DISCOVERY REPORT

An ACS member exclusive

ACS Chemistry for Life®

How will chemistry help solve world hunger?

Over 690 million people don't have enough to eat.

c&en BRANDLAB

Achieving Zero Hunger

Hunger has always been an unfortunate reality for many people. The global poverty-fighting organization Oxfam estimates that about 6 million people die of starvation every year, or 11 people per min. The United Nations has estimated that 22% of children under 5 worldwide suffer from stunting (low height for their age), a sign of long-term undernourishment. Stunting is also connected to cognitive underdevelopment—children with the condition are less likely to complete school and will be less productive as adults (World Health Organization, *Matern. Child Nutr.* 2016, DOI: 10.1111/mcn12231).

While hunger has long been a concern, an alarming shift has occurred in recent years: the number of hungry people began increasing. The levels had been gradually falling for decades, reaching under 600 million people in 2014. But the trend has reversed—the UN estimates that 750 million people faced hunger in 2021.

This troubling rise is driven by interconnected crises of supply chain disruptions, war, and an unstable climate. While these are complex problems without easy solutions, scientists and engineers are well adapted to addressing such problems. That is the entire point of the job. What question could be more urgent or intellectually stimulating than feeding the world?

In 2015, the UN set 17 sustainable development goals. The second of these is to achieve zero hunger by 2030 by improving food security and nutrition through sustainable agriculture practices. While ending world hunger in line with the UN's goal will be challenging, there is still time to make substantial progress. Hunger is a tragedy but is also an opportunity for innovation, creativity, and collaboration. Today's technologies and scientific discoveries are necessary for long-term nutritional and food security.

The American Chemical Society responded to the UN's program by launching the Campaign for a Sustainable Future. It is designed to advance chemistry innovations that address the UN's goals. As part of its initiative, the ACS convened the Zero Hunger Summit, a digital event that explored how the chemical sciences and engineering can support a world without hunger. The December 2022 event brought together scientists from across academic disciplines, including experts from government, universities, and businesses of all sizes.

This Discovery Report is inspired by the presentations and discussions at the summit and highlights how chemical innovations are being used to fight hunger. We hope this draws attention to the urgency of the food crisis while inspiring like-minded scientists and engineers to join this effort so we can one day reach zero hunger.

Adelina Voutchkova, PhD
Director, Sustainable Development

INSIDE

CHEAT SHEET

5 questions about the present and future of agriculture, hunger, and climate change

P.5

FROM THE FRONTLINES

Speakers at the ACS Zero Hunger Summit

P.6

ANALYSIS

Smart farms combat climate change

P.8

Farms of the future: Innovative chemistry is changing agricultural practices

P.12

From farm to landfill

P.17

COMPANIES TO WATCH

Chemistry start-ups address food security and sustainability

P.20

MOVERS AND SHAKERS

Teaming up to tackle hunger: spotlight on collaboration

P.22

RECOMMENDATIONS

How scientists and engineers can fight world hunger

P.24

Published by

c&en BRANDLAB

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ACS Chemistry for Life®

CHEAT SHEET

5 questions about the present and future of agriculture, hunger, and climate change

Why is hunger on the rise?

» **The COVID-19 pandemic disrupted food supply chains, causing food prices to spike.** The UN estimated that over 3 billion people could not afford a healthy diet in 2020—an increase of more than 100 million from just the year before.

» **The Ukraine-Russia war has had a significant impact on global food security.** Combined, these countries were responsible for 20% of maize, 30% of wheat, and 80% of sunflower seed product exports.

» **An estimated one-quarter of the global population lives in regions affected by armed conflict.** There are more violent conflicts today than at any time since World War II. These hostilities interfere with agriculture and supply chains.

» **Climate change is interfering with crop yields.** Between increased temperatures and extreme weather events, global warming is already affecting agricultural productivity.

Are some places worse than others?

» **Lower income means higher risk.** Wealthy countries can import food and invest in agricultural infrastructure. Low-income countries are sensitive to increases in food prices.

» **Extreme weather events can create a region-specific crisis.** Events such as storms and heat waves can devastate farms.

» **Sub-Saharan Africa has a high rate of hunger.** Low economic resources, armed conflict, increased vulnerability to climate change, and a rapidly growing population have led to a food security crisis in the region.

» **Hunger is declining in the US.** Food insecurity fell from about 12.5% of households in 2015 to 10% in 2021.

What is the connection between climate change and agriculture?

» **Crops grow slowly at higher temperatures.** Every plant has a temperature range for optimum growth. Heat-tolerant crops can help mitigate this problem.

» **Extreme weather events are worsening.** Climate change is increasing the frequency, intensity, and duration of extreme weather events such as droughts and floods.

» **Agriculture is a major source of greenhouse gas emissions.** Fertilizers, transportation fuels, methane production, and other contributions make food production responsible for 25–35% of global greenhouse gas emissions.

» **Farms require a lot of land.** Over half the land in the US is farmland, which typically sequesters less carbon than natural ecosystems.

How have chemists and engineers historically supported the agricultural industry?

» **Synthetic fertilizers.** The Haber-Bosch process for catalytic production of ammonia was discovered in 1909 and is still used to make most of the world's fertilizer.

» **Pesticides.** An estimated 25% of crops are lost to pests; that percentage could be as high as 75% without pesticides.

» **Refrigeration.** Refrigerators are both an everyday convenience and a critical technology within the food supply.

» **Packaging materials.** Food needs to be wrapped to protect it from pests and damage and retain quality. Materials such as plastics help improve shelf life.

What opportunities are there for chemists to support agriculture in the future?

» **Sensors.** Precision agriculture technology, food safety equipment, and life-cycle-assessment research benefit from more and higher-quality chemical data.

» **Sustainable and effective pesticides.** Pests—especially weeds—are becoming resistant to many popular pesticides. Chemists need to find pesticides that are both effective, and environmentally sustainable.

» **Plant and soil biochemistry.** Can crops be engineered to be heat tolerant? How do soil microbiomes influence plant growth? How do we optimize carbon sequestration in the soil? Many critical questions remain unanswered.

» **Environmentally sustainable food packaging.** Single-use food wrappers are a major source of plastic waste. Sustainable materials will help reduce the waste burden.

Sources: Food and Agriculture Organization of the United Nations, United Nations, Intergovernmental Panel on Climate Change, Economic Research Service US Department of Agriculture.

FROM THE FRONTLINES

Speakers at the ACS Zero Hunger Summit bring cross-disciplinary expertise to explore the role of chemistry in addressing hunger and food security

Ashish Batra
(PANELIST)

» **Corteva Agrisciences**

Denise Bouvrette-McKinney
(PANELIST)

» **Bayer Crop Science**

Hongda Chen
(MODERATOR)

» **United States Department of Agriculture**

Wan-Ting (Grace) Chen
(PANELIST)

» **University of Massachusetts Lowell**

H. N. Cheng
(KEYNOTE SPEAKER)

» **Immediate Past President, American Chemical Society**

Thomas Connelly
(HOST)

» **CEO, American Chemical Society**

Paul Dauenhauer
(MODERATOR)

» **University of Minnesota**

Stephen Duke
(PANELIST)

» **University of Mississippi**

Molly Elrick
(PANELIST)

» **The Climate Corporation**

Kelly Gillespie
(PANELIST)

» **The Climate Corporation**

Jillian Goldfarb
(PANELIST)

» **Cornell University**

Vid Hegde
(MODERATOR)

» **Corteva Agrisciences**

Shannon Kenny
(PANELIST)

» **Environmental Protection Agency**

Jakub Kostal
(PANELIST)

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» Director of Sustainable Development, American Chemical Society

Catherine Woteki
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» Member of President's Council of Scientific Advisors

ANALYSIS

Climate smart agriculture involves practices designed to support farming in a warming world. CREDIT: ANDRESWD/ GETTY IMAGES

Smart farms combat climate change

Global warming is here. Temperatures are about 1 °C over preindustrialized levels now, and current trajectories indicate that could rise to 5 °C by 2100 (*Nature* 2020, DOI: 10.1038/d41586-020-01125-x). Crop yields are threatened by these higher temperatures and the growing frequency of extreme weather events, including heat waves, storms, and droughts, caused by global warming.

Climate-smart agriculture is a set of farming practices designed to be compatible with the warming climate. According to the World Bank, it addresses both the challenge of food security and climate change by pursuing three goals:

» Enhanced resilience to extreme weather events
» Increased crop productivity
» Reduced agricultural carbon emissions

This section explores the necessity of these actions and how researchers—in academia and the private sector—are finding innovative solutions to support climate-smart agriculture.

Disaster-ready crops

The extreme weather events of 2022 were devastating. East Africa is experiencing its worst drought in more than two generations; UNICEF estimated that over 20 million children were at risk of severe hunger in December. The foreign minister of Pakistan told reporters that floods in the country damaged 80–90% of its crops and killed 800,000 livestock. The year 2023 began with a series of floods in California that may have caused as much as a trillion dollars in damage.

These catastrophes are on the rise. In the US, the number of disasters resulting in costs of over $1 billion have surged in the past 40 years. While it is challenging to prove a given event was caused by climate change, there is strong evidence that global warming increases the frequency, intensity, and duration of extreme weather events. For example, the World Weather Attribution Project estimates that climate change made floods in West Africa in 2022—events that killed more than 800 people and damaged over half a million hectares of farmland—80 times as likely and 20% more intense.

Storms, heat waves, and droughts can devastate food supplies for entire regions. This is an enormous risk for farmers and consumers, who face constrained supply or higher prices for the affected crops. Populations in low-income countries are particularly vulnerable because they lack the economic resources and robust supply chains to import food to cover shortfalls in local crops.

The situation is concerning, but several low-tech methods may help improve crop resilience in the face of extreme weather. "We can change planting days, grow different varieties or even different crops. We can employ irrigation systems to conserve water to ensure we have production in the case of droughts. We can manage soil using conservation agriculture," says Megan O'Rourke, national science liaison at the US Department of Agriculture's Institute of Bioenergy, Climate, and Environment.

Beyond this, many scientists and engineers are searching for innovative strategies to increase crop resiliency. A clever approach is short-stature corn such as the varieties developed by Bayer Crop Science. The most popular varieties of corn can reach 3.5 meters (12 feet). Fast-growing corn is weak, so a strong wind can cause it to break, spoiling the corn and ruining the yield for the farmer. This is known as green snap or brittle snap.

"When we ask our customers about their biggest challenges when producing corn in the US, one of the things that always seems to rise to the top is storm damage and the yield losses farmers see," says Denise Bouvrette-McKinney, the North America corn project and launch lead at Bayer Crop Science.

By targeting a hormonal pathway responsible for stalk elongation, Bayer Crop Science produced a variety of corn that reaches a maximum of approximately 2 meters (7 feet). This lower height reduces the strain on the stalks during turbulent weather. "We have been able to create a shorter-stature plant that still looks and acts like corn," Bouvrette-McKinney says. "We see an inherent improvement in standability of these plants." Increased resilience has been achieved while preserving typical corn characteristics, such as growing time or the average number of cobs per stalk.

The tall stalk of fast-growing corn makes the plant vulnerable to breaking during storms. CREDIT: KKSTOCK/GETTY IMAGES

Powering up plant biochemistry

The fruits and vegetables we grow were not bred for the world of climate change. High temperatures stress plants, meaning yields could decline as the planet gets hotter. Given the growing global population, agricultural outputs will need to increase just as the temperature is rising. Opportunities for expanding cropland are limited, and the total amount of cultivated land will likely remain relatively flat in the coming years, meaning per-acre productivity will need to increase.

Genetic engineering and synthetic biology are effective tools for finding plants better suited to higher temperatures. Research by Donald Ort, professor of plant biology and crop sciences at the University of Illinois Urbana-Champaign, demonstrated that the efficiency of photosynthesis could be improved by reducing the energy required to metabolize glycolate, a naturally occurring compound that inhibits photosynthesis. "What does this have to do with the warming climate? Our expectation is that the [activity of] glycolate metabolism pathways will increase with temperature," says Ort. Field tests have shown that transgenic plants with glycolate detoxification pathways grow faster than wild-type plants under ambient conditions while

In recent field studies, plants genetically engineered for efficient photosynthesis grew faster than non-engineered plants. CREDIT : PKUJIAHE/GETTY IMAGES

protecting against yield losses experienced at elevated temperatures (*Science* 2019, DOI: 10.1126/science.aat9077; *Plant Biotechnol. J.* 2021, DOI: 10.1111/pbi.13750).

The rise in carbon dioxide is also expected to have an impact on crops. Atmospheric CO_2 rose from about 320 ppm in 1960 to almost 420 ppm by the end of 2022. "The primary carboxylase of photosynthesis isn't substrate saturated by the current level of CO_2, and there is competition between CO_2 and O_2," Ort says. "It means when the CO_2 level goes up in the atmosphere, the rate of carboxylation goes up."

This has the net effect of leaving photosynthesis unbalanced, in which protein levels are not optimized to support efficient photosynthesis. One way to address this imbalance would be to adjust protein expression levels. Ort's team found that increasing the sedoheptulose-bisphosphatase (SBPase), an enzyme involved in the Calvin cycle, could help plant growth. When tested under heated conditions, transgenic plants with elevated SBPase had a 20% increase in biomass and growth (*BMC Plant Biol.* 2011, DOI: 10.1186/1471-2229-11-123).

Sustainable sustenance

Agriculture is a major source of greenhouse gas emissions, both directly and indirectly. While plants absorb CO_2, modern farming requires many other inputs, including fertilizers, pesticides, and water. Crops must also be transported and processed, which adds to agriculture's footprint.

Emissions are also a function of food choice. Meat is particularly inefficient: for example, it takes about 6 kg of feed to produce 1 kg of beef. "As more people move out of poverty, they desire better-quality diets—especially meat, fish, and dairy products," says Catherine Woteki, a professor of food science and human nutrition at Iowa State University and a member of the President's Council of Advisors on Science and Technology. "This is driving up the demand for grain to use as animal feed and increases the total amount of food that needs to be produced."

Ruminant animals such as cows and sheep also generate massive amounts of enteric methane during digestion. Methane has about 80 times the greenhouse gas impact of CO_2 in the first 20 years of its release (*Animals* 2021, DOI.org 10.3390/ani11040951). About 40% of carbon emissions from agricultural production come from the enteric fermentation of ruminants or their waste in pastures.

But what if cows generated less methane? Scientists are actively exploring whether certain feed additives or perhaps manipulating the stomach microbiome could reduce the amount of methane cattle produce, according to Jillian Goldfarb, an associate professor at Cornell University's College of Agriculture and Life Sciences. While none of these interventions has yet achieved widespread adoption, some interventions show promise (*Animals* 2021, DOI: 10.3390/ani11040951).

Improving plant-based and cultivated meat could reduce the demand for conventional meat as well. However, according to the Good Food Institute, consumers remain concerned about taste, cost, texture, and health effects. To address these issues, chemists, biologists, and food scientists are actively researching the development of ingredients that are tasty, safe, healthy, and sustainable (*Appetite* 2021, DOI: 10.1016/j.appet.2020.105058).

Life-cycle assessment

Interest in sustainable products can sometimes seem to be driven by marketing hype rather than hard science. Every chemist and engineer knows that environmental impact is complicated and that there are plenty of opportunities for greenwashing. How can we accurately determine which farming practices are the most environmentally friendly?

Life-cycle assessment (LCA) attempts to answer this question. "LCA is essentially an accounting framework that captures the material and energy flows within a bounded system," says Greg Thoma, a professor of chemical engineering at the University of Arkansas, at the time of the Zero Hunger Summit. That system's inputs and outputs can then be analyzed to evaluate the ultimate effect on the environment.

This systems-level thinking is critical for addressing the environmental impact of agriculture. Food systems are complex, with dozens of factors influencing every product before it reaches the consumer. LCA allows experts to identify the most important sources of environmental cost so that strategies can be developed to improve environmental performance meaningfully. Neglecting this analysis can also lead to so-called solutions in which one environmental cost is traded for another or transferred elsewhere within the system.

Sources: Intergovernmental Panel on Climate Change, ACS Zero Hunger Summit, World Resources Institute


Research into feed additives for cows could reduce the amount of methane, a potent greenhouse gas, they burp. CREDIT: SEBASTIANKNIGHT/GETTY IMAGES

Farms of the future: Innovative chemistry is changing agricultural practices

Farming efficiency has improved dramatically in recent decades. According to the US Department of Agriculture, total agricultural output in the US roughly tripled between 1948 and 2017. This was despite a substantial drop in the number of farmers, from almost 10 million in 1950 (approximately 7% of the population) to about 2.6 million in 2021, or about 1.3% of the population. These remarkable productivity gains are a result of many factors, including better seed varieties, widespread use of pesticides and fertilizers, and improved equipment.

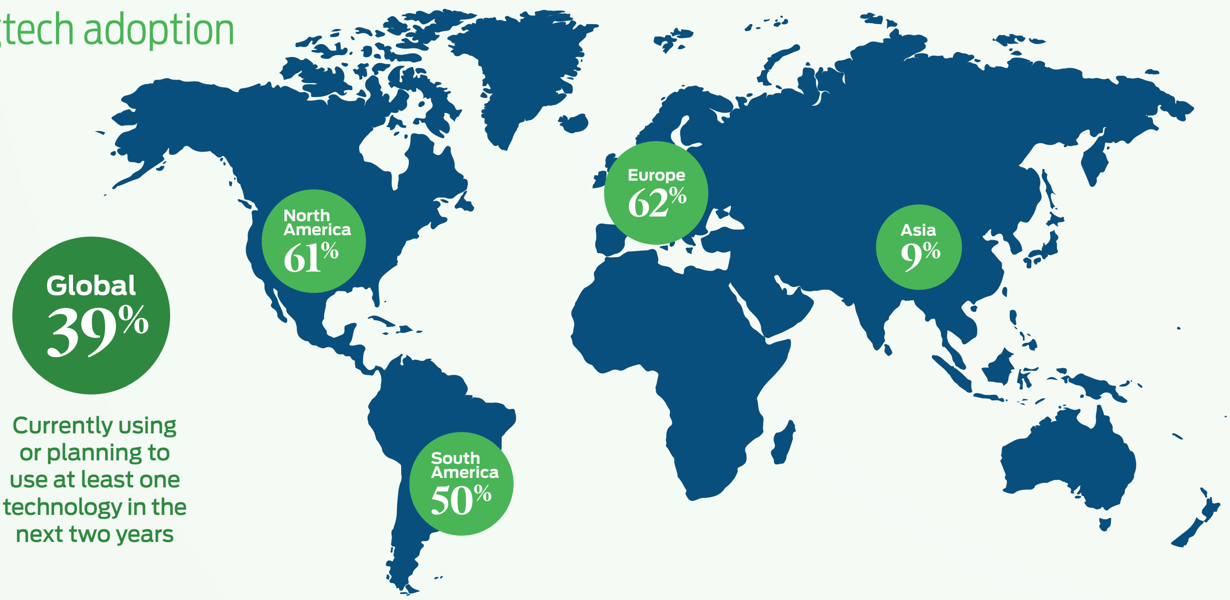
The success of the technologies boosting agricultural productivity have put pressure on farmers to continually innovate, particularly given increasing global hunger. Chemists and engineers are providing novel solutions that help growers make the most of the earth at their feet.

Farmer's dilemma

As farming productivity has increased, so too has the field's complexity. This can be captured in the explosion of decisions growers face. "About 40 years ago, a grower would make about 20–30 decisions during the growing season," says Kathleen Shelton, executive vice president and chief technology officer at FMC Corporation. Today, she says, they must make "about 400 decisions."

Why has that number risen so much? As new seed varieties, pesticides, and farming practices become available,

Agtech adoption



Farmers around the world are adopting agricultural technologies such as remote sensing, farm automation, and farm management software at varying rates. Adapted from McKinsey

Farmers can now plot crop yield across a field, offering opportunities to apply principles of precision farming such as localizing the application of fertilizer and pesticides. CREDIT: MONOPOLY919/ SHUTTERSTOCK

growers must select what is best for their situation. "Agriculture is a very local practice," Shelton says. "It adapts to and addresses crops that are being grown in local environments, with local practices, with local conditions and local pests."

Dianne Newman, a professor of biology and geobiology at the California Institute of Technology, echoes this observation. "Every soil is different," she says. "We need to think through different approaches for different soils and different crops. Moreover, even within a given soil, there is heterogeneity spatiotemporally."

Steven Mirsky, a research ecologist at the US Department of Agriculture, shares a heat map of yield in a single corn field. Yields varied from 87 to 250 bushels per acre—an almost 300% difference. Molly Elrick, director of the science enabling team at The Climate Corporation, shares a similar heat map showing yields varying by 75 bushels per acre across a field.

Farmers must address this variation to maximize their efficiency, which is one of the reasons for the growing interest in precision agriculture.

Decisions and precision

Precision agriculture is a set of practices designed to offer site-specific crop management. A combination of imaging technology, sensors, and weather monitoring tools are fed into computer models, which then generate recommendations for farmers. Precision agriculture may incorporate robotics and automation to carry out these recommendations. Ideally, this would allow farmers to optimize the production of every plant in their field while limiting the need for seeds, pesticides, fertilizers, and water.

In addition to improving yields, precision agriculture has the potential to be a radically disruptive technology for the agrochemical industry. For example, most pesticides are applied to entire fields with the goal of protecting against a broad spectrum of pests over a long period. Precision agriculture means farmers might greatly reduce their overall pesticide usage or switch from broad-spectrum, long half-life formulations to targeted, short half-life alternatives. "These will change the economics of the pesticides industry dramatically," says Stephen Duke, a University of Mississippi research professor.

> "We need accurate cloud-based, connected sensors for soil. These advancements would be key in establishing the ground truth that data scientists need to build machine learning predictive models."
>
> — Molly Elrick, The Climate Corporation

Beyond pesticides, precision agriculture can help farmers rationally select seeds through an analysis of a field's drainage, pH, and other soil properties. The data can also suggest a density of crops predicted to improve yield. Farmers can even use digital platforms to better understand their environmental impact and carbon footprint.

One of the things that will help propel precision agriculture forward is better chemical data. "We need accurate cloud-based, connected sensors for soil," Elrick says. "These advancements would be key in establishing the ground truth that data scientists need to build machine learning predictive models."

A cover crop grows between rows of harvested stalks.
CREDIT: MVBURLING/GETTY IMAGES

One example of a regenerative agriculture practice is no-till farming. "Farmers typically use a tilling implement to turn over the soil," says Kelly Gillespie, vice president of digital ecosystem services at The Climate Corporation. "In the Northern Hemisphere, this increases soil temperatures, meaning farmers can plant at a more reasonable time. It's also a weed control measure, breaking up the weed bed that may have grown over the winter." These benefits come at the cost of losing small amounts of topsoil to wind and runoff each year. Farmers can skip the tilling to maintain soil quality.

Another regenerative practice is the use of cover crops. A cover crop is a nonmarketed crop that acts as ground cover and is typically not harvested at the end of its growth cycle, Gillespie says. "It's a legume, rye, or a radish mix that the grower can plant after they harvest their cash crop. It continues to photosynthesize and is able to sequester carbon in the soil. It also helps with erosion and can help with weed control."

While many regenerative agricultural practices offer long-term benefits for soil quality and crop yields, there are trade-offs in price and complexity. "We are really struggling to get large-scale adoption of cover crops," Mirsky says. "A lot of that has to do with the challenges of getting it established." A survey conducted by Bayer Crop Science found that farmers are worried about the possible effect regenerative farming practices might have on the yield of their cash crop.

A limitation of these sustainable farming practices is lack of precision. When farmers implement no-till farming, cover crops, or any other regenerative practice, they typically apply the method to an entire field—an approach that ignores variation. Precision sustainable agriculture, which aims to combine the benefits of both precision and regenerative approaches to farming, has recently been gaining interest. An example of this is weeding robots, which use cameras to find and kill weeds within a field, reducing the need for pesticides and tillage. "This is no longer a pipe dream," Mirsky said. "New robotic weed control technology comes out annually. This is one of the hottest areas of technology for robots in agriculture."

Problems with pesticides

Among the most important—and controversial—components of modern agriculture are pesticides. This class of compounds, which can be divided into insecticides, herbicides, and fungicides, has a massive impact on crop yields. "About 25% of our crop productivity is lost due to pests, despite that we spend a tremendous amount of effort and money on mitigation of crop pests," Duke says. "Without this mitigation, the estimated loses of crop production would be almost 75%."

Yet concerns are intensifying that resistance to pesticides is diminishing their effectiveness. "We are really struggling, especially in weed science," Mirsky says, adding that the pipeline of chemistries is thin. Duke reinforces this view: "We haven't had any herbicides with new molecular targets that have had much influence on the market in the last 30 years. It's very difficult to deal with resistance at this point."

“About 25% of our crop productivity is lost due to pests, despite that we spend a tremendous amount of effort and money on mitigation of crop pests,”

— Stephen Duke, University of Mississippi

One of the challenges to developing effective pesticides is controlling persistence. Pesticides must last long enough to protect crops from relevant threats while being appropriately biodegradable. Duke shares a story that exemplifies this dilemma: “We developed an algaecide that worked beautifully in the laboratory, but its environmental half-life was 2 hours. It really didn’t work in a realistic agricultural situation.”

Fortunately, some researchers are working to expand the chemical space for novel pesticides. Jakub Kostal, an assistant professor of chemistry at The George Washington University, is using computational chemistry approaches derived from the pharmaceutical industry to discover pesticide candidates with better biodegradation properties. “Instead of trying to fix the intrinsic hazards and persistence with structural modifications after the fact, we can build from renewable alcohols, carboxylic acids, and esters, which tend to be far more benign and easier to degrade,” he says.

Ashish Batra, senior director of sustainability at Corteva Agriscience, says sustainability must be built into the entire agrichemical research and development process. Companies previously focused on pesticide efficacy during discovery, but by using chemicals that are derived or inspired by natural products, it’s possible to make the final item sustainable. “To ensure that you have a sustainable outcome, we have to embed sustainability at every stage throughout the chemical’s journey and every area of development,” he says.

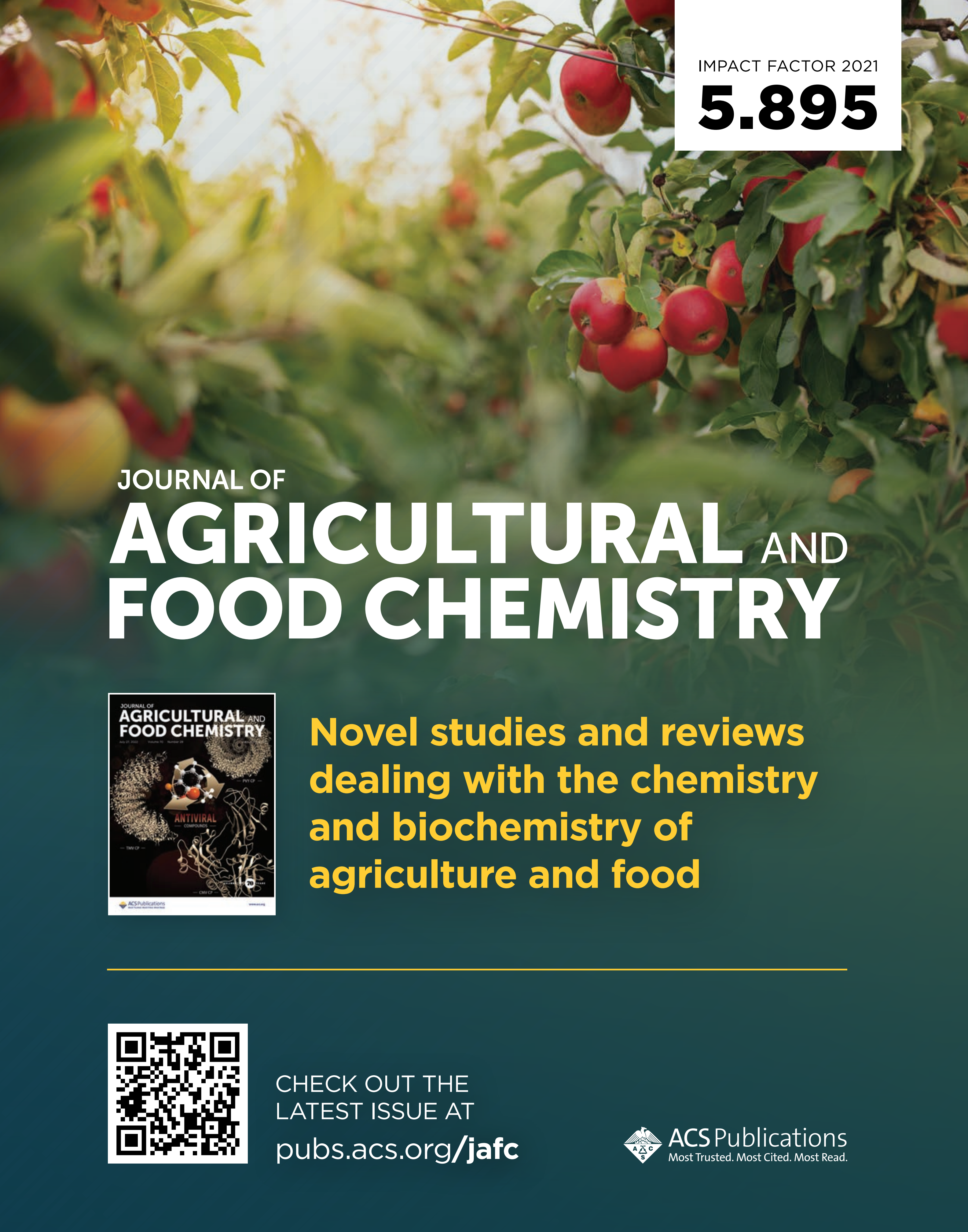
A complementary approach is developing tools that assist farmers in making decisions about effective pest management. Companies such as FMC and Trapview have created smart traps that monitor pest levels with cameras. This information can then be sent to FMC’s Arc farm intelligence app or other software systems that use computer models to predict near-term pest levels. “The grower has the understanding of and data for when to apply the insecticide and what pests might be most prevalent,” Shelton says.

Rapidly growing field

While farming technology has never been more advanced or adaptable, innovation is always needed. Chemists and engineers have plenty of research and development opportunities. This next generation of technologies will be essential to support farmers in their mission to feed the world.

Sources: US Department of Agriculture, ACS Zero Hunger Summit

Pesticides, herbicides, and fungicides mitigate crop pests and increase yields, but the pipeline for biodegradable molecules with new mechanisms of action is thin. CREDIT: FOTOKOSTIC/GETTY IMAGES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Reducing food waste is part of the United Nations' Sustainable Development Goals.
CREDIT: LUCAS NINNO/ GETTY IMAGES

From farm to landfill

Given the number of people worldwide who suffer from hunger, it might come as a surprise that there is in fact no food shortage. According to the United Nations, one-third of the food produced globally is wasted. This represents about 1.3 billion tons of food annually, valued at $936 billion, and may be more than enough to feed the hundreds of millions of hungry people.

"The key question is this: Have we done a good job to fully utilize the precious products our agricultural production systems are working so hard to provide us?" says Hongda Chen, national program leader for bioprocess engineering and nanotechnology at the US Department of Agriculture's National Institute of Food and Agriculture. "I'm afraid to say our scorecard does not look good. Actually, shockingly bad." The UN appears to agree with Chen's assessment and has asked countries to halve food waste by 2030 as part of its sustainable development goals.

How does so much good food go bad? "Food loss and waste happens at all stages of the supply chain and at consumption," Chen says. "About 14% is between the postharvest and retail stages, which is defined as food loss; 17% is at the retail, food service, and consumer stage, which we call food waste." This varies by country: low-income nations tend to lose more food as it moves through the supply chain because of a lack of refrigeration, while most waste in wealthy ones occurs in homes and restaurants.

Humans have attempted for millennia to extend food's shelf life, developing techniques to dry, ferment, and store these perishable goods. Scientists and engineers revolutionized food storage with refrigeration and plastic packaging in the 20th century. While these technologies have significantly increased shelf life, they have also had unfortunate environmental impacts. The hole in the ozone layer was primarily caused by chlorofluorocarbons (CFCs), which were used as refrigerants, and plastic waste is accumulating in landfills, oceans, and other natural habitats.

Maximizing food use and creating more sustainable solutions present many opportunities for improvement and innovation. Many experts are working to develop technologies to avoid food waste and loss. Before turning to solutions, though, it's good to first understand the problem's environmental impact.

Donating food, as shown at a food bank in Los Angeles, is near the top of the US EPA's Food Recovery Hierarchy as a strategy to prevent food waste. CREDIT: RINGO CHIU/SHUTTERSTOCK.

Wasted food, wasted resources

While food waste is not typically considered a climate issue, it is one of the key factors driving the environmental cost of food. Every loaf of bread that is thrown out represents energy, transport fuel, water, and farmland that has gone to waste. By decreasing our food loss and waste, we could boost the sustainability of the entire food system.

Shannon Kenny, a senior adviser on food loss and waste at the US Environmental Protection Agency, says EPA research on the environmental effects of such loss found that the water and energy wasted could supply 50 million homes and is responsible for emissions equivalent to 42 coal-fired power plants.

How can food loss and waste be addressed? Some solutions are preferable to others, and the EPA has structured these into a hierarchy: reducing the total volume of food waste is ranked as the best approach, while composting is less preferred. “Prevention strategies are always going to be the best,” Kenny says. “The only way to avoid environmental impact is not to waste food in the first place.”

Because some food loss and waste are inevitable, scientists are researching upcycling methods. Wan-Ting (Grace) Chen, an assistant professor in the plastics engineering department at the University of Massachusetts Lowell, is studying hydrothermal processing, which uses high temperature and pressure, to convert food waste into biofuel. “Hydrothermal processing has been proven to be an energy-efficient method for converting wet biomass, especially food waste, into energy-dense biocrude oil,” she explains.

Hydrothermal processing has advantages over other conversion processes. It requires temperatures of only 250–500 °C, significantly lower than those in pyrolysis (500–750 °C) and gasification (>800 °C). Food waste contains significant amounts of water, which is compatible with hydrothermal processing but will interfere with the efficiency of other methods.

Progress in packaging

One of the most common tools for protecting quality and reducing food waste is packaging. Food packaging thwarts pests and guards against physical damage, while offering a canvas for nutritional and marketing information. Most food comes in a package made from paper, metal, or plastic. Single-use plastic packaging has become a critical environmental concern. One study estimated that 12 billion tons of plastic could be in landfills and the natural environment by 2050 (*Science* 2017, DOI: 10.1126/sciadv.1700782). Many polymer chemists are investigating biodegradable and biobased polymer alternatives for a variety of applications (*Curr. Opin. Green Sustainable Chem.* 2020, DOI: 10.1016/j.cogsc.2019.12.005).

What about recycling? Unfortunately, plastic food packaging and recycling have a troubled relationship. To achieve optimal performance, packaging is often made from multiple layers of plastic—even the plastic used in a bag of potato chips often contains five or more layers of material.

Plastic food packaging can be made with multiple layers of plastic that are hard to separate during recycling. CREDIT: SERGEYRYZHOV/GETTY IMAGES

Though each layer may be recyclable individually, it's often not practical to separate them. In addition, food packaging plastic is often mixed in with food waste, which interferes with recycling.

There are also concerns about the safety of recycled plastic in food packaging. Recycled plastic could contain toxic chemicals or microbes that move into the food. Researchers have found that recycled plastics do contain elevated levels of many contaminants, though Yelena Sapozhnikova, a chemist for the USDA's Agricultural Research Service, points out that those levels may not represent a risk to consumers. One workaround is the use of recycled plastics as the middle layer in a multilayered plastic product, but possible leaching of organic contaminants into food still poses a concern.

Generally, more research into the safety of food packaging is needed, according to Sapozhnikova. About 12,000 chemicals are intentionally added to the packaging, and companies do not have to disclose all the components. "We know very little about the identities or levels [of chemicals] used in the production of food contact materials," she says. And beyond the 12,000 chemicals is a galaxy of unintentionally added compounds, such as impurities or degradants. Sapozhnikova notes that the list of regulated chemicals and the levels at which they are regulated differs by country, further complicating the picture.

Several food packaging strategies to reduce food waste nudge customers to change habits. One example is offering products in smaller quantities, such as half loafs of bread. Another would be revising the date-labeling system. Survey data shows that many people believe the date on a product relates to its safety, according to Kenny. "With the exception of infant formula, that's largely not true," she says. A change in the system could be complemented by public education campaigns to reduce anxiety about consuming food past its "best-before" date.

One bad apple

Beyond packaging, food quality and shelf life can be protected within the supply chain using detectors and sensors. However, there are barriers to widespread adoption of these technologies. "Quality detection technology methods for food and agriculture are limited," says Bosoon Park, lead scientist at the USDA's Agricultural Research Service. "Detection must be real time, or near real time, with minimum sample preparation." Many food safety tests rely on culturing and growing pathogens, which is incompatible with real-time testing.

Optical sensors are better suited for real-time testing. "Optical methods are a promising approach for rapid detection," Park says. "Hyperspectral microscope imaging technology can detect foodborne bacteria at the single-cell level using spectra, morphology, and scattering intensity information."

Blueberries bruised during transport have a shortened shelf life. CREDIT: UZHURSKY/GETTY IMAGES

Monitoring quality along the food chain can ultimately lead to longer shelf life. Park shared an example of blueberries. The fruits are sometimes bruised or otherwise damaged during transport, which decreases their shelf life substantially. Optical sensors could help detect bruised blueberries. That in turn would reduce the chance of the resulting rot spreading and would help identify the source of the damage. That approach would likely rely in part on artificial intelligence.

Many advancements have been made in food safety detection technology that should be available to low-income countries to impact world hunger. State-of-the-art food testing equipment is expensive and requires specialized training to use. Inexpensive food-testing instruments that are easy to use could have a meaningful impact on global food security.

Sources: United Nations, ACS Zero Hunger Summit

COMPANIES TO WATCH

Chemistry start-ups address food security and sustainability

Carbon Direct

» **carbon-direct.com**
» **Based:** New York City
» **Founded:** 2019

» **Strategy:** While the world is attempting to rapidly transition to low-carbon energy sources such as wind and solar, there is still a need to decarbonize existing infrastructure.

» **Why watch:** Bioenergy conversion with carbon capture and storage is a technology that converts biomass into energy products while capturing and sequestering any carbon dioxide generated in the process. "We transport lignocellulosic biomass to a bioenergy conversion facility that has a unique feature added to it that is different from how we normally make bioenergy: carbon capture and storage," says Daniel Sanchez, chief scientist of biomass carbon removal and storage. "That means that the waste biogenic carbon that is a by-product of these conversion processes is captured, compressed, and stored underground."

One of the strengths of this type of carbon capture and storage is flexibility. Biomass can be converted into chemical products, including ethylene, methanol, and diesel, typically associated with petrochemicals. Carbon-capture technology can be integrated into biorefining, biogas upgrading, or pulp manufacturing.

Carbon Direct offers expertise in navigating the technical world of climate policy and helps companies understand carbon markets.

hazel technologies, inc.

» **hazeltechnologies.com**
» **Based:** Chicago
» **Founded:** 2015

» **Strategy:** Develop technology that reduces fruit and vegetable waste in the agricultural supply chain

» **Why watch:** The US Environmental Protection Agency has found that fruits and vegetables represent about 40% of total food waste. This is probably unsurprising: Who hasn't found a limp head of lettuce in the crisper or moldy raspberries in the back of their fridge?

Hazel Technologies sees decaying fruit and vegetables as an opportunity for innovation. The rotting process is controlled by gases, such as ethylene, released at trace levels for signaling purposes. "When you pick an avocado off of a tree, for example, it produces very little ethylene," says Adam Preslar, cofounder and chief technology officer. But after a certain amount of time, that avocado effectively experiences a stochastic event with a positive feedback loop. "Ethylene is produced, stimulating even more ethylene, which drives senescence and breakdown," Preslar explains.

Methylcyclopropene (1-MCP) inhibits the receptors responsible for this ethylene feedback loop. 1-MCP is nontoxic, according to the EPA, and only low levels are needed to inhibit ethylene production. Hazel has developed a packet that slowly releases 1-MCP over time, significantly increasing the shelf life of many fruits and vegetables.

Atmonia

» **atmonia.com**
» **Based:** Reykjavik, Iceland
» **Founded:** 2016

» **Strategy:** Using energy-efficient nitrogen electrolyzers to produce ammonia for fertilizer

» **Why watch:** Fertilizer has a massive impact on agricultural productivity. An analysis by Our World in Data found that in 2015, almost half the world's population was fed by food produced thanks to synthetic fertilizers. Bioavailable nitrogen is the most important ingredient in synthetic fertilizers, often in the form of ammonia produced from the Haber-Bosch process. The catalytic reaction in this process happens at high temperatures, is energy-intensive, and often uses coal or gas—making it a significant source of carbon emissions.

In addition to being environmentally costly, an ammonia production facility is expensive to build and operate. "It is a very centralized, high-capital operation and needs to be running 24/7," says CEO Guðbjörg Rist. Many areas of the globe must import fertilizer from long distances, which adds to the environmental impact.

Atmonia is developing a new way to produce ammonia: catalytic electrolysis of nitrogen and water. This is a one-step reaction that requires ambient temperature and pressure, which in turn means lower energy requirements and infrastructure investment than the Haber-Bosch process.

Countries and territories can use Atmonia's technology to reduce their reliance on imported fertilizer. This would be particularly helpful for low-income nations. "There are many places in the world that aren't able to import fertilizer because they don't have the currency," Rist says. "With this kind of technology, you might be able to produce fertilizer basically anywhere."

Source: ACS Zero Hunger summit, company websites

CREDIT: MOYO STUDIO/GETTY IMAGES

Advances in agriculture science depend on collaboration across scientific fields and professions, from academic researchers to industrial R&D to farmers using commercial technologies. CREDIT: LIGHTSPRING/SHUTTERSTOCK

Teaming up to tackle hunger: spotlight on collaboration

One of the themes echoed by participants at the American Chemical Society's Zero Hunger Summit was the importance of collaboration. This chapter captures why these relationships are essential and identify best practices for cultivating partnerships.

Cross-pollinating research

Agriculture is a cross-disciplinary field. Chemists, engineers, biologists, nutritionists, and environmental scientists work together to understand crop productivity, livestock, diet, and sustainability. Almost every modern technology or farming technique adopted by growers has relied on scientific contributions from multiple fields.

This cross-disciplinary work also includes basic scientific research. Take soil microbiomes as an example. They play a critical role in the health and productivity of crops, yet there is a great deal we do not know about these microbial communities. "We know there are interactions between microbes in the soil and many types of plants, from fungi to bacteria, that are profoundly beneficial," says Dianne Newman, a professor of biology at the California Institute of Technology. "There is a great need for basic science research in the field of microbial metabolism to lead to applications with relevance to crops." Scientists in fields such as analytical chemistry, metabolomics, and microbiology are working toward a goal of enhancing crop productivity by manipulating microbial communities.

Despite the known benefits of reaching across disciplinary boundaries, some experts worry that academics aren't getting out of their bubbles. "Simply put, there isn't enough discussion on multidisciplinary issues," says Jakub Kostal, an assistant professor of chemistry at The George Washington University. How can successful cross-disciplinary teams be fostered? Here are some of the suggestions offered by the panelists:

- Participate in cross-disciplinary conferences, professional organizations, and events.
- Form a cross-disciplinary team at the beginning of a project rather than bringing in outside experts as ad hoc consultants or service providers.
- Encourage students and early-career scientists to develop cross-disciplinary experience.

A common path for academia and industry

Kostal shares a story about submitting a grant proposal when he was first getting involved in computer-assisted pesticide design. "Two reviews came back from industry. One of them said, 'This will never work,'" and the other said, 'We tried this, and it doesn't work.'"

This highlights how the barriers between industry and academia can slow research. Had these companies not reviewed his grant, Kostal's group could have spent months or years investigating a scientific dead end.

It can be challenging for companies to identify researchers for collaborations because academics do not understand their business needs. "Scientists, when we work in a vacuum, we don't consider stakeholder needs or policy landscapes. We're limiting the application of our own work," says Jillian Goldfarb, an associate professor of biological and environmental engineering at Cornell University. "To advance applied science, we need to cultivate partnerships and understand the needs and constraints of the agriculture industry."

Bringing academics and industry together could be a matter of providing educational opportunities, which have been limited. Vid Hegde, Corteva Agriscience's vice president of crop protection discovery and development, says that "as an industry, I don't think we have done a good job of education or talking about how things are done."

Education could come in the form of a hands-on experience involving internships, project-specific engagements, or academics advising private companies. Facilitating these arrangements takes effort, but they can benefit both parties and further the goal of achieving zero hunger.

Farm to table

Farmers obviously play an essential part in the food production process, so it is worth understanding their needs when adopting technology. Each farm is a small business, responsible for managing its own resources. This means agricultural companies do not have direct control over what technology or agricultural practices farmers use, so they must find ways to encourage sustainable practices. Practically, this means innovations need to be designed so farmers understand them and want to use them. "We need to consider the farmer and what challenges they're facing in adopting new practices or technologies that could reduce their greenhouse gas emissions," says Kelly Gillespie, vice president of digital ecosystem services at The Climate Corporation.

Financial incentives are helping drive the adoption of sustainable farming practices, according to Molly Elrick, director of the science enabling team at The Climate Corporation. "It's not just about yield," she says. "It is also about profitability for the farmer, field health, and sustainable practices."

In some cases, these financial incentives are ultimately driven by consumer demand. "Society rightly expects more from agriculture," Hegde says. "Consumers, regulators, and food companies want to know where food comes from, how it was produced, and that it is produced sustainably." People all over the world want food that is affordable, sustainable, nutritious, and delicious. Science communicators can also play a role in generating demand for environmentally responsible foods.

Reeling in regulators

Most novel technologies need to undergo some form of regulatory approval before they are publicly available. This is especially true in agriculture, where food safety is a concern. Government institutions and regulatory agencies have tremendous control over what technologies are available on the market, who has access to them, and how they can be used.

Policy can spur innovation and change adoption. California's action on livestock methane emissions is an interesting case study. The state requires that livestock and dairy producers reduce emissions 40% from 2013 levels by 2030. When the law was enacted, the technology wasn't yet available to achieve this goal, Goldfarb says. "A recent analysis by the California Air Resources Board shows that at their current pace, they are projected to hit just 22% of the required target by 2030, suggesting that technology has not come far enough to meet these policy goals." But without these policies in place, she adds, "it would be difficult to get buy-in from industry members to adopt this new technology."

Scientists can help shape the legislative agenda. "We need evidence-based policies to present to the government and work with them as partners," says H. N. Cheng, 2021 ACS president. Trading carbon credits is an example of scientifically informed policy encouraging sustainable behavior. Government subsidies have been essential in establishing carbon markets. While it is still early days in this space, many agriscience companies are already active in it.

How scientists and engineers can fight world hunger

World hunger is a massive challenge but also an opportunity for scientists and engineers to make a positive impact. There are an almost endless series of research questions to consider. What follows are research recommendations from panelists at the American Chemical Society's Zero Hunger Summit.

Accessible data collection

Data are the lifeblood of research. Every scientist or engineer who has conducted experiments knows that acquiring high-quality results requires tremendous amounts of time, attention, and effort. This is particularly difficult in agricultural science, as data collection is often constrained by the growing season.

Farmers are frequently responsible for much of the data collection, and that creates a challenge. Kelly Gillespie, vice president of digital ecosystem services at The Climate Corporation, says, "Data collection is a huge burden

Research areas that intersect with the goal of reducing global hunger

Soil

- Soil degradation
- Soil microbiome communication
- Carbon sequestration
- Fertilizer development

Biochemistry

- Development of crops that are drought and flood resist
- Development of crops that are tolerant to changes in temperature
- Reduction of cows' methane emissions

Chemical engineering

- Upcycling of food waste
- Carbon capture
- Fertilizer manufacture

Food chemistry

- Increase in crops' nutritional value
- Ingredients for meat alternatives
- Increase in the shelf life of produce
- Extraction of nutrients from foods

Synthetic chemistry

- Novel pesticides
- Food preservatives
- Food-safe, biodegradable packaging

Sensors

- Sensors for food safety applications
- Sensors for crop monitoring
- Low-cost sensors

Automation and machine learning can streamline the process of collecting agricultural data, and agricultural scientists want standards for this data to ensure its quality.
CREDIT: IGOR BORISENKO/GETTY IMAGES

for farmers to enroll in any of the carbon programs. Most carbon programs rely on web-based, manual data collection. [Farmers] have to track their yields, how much fertilizer they use, when they put fertilizer on their field, what cover crops they use. … It's a survey a mile long." Bayer has developed a device that attaches to farm equipment to help automate the data collection process, but there is broader demand for innovations that simplify it.

The need for high-quality data is growing, given the rapid proliferation of artificial intelligence and machine learning applications. This technology has many uses in food and agriculture research, including life-cycle analysis, precision agriculture, pesticide design, supply chain management, and food quality testing. The caliber of the data available will ultimately determine the usefulness of these tools. "I want more, not just data, but reliable data and standardized data," says Bosoon Park, lead scientist at the US Department of Agriculture's Agricultural Research Service.

Despite this demand, institutions continue to have inaccessible data. Agricultural, agrochemical, and food businesses with considerable research and development departments have mountains of information in the form of proprietary data that allows companies to develop innovative products that help consumers. Even if the data could be shared publicly, significant work is needed to implement systems that let outside experts access the information.

This dilemma is not new, nor is it unique to the agriscience space. Here are some possible approaches to consider:

- Bayer is partnering with Microsoft to develop cloud-based data science solutions.
- In academia, sharing data is expected as part of the publication process.
- The pharmaceutical industry uses agreements or consortia to share precompetitive information on specific topics.

The challenges of food security, climate change mitigation, and environmental sustainability will be present for the foreseeable future. Addressing these problems over the long term will require more experts trained in sustainable chemistry and systems-level thinking. Introducing courses and lessons on these topics will prepare and encourage young chemists and engineers to work in these fields.

For example, teaching life-cycle assessment (LCA) at the undergraduate level is an educational change that could make a lasting impact. Jakub Kostal, an assistant professor of chemistry at The George Washington University, says that one of the most important priorities is "training chemists early on to understand the repercussions of making chemicals and the need for systems-based thinking." Even for chemists and engineers that do not actively conduct LCA research, this field is relevant to their work in other ways:

Developing sensor technology: Better sensors improve the accuracy and robustness of LCA.

Gathering data: LCA requires immense quantities of data —researchers can participate by performing the experiments that provide these data.

Thinking at the systems level: Understanding LCA will help engineers and chemists direct their research toward developing effective technologies.

Professional engagement

Another suggestion made by panelists and keynote speakers at the summit: engaging with professional societies. In addition to being a space to network and keep current with trends in your field, they offer the opportunity to influence the goals and priorities of these institutions.

Those interested in shaping policy can also join a public action committee. Most professional societies have various panels supporting members' needs and interests. Public action committees work to influence government policy with activities that include contacting political representatives and commenting on legislation. Members passionate about world hunger can join committees focused on that fight.

> "I want more, not just data, but reliable data and standardized data."
>
> — Bosoon Park, USDA Agricultural Research Service

The American Chemical Society is an example of a professional organization with a robust public action function. "ACS has been very active in trying to influence policy. We have worked with congressmen, senators, and even in local government to try to influence legislation," says H. N. Cheng, 2021 ACS president. "When there is major legislation, we have been engaging members to write to legislators in order for them to understand the issues and support legislation that is favorable to scientists." These groups not only influence policy effectively but offer opportunities for scientists to meet researchers with common interests, which helps build collaborations and partnerships.

CREDIT: MOYO STUDIO/GETTY IMAGES

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