farming as an occupation is on the decline as young generations increasingly migrate to urban areas in search of better livelihoods there.

In this context, providing sufficient nutritious food for 9 billion people by 2050, while protecting our planet, presents an enormous task.

Beyond these indicators, consumer trust in food and key actors in the food system has been declining. In a recent study of US consumers, only 33% of survey respondents said they "strongly agree" that they are confident in the safety of the food they eat, compared to 47% in 2017.[11] Only 25% said they believe meat is derived from humanely treated animals, and a mere 30% strongly agree that farmers take good care of the environment, compared to 42% in 2017. Less than half of respondents (44%) said they have a positive impression of food manufacturing.

3. Innovating the food system

In recognition of these challenges, stakeholders across sectors are in broad agreement on the need to transform the food system. They acknowledge the imperative to develop healthier, more diverse, inclusive and environmentally sustainable ways of producing, distributing and consuming food. Improvements in these areas will move the needle on making progress towards multiple United Nations Sustainable Development Goals (SDGs).[12] The food system is a central lever of change and is in need of innovation.

It is important to recognize that addressing the challenges outlined above will require changes and innovations beyond the food system, including promoting gender parity, facilitating access to education and healthcare, fostering financial inclusion and addressing basic infrastructure needs.

Even within the context of the food system, innovation is a broad concept and can occur in many relevant areas. Within the technology realm, advances in big data and analytics, blockchain, mobile services, internet of things and biotechnologies, among others, are all changing the way food is produced, distributed and consumed.[13] Beyond the development of new technology solutions, innovation encompasses social innovation: new economic and business models, new policy and governance approaches, as well as new food paradigms and narratives and improved education on the food-health-environment nexus. Finally, innovation in the food system can touch diverse parts of the value chain (in-field production or retail), different production sectors (cropping, livestock, fisheries, forestry), product categories (grains, fruits, vegetables, root crops, meat, dairy, etc.), or benefit areas (nutrition, livelihoods, biodiversity, soil or water quality, etc.).

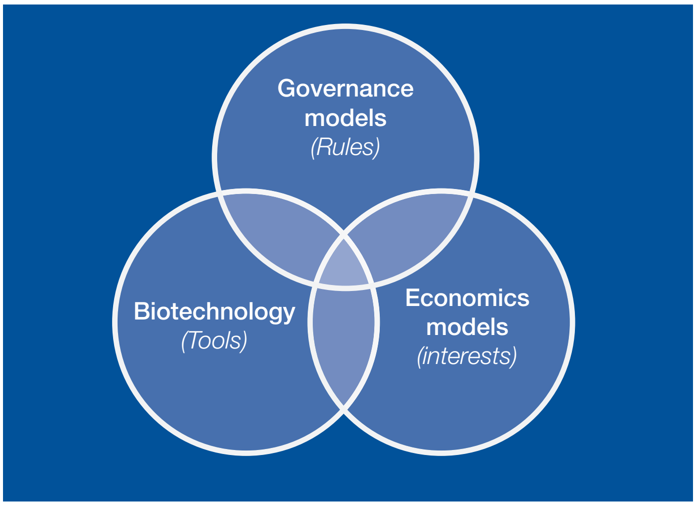
4. Bio-innovation in the food system

To make sense of the complexity, it is therefore necessary to take a more focused view of food system innovation at any given moment. Bio-innovation offers only one lens, but a unique and highly relevant one, for addressing food system challenges and opportunities.

What is bio-innovation? And why does it matter in the context of our broader efforts to achieve the SDGs and transform the food system through innovation?

Bio-innovation is defined as a set of advances in biotechnology, coupled with evolving economic and governance models (see Figure 1). This integrated definition recognizes that innovation is shaped by both technological and social factors and that the role and impact of technology cannot be dissociated from the interests and norms in society that shape it, and are shaped by it.

Figure 1: Defining bio-innovation



Source: World Economic Forum

- **Biotechnology**, at the broadest level, describes “any technological application that uses biological systems, living organisms, or derivatives thereof, to make or modify products or processes for specific use”.14 This includes a range of tools available to scientists, technology providers and users that can be applied throughout the value chain – from soil, plant and animal health to food processing, packaging, retail and the consumer – as well as across the crop, livestock, fisheries and forestry sectors.15 Box 1 describes certain emerging biotechnology areas that have attracted increased attention in recent years due to their potential to transform the broader bio-innovation ecosystem.

- **Economic models** describe the relationships and interactions between economic agents who have a direct economic stake in the development, dissemination or use of biotechnology, or whose economic assets and livelihoods are otherwise affected by these activities. Investments in biotechnology research and development – whether made by the private or public sectors – also require economic value to justify the costs. In some regions, investments in biotechnology R&D are drivers of employment and economic growth.

– **Governance models** describe a set of mechanisms and rules intended to influence the development, dissemination or use of biotechnology, as well as relevant economic models, with a view to maximizing the positive and minimizing the negative impacts. Such mechanisms and rules can include hard-governance tools (government policy and regulation), soft-governance tools[16] (standards, guidelines, norms, codes of conduct) and other forms of formal or informal organization among stakeholders.

Stakeholders acknowledge that technologies, economic models and governance are intrinsically linked and need to be considered holistically. At the holistic level, bio-innovation must draw on all three to be aligned with the overarching purpose of achieving the SDGs. In the context of multistakeholder collaboration, governance plays a particularly crucial role; the "rules" governing bio-innovation will determine how successfully a complex system of "tools" and "interests" can contribute to the pursuit of commonly agreed goals.

Box 1

New frontiers of biotechnology

Biotechnology encompasses a diverse and complex set of tools. Among emerging biotechnologies with the biggest potential to transform bio-innovation in the food systems in the coming years are the fast-evolving fields of microbiome studies, advanced genomics, gene editing and synthetic biology. These enabling technologies have the potential to fundamentally change our understanding of biology, enhance our capacity to promote or design specific outcomes and products based in biology, and disrupt the ways in which biotechnology is developed and used by stakeholders.

Advances in these fields must be seen in the context of broader technology trends. On the research and development side, the convergence of the life sciences with computer and data sciences has been a central factor in accelerating techniques that allow to more easily and cheaply map, analyse and combine biological information and processes. Uncovering how the genome, the microbiome or other complex ecosystems work requires the collection and analysis of big data. Similarly, on the user side, combining biotechnology applications with other innovations – for example linking improved seeds with precision agriculture solutions that harness weather, soil and market data – has the potential to unleash powerful systemic benefits such as optimized plant nutrition or reduced food loss and water use.

What is the microbiome?

Microbiomes are microorganisms that live on and in humans, animals, plants, soil, oceans and the atmosphere. All are relevant for the production, preservation, intake and metabolism of food and nutrition. For example, "the plant soil microbiome is the dynamic community of microorganisms associated with plants and soil. This community includes bacteria, archaea, and fungi and has the potential for both beneficial and harmful effects on plant growth and crop yield. The composition of any particular microbiome is influenced by myriad factors, including: environmental, soil physical properties, nutrient availability, and plant species."[17]

Example: Scientists discovered specific fungi that colonize plant roots and help them penetrate the soil. By sending out networks of their own underground filaments, these fungi effectively generate secondary root systems, improving the plants' access to moisture and nutrients, which enhances plant resilience to drought.[18]

What is genomics?

Genomics is "the study of genes and their functions, and related techniques. The main difference between genomics and genetics [the study of heredity] is that genetics scrutinizes the functioning and composition of the single gene [or a handful of genes] whereas genomics addresses all genes and their inter relationship in order to identify their combined influence on the growth and development of the organism".[19] Genomics usually involves sequencing and bioinformatics analysis and is an enabling technology for gene editing and synthetic biology.

Example: Genomics is used in livestock production to develop intelligent breeding programmes. Until recently, the work of breeders revolved primarily around studying and observing animal traits, such as productivity, disease resistance and longevity. Today, genomics increasingly allows the identification of such characteristics directly from the genome.

What is gene editing?

"Genome editing (also called gene editing) is a group of techniques that give scientists the ability to change an organism's DNA [genetic code]. These technologies allow genetic material to be added, removed, or altered at particular locations in the genome. Several approaches to genome editing have been developed. A recent one is known as CRISPR-Cas9, which is short for clustered regularly interspaced short palindromic repeats and CRISPR-associated protein 9. The CRISPR-Cas9 system has generated a lot of excitement in the scientific community because it is faster, cheaper, more accurate, and more efficient than other existing genome editing methods."[20]

Example: Porcine Reproductive and Respiratory Syndrome (PRRS) is a virus that causes breathing problems and deaths in young pigs and can cause pregnant sows to lose their litter. There is no effective cure or vaccine. The virus is prevalent in most pig producing countries worldwide; in England, for example, 30% of pigs are estimated to be infected at any given time. Using the CRISPR gene editing technique, researchers made specific DNA changes in a test population and found that none of the animals became ill when deliberately exposed to the virus, as blood tests found no trace of the infection.[21]

What is synthetic biology?

Synthetic biology does not have a commonly accepted definition. However, "it is commonly understood as a field where engineering principles are applied to biology to design, construct or modify biological parts or systems."[22] Synthetic biology can be thought of as "a further development and new dimension of modern biotechnology that combines science, technology and engineering to facilitate and accelerate the understanding, design, redesign, manufacture and/or modification of genetic materials, living organisms and biological systems".[23] Gene editing is a key enabling technology for synthetic biology. However, synthetic biology goes beyond gene sequencing (reading DNA) and gene editing (editing DNA) to synthesizing (writing) new DNA. Synthetic biology is also often referred to as "engineering biology".

Example: Today's cultivation of many crops depends on the application of nitrogen fertilizer to fulfil the plants' nutritional needs for growth. Based on the expanding field of microbiome studies, researchers are increasingly looking at the role of microbes in the plant and soil that help the plant's roots fix nitrogen. In many cases, plants are not pairing up with microorganisms to support this process. By biologically engineering microbes, synthetic biology has the potential to improve the microbes' ability to make nitrogen available for plants. This offers the prospect of lowering and more optimally applying nitrogen fertilizer.

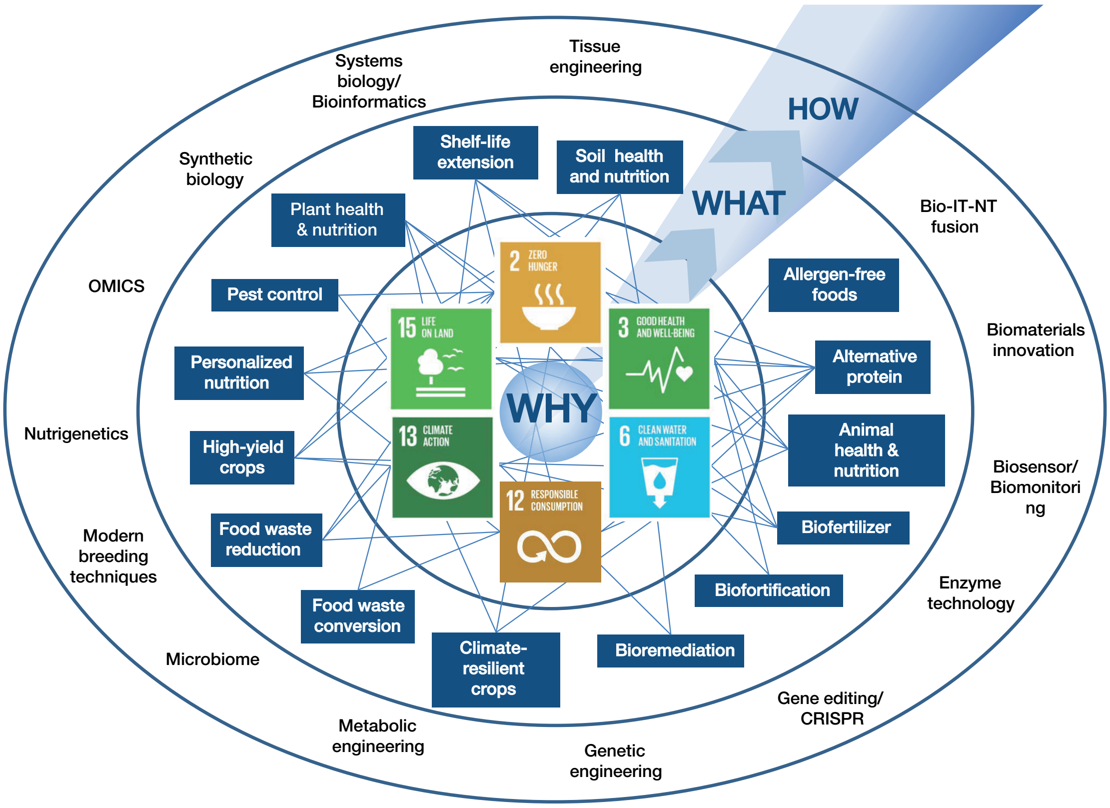
5. Bio-innovation with a purpose

The SDGs set out a shared framework for guiding food system transformation. While all goals are important in the context of the food system, goals 2 (zero hunger), 3 (good health and well-being), 6 (clean water and sanitation), 12 (responsible consumption and production), 13 (climate action) and 15 (life on land) are among the most relevant.

What role can bio-innovation play to contribute towards achieving these goals?

Figure 2 gives examples of specific food system outcomes (the "what" circle) that link bio-innovation to the SDG agenda. For instance, one of the outcomes is "animal health & nutrition". Animal health and nutrition plays an important role in achieving goals 2 and 3 (among others), as animal products are an important source of protein and nutrients, and animal health in the livestock sector is key to ensuring human health (conversely, animal disease poses a human health risk). A wide range of existing and emerging biotechnologies are – or have the potential of being – applied towards this outcome: microbiome technologies that help analyse a chicken's gut microbiome to optimize feed; GMO vaccines to prevent an infectious disease from spreading in an animal population; lab-grown meat cultivated through tissue engineering to avoid slaughtering cattle; enzymes engineered to help salmon better absorb protein from feed.

Figure 2: Bio-innovation in the food system – mapping exercise (illustrative)



Source: World Economic Forum, developed in collaboration with the World Economic Forum Global Future Council on Biotechnology

Box 2 describes in more detail a few examples of how bio-innovation can contribute to certain desired food system outcomes.

Stakeholders recognize that in the complexity of the food system, any given biotechnology solution will be considered in the context of other biotechnology solutions, results from other technology areas, as well as non-technology solutions. Furthermore, specific outcomes are often interrelated with other outcomes, leading to trade-offs, even within and across the SDGs themselves. For example, achieving increased animal health in the livestock industry can lead to growth in global demand and the supply of safe and affordable meat, helping with SDGs 2 and 3. At the same time, the potential overconsumption of meat and heightened pressure on water, land and other natural resources can work against SDGs 3, 6, 13 and 15. Finally, different stakeholder groups will be affected in different ways depending on what specific solutions and outcomes are being pursued.

Shaping the role of bio-innovation in the food system therefore requires a holistic approach that weighs specific outcomes against broader systemic implications. Moreover, longer-term structural solutions do not negate the need for near-term fixes, and vice-versa. For example, the necessity for climate mitigation solutions does not detract from the need for climate adaptation solutions; bio-innovation can play a role in both.

Box 2

How can bio-innovation support climate-smart agriculture?

Climate change has a profound impact on agricultural systems, and smallholder farmers are the most vulnerable. Systems that are more resilient can better manage risk, which offers economic benefit to the farmer. Technologies in soil and plant health can potentially help farming systems both adapt to and mitigate the effects of climate change.

Advances in breeding, digital tools and biologicals (products that contain or are derived from living microorganisms) have all contributed to farming systems that produce more while using less. One example is the development of microbial products for use by farmers. Microbes are an inherent part of the world around us. As humans, we rely on microbes for our digestive system to function properly, to ferment our beer and wine, and to make our bread rise. Plants rely on relationships with microbes too, and microbial products aim to utilize this relationship to improve the health of plants. In a sense, microbial products can be thought of as probiotics for plants. These "probiotics" have the potential to increase the biomass of crops, meaning the plants grow more, often allowing them not just to be healthier and to yield more, but also to sequester more carbon, removing CO_2 from the air. Biologicals can reduce fertilizer needs, which reduces fuel use, yet another reduction in the amount of carbon being emitted by the farming system.

How can bio-innovation help address food waste and loss?

An estimated one-third of the food the world produces does not contribute to nutrition outcomes because it is lost or wasted in the value chain.[24] This imposes significant economic, social and natural resource costs. Food lost in production and post-harvest activities is more prominent in developing regions, contributing to food insecurity, reducing the availability of nutritious food and limiting market opportunities and profitability along the food supply chain. Food waste, intentional discards occurring at the retail and consumer levels, is most significant in developed countries and rapidly urbanizing economies.

Alongside awareness raising, policy interventions and private-sector incentives, capacity building along the value chain, marketing schemes and infrastructure investment, improved technology is an important part of the solutions. Within the technology space, bio-innovation can potentially contribute both to preventing food loss and waste from the outset, and to extracting new value from damaged or discarded food no longer destined for commercialization or consumption.

In the area of prevention, for example, biotechnologies improving the quality of seeds and of plant nutrition have a direct impact on the shelf life of harvested produce. "Active" and "intelligent" packaging solutions that use biotechnologies to measure, influence and communicate biological activity in perishable products (e.g. bacteria count) could also make a difference: beyond helping to extend shelf life, they could provide valuable data to logistics companies, retailers and consumers to help them improve the quality of their pricing, operational, purchasing and consumption decisions.

Finally, biotechnologies play a central role in safely and efficiently converting post-harvest losses and by-products from farming, as well as wasted food, into renewable energy sources for fertilization or other applications, such as biofuels. One example is the conversion of discarded frying oil from restaurants into renewable energy. Communities, businesses, social organizations and innovators around the world are looking into how to build a more integrated "food waste-to-energy" ecosystem.[25]

How can bio-innovation support biodiversity conservation?

The food system is putting significant strain on biodiversity by destroying or compromising a wide range of natural habitats.

For example, climate change induced pest pressures on cocoa trees is starting to push cocoa farming into higher altitudes, running the risk of destroying additional tropical forest habitats on which many species depend. Scientists are working on bio-innovation solutions, including the use of CRISPR gene editing technologies, to make cacao plants more resistant to the rise in both viral and fungal diseases in warmer temperatures.[26]

Bio-innovation can also play a role in conserving soil and water quality that form the basis of biodiversity ecosystems. Advances in understanding the crop microbiome, genetic information and microbial behaviour represent a fast-evolving area of innovation to optimize plants' access to nitrogen and thereby minimize water and soil contamination from excess nitrogen fertilizer use.

In another example from the fishing sector, strong demand for some products – such as salmon or tuna – pose a direct threat to fish populations and the wider marine ecosystem, even in the context of aquaculture. Some applications of biotechnologies are looking more specifically into how the pressures on ecosystems can be reduced by switching to alternative nutrient sources for food and feed. In salmon aquaculture, for example, omega-3 fatty acids are an important nutrient contained in salmon feed. This nutrient is derived from fish oil from wild-caught fish, a finite resource. As global demand for salmon increases, so does the demand for salmon feed and omega-3 fatty acids. By producing the same acid from natural marine algae, biotechnology offers an alternative source of omega-3 without relying on wild-caught fish.

6. A new context for bio-innovation

Understanding the role of bio-innovation in the present-day food system is difficult enough. To make matters more complex, bio-innovation is evolving at an ever-faster pace, creating a new context that is challenging to grasp more holistically. Stakeholders often have a limited, specialized perspective into the broader food ecosystem. For the average consumer, bio-innovation is not top-of-mind, especially at a time when the impact of significant recent innovations is not yet fully understood, discussed or felt more widely; the latest advances pertaining to soil microbiome, or gene editing technologies such as CRISPR, are barely starting to capture wider public attention.

Looking through the lens of rapid advances in microbiome technologies, genomics, gene editing and synthetic biology in particular, a number of interrelated trends shape the current direction of bio-innovation:

1. **Falling technology cost and increased ease of use**: The cost of sequencing (reading) a human genome has fallen from $10 million to as low as $1,000 or less within the past 10 years.[27] The cost of synthesizing (creating) new genes is still higher but also falling precipitously. In the area of gene editing, new techniques such as CRISPR have allowed scientists and researchers to make more targeted changes to genetic material at increasingly low cost. At one extreme end of the spectrum, do-it-yourself gene editing kits – while limited in their functionality – can be purchased at $100 or less and are already used in high-school classrooms to familiarize students with gene editing technologies. The digital interconnectivity of today's scientific and technology communities has driven down transaction costs for innovation to record lows. Through digitalization, standardization and automation, much of biotechnology is transforming from hardware to a software model, providing cheaper and more user-friendly interfaces for biotechnology developers and users.

2. **Growing capabilities and impact potential**: The growing capacity to map and analyse microbiomes and genomes is unleashing a knowledge revolution in the biosciences. In labs around the world, this advanced understanding, combined with cheaper and more precise ways of modifying and synthesizing organisms, allows for experimenting with a wide variety of desired traits in microorganisms, plants or animals. The real-world application of these technologies has the potential to transform food, food production and environmental stewardship. Gene drives – genetic changes designed to self-replicate and spread within a species or population – could have powerful implications for biodiversity and ecosystems. Biotechnology also holds the potential to decouple parts of food production entirely from using land resources or live animals by enabling the production of plant-based meat substitutes and lab-cultured "clean" meat.

3. **Diversification of active players in bio-innovation**: The falling cost and growing ease of use of new biotechnologies has led to a sharp increase in the number of players developing and using them. Alongside larger biotech players, start-up companies, public and private universities and independent labs are increasingly taking up the new techniques to do basic research and develop novel applications. Non-profit and for-profit entrepreneurs are offering gene editing workshops to the general public.[28] New communities and initiatives are forming around emerging technologies such as synthetic biology[29] and CRISPR[30] to promote, debate or guide their development.

4. **Diversification of potential applications of biotechnology**: In light of the sprawling activity and diversification of players active in bio-innovation, the spectrum of potential applications has widened. Smaller-scale solutions are more likely, for example targeting local plant diseases, local crops, niche products, personalized nutrition needs, specific animal health issues or biodiversity conservation.

5. **Open innovation**: As bio-innovation becomes more digital and data-driven, innovation increasingly drives, and depends on, data sharing, data pooling and the interoperability of standards and methods. Especially smaller players depend on accessing external data sets and outsourcing more costly processes such as gene synthesis or data analytics to third parties. This promotes the emergence of platform models and new partnerships and collaborations across varying players, rather than end-to-end in-house R&D processes. For these reasons, bio-innovation tends to become more distributed and open. On the research side, open innovation is advancing rapidly; more distributed activity and open data in the commercial development of technologies will depend in part on the evolving intellectual property and regulatory environment.

6. **Accelerating speed of innovation**: Finally, due to the above factors, the pace of bio-innovation is accelerating at an unprecedented rate. The advent of robotics, machine learning and artificial intelligence will further speed up advances in next-generation biotechnologies and the transformation of bio-innovation.

7. Growing opportunities and challenges

The trends identified above entail a number of opportunities and challenges for bio-innovation.

Opportunities

The diversification of players and biotechnology applications has the potential to advance solutions that are more relevant to local communities, end consumers and different types of farmers, achieving benefits more fully. More diverse bio-innovation could better respond to the diversity of needs that are specific to local environmental conditions, economic realities, dietary needs and culture. At the global food system level, this trend could benefit cultural diversity, dietary diversity and biodiversity.

The diversification of applications could lead to more consumer-centric and/or environmental applications of biotechnology. In crop production, applications of transgenic technologies in previous decades have focused on pest and weed control to increase the efficiency of production in major row crops – with farmers serving as the first-tier beneficiaries, and with consumers only benefitting indirectly through lower food prices. That followed the general historical trend in most agricultural research and product development, which was to increase yields and efficiency for both small- and large-scale farmers. The potential with new forms of bio-innovation, in addition to addressing growers' needs, could be to contribute more directly to consumer well-being (e.g. allergen-free foods, bio-fortified foods, extended shelf life of fresh produce). The possibility also exists to address causes some consumers feel strongly about (e.g. the reduction of chemical use in the agro-food chain, sustainable animal pest and disease management, and alternative protein solutions that could increase consumer choice and balance the environmental and animal welfare impact of livestock and aquaculture).

If more tailored solutions become affordable and economically viable, the barrier to entry for local communities to participate in the development and use of biotechnology will fall. They would be able to partner more closely with scientists and technology providers to co-develop solutions. In a best-case scenario, local players will be in a position to have a more direct stake in developing environmentally, economically and socially sound responses to their most pressing needs.

Rural communities in developing countries could derive particular benefit from more affordable and accessible bio-innovation, given that they tend to rely more heavily on small-scale operations, represent smaller markets and have fewer resources to invest. Still, enabling smallholder inclusion in bio-innovation will require targeted investment, financial support, extension and information services, and public oversight.

From a public participation and education perspective, the falling cost and ease of use of next-generation biotechnologies could help engage a wider audience. For example, bringing new technologies into school and university classrooms could increasingly familiarize younger generations with the new tools and concepts. Promoting public discourse around their role and impact would broaden the conversation in society beyond more specialized stakeholders from the scientific, industry and regulatory communities. Such increased access, combined with more open and participatory innovation models across public and private research institutions, could contribute to higher levels of transparency, familiarity and trust in bio-innovation.

In the context of evolving economic structures, bio-innovation in the food system can play an important role in helping build the bioeconomy, a vision for new production and consumption systems that use renewable biological resources to produce food and feed, materials and energy. Closing the biological cycle is a key pillar for circular or closed-loop models that are currently being developed and tested worldwide.[31] For example, the city of Amsterdam is pioneering work at the municipal level to develop both biological and technical circular models.[32] Addressing food waste and food loss at the farm and consumer levels offers particularly compelling opportunities for bio-innovation to contribute to more circular models; for example, the safe and efficient conversion of post-harvest losses and by-products from farming as a renewable energy source for fertilization or other applications is a win-win situation for farmers and the environment.

Challenges

At the same time, the fast-changing context of bio-innovation raises a number of challenges.

To start, the proliferation of biotechnology research and development raises questions of control and safety. The more players have access to next-generation tools, the more challenging it will become for any single player, for example a regulator, to have visibility into who does what. Genetic data can be shared, traded and compromised without sufficient oversight. Lower technology cost and ease of access can lead to do-it-yourself garage-type biology beyond government sanctioned or otherwise certified laboratories. With more actors handling biotechnology, genetic material and data, the probability of potentially harmful organisms being released into the environment or the food chain without central oversight may increase, irrespective of whether these releases are legal or illegal, intentional or accidental.

Beyond the proliferation of players, the changing nature of new breeding and/or genetic modification techniques is blurring the lines between the two. In some cases, it is becoming increasingly difficult to verify the presence and nature of genetic interventions by examining a given organism or end product; more targeted alterations can resemble the outcomes of natural mutation or of conventional breeding. This further exacerbates the challenge of control and oversight: not only are more players involved, but their actions are harder to detect and assess. In the specific case of new gene editing techniques, such as CRISPR, their use can be graduated; gene editing allows for targeting one, two, three or any number of parts of a genome. The degrees of intervention make up a more continuous spectrum. Determining "low" vs "high" levels of genetic alteration, "natural" vs "artificial" outcomes, or "low risk" vs "high risk" cases is becoming a question of judgement on a continuous spectrum. Such judgements are related to how the technology changes the product properties, rather than whether or not it is used. Therefore, depending on the type of graduated change in an organism's genome, gene editing could produce a product identical to one created with "traditional" mutagenesis or a product identical to a transgenic GMO. The result is that the many different methods to produce improved crops and animals form a spectrum whose lines are blurring. No longer are there clear distinctions for "transgenic methods", conventional breeding, biotechnology, and other methods and techniques to develop improved crops and animals. This raises the question of how regulatory oversight needs to evolve in the new context (see Box 3).

Moreover, some emerging biotechnologies have the potential to change or disrupt environmental or social ecosystems more profoundly. The prospect of gene drives, for example, opens new possibilities in areas such as biological pest control; at the same time, it raises particularly challenging questions of risk assessment and management. What are the unintended or undesired consequences, for example, of modifying or eradicating an entire insect species that carries a plant disease? The more powerful a technological solution may be, the higher the potential impacts on complex ecosystems, impacts that are by definition more difficult to predict for the short term, let alone for the longer term. Society needs to deliberate benefit–risk trade-offs and the ethical principles that should govern this type of technology and how it is used. In another example, emerging biotechnologies could take some food production off the field or the pasture altogether. The scaling up of plant-based meat substitutes or cultured clean meat grown in labs could significantly affect regions and farmer livelihoods that depend on the traditional livestock sector.

A different type of challenge has to do with the increasingly data-driven nature of bio-innovation. With more data being collected, stored and analysed, data privacy and ownership issues become more acute. Like in other sectors, the rise of larger platform players owning data or dominating data analytics capabilities raises new questions around who controls information and how it is used. While these issues are not unique to bio-innovation, their significance is compounded in the area of biology and genomics given underlying ethical and security considerations.

The disruption of the bio-innovation space also poses challenging questions about future approaches to intellectual property. Who will own the technology tools, the seeds and strains? How will they be licensed, and who has access? How will businesses and innovators be able to monetize their investment in research and development? When it comes to genetic engineering and the ownership of living things, some stakeholders are concerned more fundamentally with the ethical and legal implications of intellectual property. These types of questions are not new but merit a fresh look in the context of an increasingly distributed bio-innovation ecosystem. Will distributed research, development and manufacturing lead to distributed ownership?

Finally, as in other technology domains, the rapid speed of change means that some stakeholders may be deprived of the opportunity to play any meaningful part in shaping the future of bio-innovation. The voices of disadvantaged minorities, low-income communities, underdeveloped countries, but also those of the millions of species without a human voice, are most at risk of being absent from the conversation. In a context of known and unknown health, environmental, social and ethical trade-offs, what is the appropriate balance between disruption and inclusion, between risk and precaution, when deploying new technologies? The risks of key groups in society being left behind, disempowered or feeling threatened by bio-innovation include polarization and a further erosion of trust in the food system and its governance. In the face of a rapidly transforming and increasingly distributed bio-innovation ecosystem, the challenge will be to converge on a vision and set of key principles that are shared globally across all stakeholders.

The polarized debate on the role of GMOs from the past decades continues to inform many stakeholders' perspectives on bio-innovation, including those of many consumers. Against the backdrop of the entrenched views on GMOs, today's rapid and profound transformation of bio-innovation offers an opportunity for a new type of conversation. If bio-innovation allows people to gain a better understanding of biological systems, can this enhanced understanding in turn support the effective and responsible use of bio-innovation? How will our perspectives continue to evolve of what is "natural", "organic", "conventional", "modern", "artificial" and "synthetic"? And how will new trends in bio-innovation shift values and views on a range of issues as diverse as intellectual property, sustainable consumption or animal welfare?

Against this background, the narratives, norms, business models and, indeed, the next-generation technologies themselves are yet to be shaped. Any collective effort to navigate the new context is both a big challenge and a big opportunity for all actors in society.

Box 3

Emerging government responses to gene editing

As gene edited agricultural products begin to move from the laboratory to the farm, the question arises about the type of governmental oversight needed to ensure safety to human, animals and/or the environment. Appropriate science-based and proportionate oversight could provide predictable and transparent rules that enable developers to bring products to market and an independent safety assessment that consumers can trust. Alternatively, overly stringent and costly regulation could prevent many beneficial products from entering the marketplace, while no regulation could cause consumers to question their safety.

The current global debate over how to regulate gene edited agricultural products can be summarized as a discussion of whether the gene edited product is or is not a GMO. If it qualifies as a GMO, then it is regulated. If it is more like "traditional" or "conventional" breeding, then it is not a GMO and escapes any significant safety oversight. Criteria being discussed to decide if the gene edited agricultural product is regulated include: (1) whether there is "foreign" DNA or a transgene in the final product; (2) whether the edit in the product is or could be "found in nature"; or (3) whether the edit could have been produced through "conventional" or "traditional" breeding methods, including chemical mutagenesis and irradiation breeding.

Most countries have not finalized their positions on this topic. The United States and Canada seem to be regulating gene edited agricultural products in the same fashion as they regulate GMOs. Countries such as Argentina and Israel have stated that they will look at each gene edited product on a case-by-case basis, with the answer about applying government oversight primarily dependent on whether there is foreign DNA in the final product. Other countries, such as New Zealand, have determined that gene edited products fall within their definition of a GMO. In the European Union, a recent European Court of Justice ruling stated that gene edited products are to be treated as GMOs under existing European legislation. The vast majority of countries have not yet made any definitive decision on regulating these products.

8. Looking ahead: Multistakeholder collaboration and governance

Navigating this fast-changing context of bio-innovation presents an exciting opportunity and will require a new chapter of multistakeholder dialogue, collaboration and action.

At a broader level, stakeholders need to support the idea that working together across sectors and disciplines forms the foundation for any progress. Embarking on this journey, no single actor or single group of actors can claim a monopoly on truth. Conversations should be grounded in mutual respect, transparency, inclusivity and good faith, placing at their core human and ecological imperatives to evaluating the role of bio-innovation. Stakeholders will also need to step out of traditional comfort zones, to engage with a diverse set of players, to understand and learn from a variety of viewpoints, as well as to question binary positions on the role of bio-innovation. This approach will help shift the dialogue from a zero-sum mentality towards a common-interest approach around new solutions and increased transparency.

The ultimate objective of any multistakeholder journey is to build a shared understanding, a shared vision, shared commitment and accountability, and a shared action agenda (see Box 4). These elements do not fall into a clean, linear process but are dynamic and interrelated, continuously influencing each other. For example, joint action will inform shared understanding and reshape the shared vision over time.

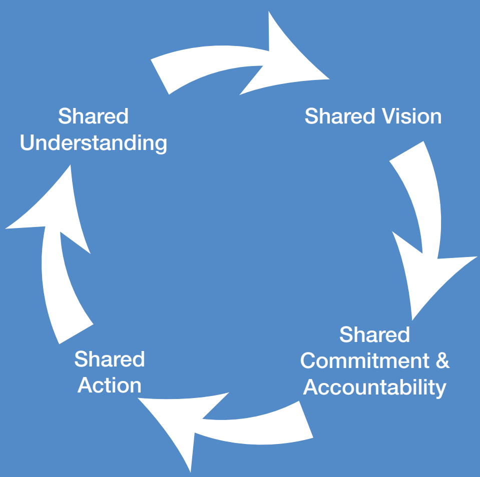
Box 4

Building a shared vision

- Align on a common purpose (Why are we embarking on journey?)
- Articulate opportunities and challenges from bio-innovation (What impact do we want to see, and for whom?)
- Identify shared reference points, such as the SDGs (What do we measure progress against?)

Building shared commitment and accountability

- Facilitate ownership and continuity through an engaged network of relevant stakeholders (Are we committed to the journey and what we want to stand for collectively?)
- Promote transparency and accountability (What interests and perspectives are represented? What voices are missing?)



Building a shared action agenda

- Articulate shared principles (What are the framework conditions for collaboration and action?)
- Converge on new governance solutions for bio-innovation (What actions do we want to take to drive impact?)

Building shared understanding

- Converge on the scope and definition of bio-innovation in the food system (What are we talking about?)
- Identify and contextualize key trends in bio-innovation and their implications (What is happening and what does it mean?)
- Identify open questions and knowledge gaps (What is it we don't know?)

Connecting existing efforts

Given the distributed nature of multistakeholder conversations in this area, raising the greater awareness of and connecting various relevant initiatives are needed. By mapping and strengthening interlinkages between existing efforts, the "conversation of conversations" will become more diverse, inclusive and robust. Over time, expanding this network will be instrumental in building out an impactful community of learning, interest, purpose and action.

Given the breadth and complexity of bio-innovation in food systems, the task of capturing initiatives in a clearly structured, let alone exhaustive, fashion is challenging. Box 5 lists some illustrative examples of initiatives that seek to build connectivity and alignment across stakeholders and are relevant for the interplay of biotechnology with environmental, economic and governance questions. Moving forward, special attention should be paid to regional diversity, ensuring that developing country-based initiatives can contribute effectively to the conversation.

Box 5

Bio-innovation governance – Illustrative examples of relevant initiatives

BioBricks Foundation (BBF) projects: The BBF is a charity whose mission is to "advance biotechnology in an open and ethical manner to benefit all people and the planet".[33] Ongoing projects include the bionet,[34] a free-to-use, peer-peer information and inventory management system supporting the scalable exchange of functional biomaterials, the Open Material Transfer Agreement[35] and the SBx.0 conferences gathering leading practitioners of synthetic biology to openly discuss the evolution of the field.

Coalition for Responsible Gene Editing in Agriculture: This coalition was formed by leaders in the fields of science, agriculture and ethics in 2016 as a project of the Center for Food Integrity.[36] The coalition's mission is to cultivate support for the responsible use of gene editing in agriculture, and it understands the importance of engaging stakeholders in that process. It is led by organizations from the fields of science, agriculture and food production and engages with other relevant stakeholder groups, including civil society. The Coalition has developed "Principles and Guidelines for Responsible Use of Gene Editing in Agriculture".[37]

Cornell Alliance for Science: This initiative seeks to promote access to scientific innovation as a means of enhancing food security, improving environmental sustainability and raising the quality of life globally. It looks to build a global network of science allies who share a commitment to solve complex global hunger issues by leveraging advances in agriculture, including biotechnology.[38] Through networks, trainings and communications, the Alliance aims to empower the scientific community and improve the way it engages with other stakeholders.

CRISPRcon: Together with key partners in the scientific community, the Keystone Policy Center brings together leading voices from diverse sectors to discuss the future of gene editing technologies across a variety of applications, including conservation, health and agriculture. Following multistakeholder events in Berkeley, California and Boston, Massachusetts in 2017 and 2018, the organizers and the CRISPRcon Steering Committee are exploring how to best multiply and regionally diversify the conversation.[39]

Engineering Biology Research Consortium: The EBRC aims to be the leading organization bringing together an inclusive community committed to advancing biological engineering to address national and global needs. It is comprised of academic members from over two dozen US universities and biotechnology firms, ranging from start-ups to multinational conglomerate companies.[40]

IUCN Task Force on Synthetic Biology and Biodiversity Conservation: The IUCN in 2016 initiated efforts to examine the impacts of the production and use of the products resulting from synthetic biology on the conservation and sustainable use of biodiversity, engage in ongoing discussions and deliberations with the synthetic biology community, and develop guidance on the topic.[41] Scientists and experts from diverse disciplines, geographies and sectors comprise a task force guiding this work.[42]

OECD Working Party on Biotechnology, Nanotechnology and Converging Technologies (BNCT): This Working Party of the Organisation for Economic Co-operation and Development (OECD) aims to "contribute original policy analysis and messages to the global community, and to make ground-breaking proposals to policy makers. It advises upon emerging policy issues related to the responsible development of biotechnology, nanotechnology and converging technologies, and assists [OECD] Member countries in understanding and managing the changing nature of research, development and innovation".[43]

Scholarly Publishing and Academic Resources Coalition (SPARC): SPARC aims to "enable the open sharing of research outputs and educational materials in order to democratize access to knowledge, accelerate discovery, and increase the return on our investment in research and education. As a catalyst for action, SPARC focuses on collaborating with other stakeholders—including authors, publishers, libraries, students, funders, policymakers and the public—to build on the opportunities created by the Internet, promoting changes to both infrastructure and culture needed to make open the default for research and education".[44] While US-centric, the initiative has global affiliates in Europe, Japan and Africa.

World Economic Forum Young Scientists community: This community brings together the forward-thinking young scientific minds of the world, selected from all regions and a wide range of disciplines, including biology, physics, environment and computing.[45] The Code of Ethics[46] is the result of the community's collective reflection on the cross-cutting ethical issues they are faced with, as well as thorough and extensive consultations with researchers and ethicists around the world.

A multitude of additional organizations and initiatives around the world are advancing relevant conversations, often with a more targeted national or regional purview. The deliberations on regulating gene editing technologies by the Norwegian Biotechnology Advisory Board;[47] the work of the African Biosafety Network of Expertise (ABNE);[48] the European Commission's Food 2030 Initiative, Bioeconomy Strategy and Open Science initiatives;[49] the US National Academy of Sciences and the National Academy of Medicine's Human Genome Editing initiative;[50] the Genetic Engineering and Society Center at North Carolina State University;[51] the APEC High Level Policy Dialogue on Agricultural Biotechnology;[52] the University of Ottawa's Institute for Science, Society and Policy;[53] Arizona State University's Lincoln Center for Applied Ethics;[54] and the Agricultural Biotechnology Project of the Center for Science in the Public Interest[55] are just a few examples. In addition, global multilateral organizations, such as the World Trade Organization, World Health Organization or the United Nations Environment Programme, address issues related to bio-innovation.

The Bio-Innovation Dialogue Initiative of the World Economic Forum should explore and, where appropriate, facilitate closer collaboration with relevant existing and emerging conversations, such as those mentioned above.

Building systemic governance solutions

Leveraging a diverse network of relevant actors and initiatives, stakeholders should identify the gaps in today's fragmented governance structures for bio-innovation in the food system, and work towards building a more holistic framework. New research on emerging technology governance should inform this effort.[56]

Structurally, a more systemic governance architecture could centre on a "trusted broker" or global coordination hub that can respond to a more distributed and complex bio-innovation landscape by:

- Providing a comprehensive and dynamic overview of relevant actors and activities in bio-innovation
- Ensuring connectivity and, where possible, consistency and coordination among existing governance efforts
- Building broad public and multistakeholder engagement and earning trust in bio-innovation governance
- Facilitating the development of new governance concepts and prototypes, at the global, national and local levels.

The increasing decentralization of bio-innovation across industrial, sectoral and political boundaries requires exploring the role of all the tools of hard and soft governance that exist, as well as experimenting with novel frameworks.

Balancing diverse levels of governance, from local to global, is an important consideration in the new context of bio-innovation. At one end of the spectrum, a rapidly growing number of local actors and applications will require locally developed and owned governance solutions. Governance solutions would then be aligned with local needs and culture, and local communities would be empowered to make their own benefit and risk assessments. At the other end of the spectrum, the global implications, even of local activities, on shared natural resources and biodiversity, cross-border ecosystems and trade, and our shared culture of ethics call for more general principles and guideposts. In addition, the trend towards more open and distributed bio-innovation is underpinned by large-scale data and technology platforms, whose ownership and influence raise global governance questions in their own right. Last but not least, national governments will continue to play a crucial role in setting framework conditions for bio-innovation, for example by providing research funding, defining rules for competition and intellectual property, ensuring food safety and providing information to the wider public.

Stakeholders acknowledge that the following are among the high-priority areas for advancing coordination in bio-innovation governance:

- Public and multistakeholder engagement, communication and education efforts on bio-innovation and related issues, inclusive of underserved communities, with a view to fostering transparency, enhancing understanding and facilitating public discourse
- Global Codes of Conduct, quality standards and information requirements for research and innovation using biotechnologies
- Best practice sharing and alignment across national jurisdictions on emerging biotechnology governance
- Shared depository for logging potential benefits, risks and issues (resolved and open), including the identification of gaps in shared knowledge, data and metrics

– Shared principles, risk assessment protocols, risk management and contingency planning for high-risk applications of biotechnologies (such as gene drives)

– International harmonization of regulatory regimes with a view to safeguarding the international trade of food, food ingredients and bio-based inputs, as well as any biological materials required for the pursuit of cross-border research and innovation

– Coordinated development of open innovation policies, standards and practices, including the governance of data and technology platforms underpinning bio-innovation.

The Bio-Innovation Dialogue Initiative of the World Economic Forum will make use of relevant upcoming workshops and events to facilitate multistakeholder conversations that help advance the definition of a more comprehensive governance framework for bio-innovation in the food system.

9. Conclusions

Shaping the future of bio-innovation in the food system presents a tremendous opportunity for all stakeholders.

Looking back, bio-innovation has been an integral part of a food system that, especially since the 1960s, has managed to dramatically increase world food production through technological innovation and economic efficiency. Economies of scale in research and development, production, marketing and distribution across sectors have shaped the evolution of the food system, reflected in more consolidated and centralized economic and governance models. Looking ahead, the next wave of bio-innovation can serve as a powerful enabler for a future food system that promotes access to more diverse, nutritious and sustainable food through a diversity of actors and solutions, the smarter stewardship of natural resources, holistic ecosystem approaches, and an improved understanding and use of biology and biodiversity.

Current trends in bio-innovation offer a promising perspective in this regard. However, the onus is on all stakeholders to collaborate and learn from each other, connect existing conversations and initiatives across sectors and disciplines, and converge on holistic governance solutions that can respond to society's needs and earn its trust.

To that end, the organizations and individuals engaged in the Bio-Innovation Dialogue Initiative of the World Economic Forum are committed to advancing a forward-looking "conversation of conversations" to help define a more holistic governance framework for bio-innovation in the food system, as proposed in Section 8.

The overriding purpose of this discussion paper is to prompt further conversation and invite additional voices that have not engaged to date to join a shared journey. All stakeholders are therefore welcome to share their comments and perspectives to help shape a future vision and roadmap for action.

For further information on the Bio-Innovation Dialogue Initiative and how to get involved, please contact Christian Kaufholz, Community Lead, Agriculture, Food and Beverage Industries, at Christian.Kaufholz@weforum.org.

Acknowledgements

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*On 7 June 2018, Monsanto was acquired by Bayer. As a condition of the US Department of Justice approval of the transaction, Monsanto will operate independently from Bayer for an interim period while Bayer completes the sale of some of its businesses to BASF.

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