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FRONTIERS:

BIOTECH

Five Big Ideas Shaping the Biorevolution

A little over a decade ago, Steve Jobs made a prediction. "The biggest innovations of the twenty-first century will be at the intersection of biology and technology," he said. "A new era is beginning."

It proved to be remarkably prescient. In 2012, a year after his death, a patent would be filed for a novel gene-editing technique known as CRISPR that would make it possible to rewrite genetic code inexpensively and accurately. It lit a rocket under the field.

A "word processor" for nature, in that it enables the deletion or insertion of specific pieces of DNA with unrivaled precision, CRISPR was to become just one of a cluster of innovations that are continuing to define a new, momentous chapter for biotech. And this biorevolution is impacting myriad sectors, from healthcare to agriculture to energy and beyond.

"There are many examples of things which have evolved in nature that are now finding application in the modern world, not just in medicine but other sectors too," says Kevin Lyne-Smith, Global Head of Equities, at HSBC Global Private Banking and Wealth. "It's hard to draw a conclusion on where it will end, but it's already got the characteristics of the early stages of the digital revolution."

The idea of exploiting nature for goods and services is nothing new. Ancient people used yeast to make bread and beer; in the twentieth century biology has given us penicillin antibiotics and enzymatic laundry detergent. But the practice entered its modern era in the 1970s, with the advent of genetic engineering and the establishment of the first biotech companies. This brought together science and business like never before, and the influx of capital galvanized research and development efforts.

Over the three decades that followed, the field was accelerated by breakthrough devices such as DNA sequencers and synthesizers, and biology itself slowly morphed into a computational, data-driven discipline. Following the turn of the

millennium, as researchers successfully charted ever greater regions of the human genome, and the cost of sequencing that genome rapidly declined—from around $100 million in 2001 to less than $1,000 today—the potential of biotech to transform our lives has become electrifyingly apparent.

Over the past few years, the possibilities unlocked by biotech advances—from treating genetic diseases to de-extincting animal species—have been enlarged by progress in complementary fields such as artificial intelligence. This has underpinned a coming-of-age moment in this space. And while genomics has defined the inflection points of the biorevolution, its scope goes well beyond. Contemporary bioengineering also encompasses emergent domains including biomaterials, biointerfaces, and biocomputing.

The sector has duly become highly investable. Biotech companies now populate stock market indices, and there is a thriving tier of startups with the demeanor of polished Silicon Valley businesses.

The Covid-19 pandemic only thrust the sector further into the limelight. “From a priority perspective, we all realized how precious our health is, so we’re more willing to invest in it and there’s more attention on it,” says Willem Sels, Global Chief Investment Officer at HSBC Global Private Banking and Wealth. “That makes social sense, because people care more about it, and it often makes economic sense too, because you can offer that service at the best possible cost.” Biotech is now front-of-mind for larger economies such as the US and China. Indeed, HSBC believes that the market for products using CRISPR technology alone could be worth $7 billion by 2030.

“For investors, there are huge opportunities for gain not only in the public space, but also the private space, where there is higher risk but higher rewards,” says Sels. “Diversification and specialist knowledge or expert advice is key to charting your way through this sector.”

This edition of Frontiers explores the verge of this brave new world, shining a light on five cutting-edge trends. All of them are enjoying serious venture capital flows and are attracting attention from credible experts. For each story, we’ve interviewed one such specialist to hear why they’re excited, but also what challenges still need to be solved.

Those stories are:

1 **Is DNA the future of computer storage?**

2 **Plastic-eating bacteria could revolutionize recycling**

3 **Antibiotic resistance is a looming crisis. CRISPR may hold the answer**

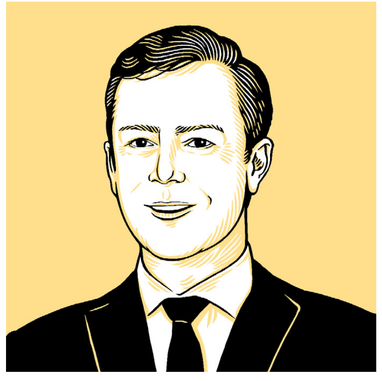
4 **Could `augmented wood' be the future of construction?**

5 **Welcome to the golden era of rejuvenation science**

These are testing times for humankind, and therefore the importance of looking for smarter answers to our problems is greater than ever. "We need to do things better, and that urgency has made people realize that there are often simple solutions already available that don't require extreme physical or chemical processes," says Lyne-Smith. "This is creating opportunities, and people are opening themselves up to what exists in nature."

Meet the experts

Willem Sels
Global CIO, HSBC Global Private Banking and Wealth



Kevin Lyne-Smith
Global Head of Equities, HSBC Global Private Banking and Wealth

FRONTIERS: DNA COMPUTING

IS DNA THE FUTURE OF COMPUTER STORAGE?

We're producing more information than ever, and data centers are struggling to keep up. Nature's original storage system may provide an answer...

n 2022, humans created just under 100 trillion gigabytes of data, and that volume will nearly double again by 2025. With this, the pressure to find innovative ways of storing it grows, because traditional methods are bursting at the seams.

But to some scientists, the best answer has existed for billions of years: DNA. If it can store genetic code, can it also store the world's digital information?

"Synthetic DNA has the potential to store orders of magnitude more data than today's devices, and in a manner that promises to be much more sustainable," says Karin Strauss, Senior Principal Research Manager at Microsoft Research and an Affiliate Professor at the University of Washington's School of Computer Science and Engineering.

Strauss has led research in emerging memory technologies, which have drawn increasing interest as global data volumes have mushroomed. Media that once existed physically now predominantly exists digitally; the world is being photographed from space like never before; businesses are increasingly operating on cloud platforms; scientists are amassing massive research data sets. The billions of connected devices and sensors that make up the Internet of Things are forecast to contribute nearly 80 zettabytes—meaning 80 trillion gigabytes—by 2025.

There is a particular question over where to store archival data—information that is infrequently accessed again

"SYNTHETIC DNA HAS THE POTENTIAL TO STORE ORDERS OF MAGNITUDE MORE DATA THAN TODAY'S DEVICES, AND IN A MANNER THAT PROMISES TO BE MUCH MORE SUSTAINABLE"

Karin Strauss, Senior Principal Research Manager, Microsoft Research

after creation. Companies are incentivized to store rather than junk this kind of information. Partly that's because the public doesn't expect data to disappear. But a more significant driver is the rise of artificial intelligence and analytics. The more data you have, and the higher quality it is, the more powerful your algorithms can be.

There are various conventional ways to approach this problem. Tape drives consume minimal energy, but accessing the data is slow and preserving it is costly. Solid state and hard disc drives are an appealing alternative because of their low access latency, allowing for prompt retrieval of specific data from storage. But because both of these storage mediums have finite lifespans, they require the periodic transfer of data to newer storage media. This recurrent data migration process contributes significantly to environmental waste, as both hard drives and tapes are typically destroyed after use. Solid state and hard drives also require continuous power to maintain their storage and retrieval functions. Significant portions of today's archival data is stored in vast data centers packed with them. Not only does this take up a great deal of physical space, but they also produce vast amounts of greenhouse gas emissions.

And still we can't build them quickly enough. "The capacity of existing storage media is not keeping up with the ever-growing demand for data storage," says Strauss. This has ignited a search for a more efficient storage medium, particularly for archival cloud storage.

The idea of stashing digital information on synthetic strands of DNA has existed since the 1960s, inspired by the fact that DNA is itself a storage system. It is made up of chemical building blocks called nucleotides, each of which is composed of a sugar group, a phosphate group, and one of four nitrogen bases. Each of these nitrogen bases is identified by letters: A (adenine), T (thymine), G (guanine), and C (cytosine). It is the order and sequence of these nitrogen bases that determines the biological messages in any strand of DNA.

Digital information exists as binary code, and DNA storage works by translating its zeroes and ones into sequences of those four letters. For instance, 00 might equal A, or 10 might equal G. Synthetic DNA can then be

"THE CAPACITY OF EXISTING STORAGE MEDIA IS NOT KEEPING UP WITH THE EVER-GROWING DEMAND FOR DATA STORAGE"

Karin Strauss, Senior Principal Research Manager, Microsoft Research

produced which contains that sequence. This DNA can then be stored and, at a later stage, decoded into text, say, or video.

The appeal is that DNA can store massive quantities of information at a high storage density, around one exabyte (one billion gigabytes) per cubic inch. DNA is also durable—it can last tens of thousands of years—and doesn't consume vast amounts of energy.

"It would take billions of tape drives—the current densest commercial storage media—to store tens of zettabytes of information," says Strauss. "Whereas it would take the footprint of one small refrigerator if stored in synthetic DNA."

Research into the idea has exploded in recent years. Various companies are developing the technology, some working on synthesizing or reading DNA, others on translating binary code into the DNA alphabet. In 2020, Microsoft co-founded the DNA Data Storage Alliance, bringing together 41 organizations with the twin aims of realizing the potential of DNA storage and recommending the creation of specifications and standards to aid interoperability. And there have been proofs of concept. Scientists have already encoded books into DNA and, recently, a startup released a credit card-sized device that can store a kilobyte in DNA form.

For businesses, the potential rewards are significant. The global data storage market size was valued at $217.02 billion in 2022 and is projected to reach $777.98 billion by 2030. The emerging DNA storage market will hit $3.34 billion by 2030 according to one recent report.

DNA storage is not going to replace traditional data centers, especially as that data is required quickly. But eventually it might enable archival data to be stored in greener, more compact data centers, which produce minimal waste and carbon emissions. In these centers, files will be encoded and synthesized, and then stored in capsules. To read them, a robotic arm will remove a capsule, read its contents, and place it back.

If that sounds a way off, that's because it is. DNA synthesis remains expensive, and therefore its uses are limited to when you have a small bit of extremely valuable data. Additionally, there is a need to increase how much data can

"THE GLOBAL DATA STORAGE MARKET SIZE WAS VALUED AT $217.02 BILLION IN 2022 AND IS PROJECTED TO REACH $777.98 BILLION BY 2030"

be written simultaneously by a single device, something that Strauss herself has explored with a team of Microsoft and University of Washington researchers. In 2021, they demonstrated that it is possible to reach reasonable write speeds, and she expects those to improve further in the future. “Technologies to write data to synthetic DNA are improving quite rapidly, and recent developments—such as a nanoscale DNA storage writer we developed with University of Washington—show paths toward commercial-scale DNA data storage,” says Strauss.

Strauss and her University of Washington colleagues have also turned their attention to another crucial challenge: How to pick out the desired file from a mixture of many pieces of DNA. They have demonstrated that DNA molecules themselves can actually find images that look similar to an image of interest. This ability would enable the location of files without having to decode an entire database—perhaps paving the way for new kinds of computers altogether. “The ability of DNA molecules to perform computations, alongside their storage capacity, opens up new possibilities for the future of computing,” she says. “Showing that such processes scale to trillions of data items will be the next frontier in applying DNA technology to information technology.”

Meet the expert

Karin Strauss is the Senior Principal Research Manager at Microsoft Research. She is also an Affiliate Professor at the University of Washington’s School of Computer Science and Engineering.

FRONTIERS: NATURE'S RECYCLERS

PLASTIC-EATING BACTERIA COULD REVOLUTIONIZE RECYCLING

A new front is opening in the war on waste, but can it scale?

In France, biotech startup Carbios recycles polyethylene terephthalate (PET), a strong and lightweight plastic that's used to make drinks bottles, food trays, and textiles. But instead of grinding it down or using chemicals, it mixes the PET with a bacterial enzyme that chews it up. It's a pioneering process—and it might just offer a glimpse of the future.

Carbios is commercializing an idea that has steadily been gaining traction in biochemistry research: Enlisting microbes to eat plastic, breaking it down for reuse. And as we look to minimize global carbon emissions, this experimental approach could prove invaluable.

"This offers a way to remake new plastics without having to go back and dig out more fossil fuels to make fresh ones," says Dr. Elizabeth Bell, who works on the discovery and optimization of enzymes for the recycling of plastics at the US government's National Renewable Energy Laboratory.

Plastic is a popular material because it is cheap and versatile. We produce around 450 million tonnes of it each year, but this has a deleterious impact on the environment because it's mostly made from petrochemicals. It is often thrown away after a single use, so we also produce around 400 million tonnes of plastic waste each year.

Huge quantities of this waste are incinerated, releasing the carbon into the atmosphere, and what escapes the incinerators accumulates in landfills and the natural

"THIS OFFERS A WAY TO MAKE PLASTICS WITHOUT HAVING TO DIG OUT MORE FOSSIL FUELS"

Dr. Elizabeth Bell, Postdoctoral Researcher, US National Renewable Energy Laboratory

environment. At least 14 million tons of plastic end up in the ocean every year, according to a report by the International Union for Conservation of Nature. Another influential report anticipates that, by weight, there will be more plastic than fish in the sea by 2050.

To reduce plastic's environmental impact we must find ways to do more with the plastic that's already out there. Conventional methods of recycling cause it to degrade, so eventually new plastic has to be made from virgin materials.

To recycle plastic indefinitely, you have to break it down into its fundamental building blocks, called monomers. But the chemical reaction to do this doesn't work very well unless the stream of plastic is pure. Problem is, most plastic waste is a mixture of different types.

That's where enzymatic recycling comes in. The field has exploded since 2016, when a team of Japanese scientists published a paper about a bacteria that could metabolize PET using an enzyme that we now call *Is*PETase.

The process appeals because it works under mild conditions and requires no noxious chemicals. It also means that the PET may not need to be separated out from other types of plastic, since enzymes are specific.

"What the enzyme could potentially do is chemically sort out the PET from the mixed waste sample, without you having to do any manual sorting," says Bell.

Enzymatic recycling is potentially lucrative. Annual demand for common types of plastic is expected to grow by 90 percent to 403 million metric tons by 2050. Over that same timeframe, Carbios—which has raised over €70m in public funding and €314m in equity since its 2013 IPO—expects advanced recycled PET to grow into a €200 billion market.

The discovery of *Is*PETase has kickstarted a search for other plastic-eating bacteria as part of a broader trend of looking for organisms for commercial applications known as bioprospecting. Microbe hunters go to a place where they might find a bacterium capable of breaking down a target plastic, and starve it of all types of food other than the plastic they want to see it metabolize. If it survives, they know it has eaten the plastic; then they must isolate the enzyme that has enabled this to happen.

"BY WEIGHT, THERE WILL BE MORE PLASTIC THAN FISH IN THE SEA BY 2050"

This process takes a long time. The bacteria discovered by the Japanese group remains the single documented case of any microbe that can use PET plastic as a sole food and energy source. Others do it as a side-function but, currently, they're all too slow to have a meaningful impact on global plastic waste.

Scientists, then, must improve them by tinkering with bacterial DNA. Bell has used genetic engineering to optimize *Is*PETase to work faster, but believes we will inevitably discover new enzymes altogether. "Enzymatic recycling is still in its infancy for many other types of plastic," she says.

Within a decade, enzymatic recycling of PET is likely to become more commonplace, she predicts, and other plastics will follow. The technique uses equipment that has already been proven for large operations, which means it has the capacity to scale up. In 2025, Carbios plans to open its first commercial plant, which it claims will recycle 50,000 tonnes of PET waste per year.

This potential shift in recycling technology could open up a variety of new possibilities.

In theory, if this new technology becomes mainstream, each city could have its own semi-automated recycling plant. The monomers would feed directly into a nearby processing facility and the plastics would be passed on to local industries.

What's more, enzymatic recycling may eventually help clear up our oceans. In 2019, scientists genetically engineered marine algae to produce and secrete *Is*PETase, enabling it to break down plastic in saltwater. Bell explains that this could possibly be industrialized via a sewage plant-like system; ocean plastic would be collected and put into a controlled reactor with the engineered algae. She notes that one wouldn't want to release genetically modified organisms into the oceans without knowing exactly what they might do.

And, if we wanted to eliminate certain plastics altogether, we may be able to engineer microorganisms that consume the products of enzymatic recycling. "So you can break down the plastic into monomers, then another organism can come along and basically eat those monomers as food," says Bell.

"ONE WOULDN'T WANT TO RELEASE GENETICALLY MODIFIED ORGANISMS INTO THE OCEANS WITHOUT KNOWING EXACTLY WHAT THEY MIGHT DO."

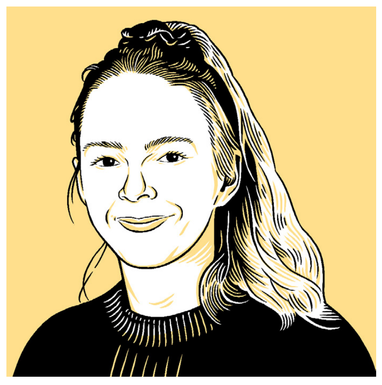
However, it's unlikely that all kinds of plastic can be efficiently digested. In some cases, such as polyethylene, their chemical bonds will be too strong for the enzymes to overcome. It's also expensive, though Bell is confident that costs will come down as the technology matures.

And then there are the possible legal hurdles because of the risks of genetically modified plastic-eating bacteria escaping into the environment. In Bell's view, however, the risk is minimal because large-scale reactions such as Carbios' are being done using the enzyme alone, and the engineered microbes from which the enzyme is harvested wouldn't work outside of a controlled laboratory environment.

"The risks of industrial plastic-degrading bacteria escaping into the environment are very low," says Bell. "Scientists work hard to develop fail-safe mechanisms to ensure these bacteria can't survive on their own in the wild."

Ultimately, it is likely that the global plastic problem will call for a diverse mix of technological solutions—as well as ratcheting up the drive to simply use less of it. "But enzymatic recycling is filling an important gap."

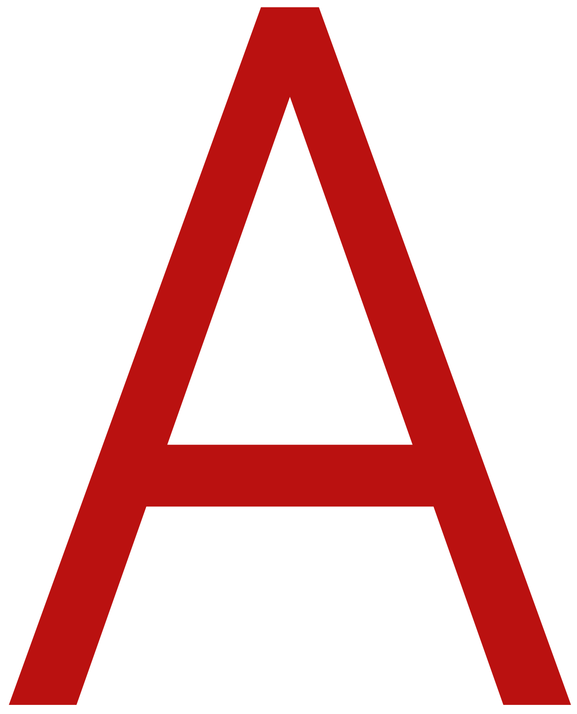
Meet the expert



Dr. Elizabeth Bell is a Postdoctoral Researcher working on the discovery and optimization of enzymes for the recycling of plastics at the US government's National Renewable Energy Laboratory.

ANTIBIOTIC RESISTANCE IS A LOOMING CRISIS. CRISPR MAY HOLD THE ANSWER

From resensitizing bacteria to destroying them altogether, gene-editing offers new hope



round 10 million. That's the number of lives forecasters believe we will lose each year by 2050 as bacteria develop defenses against the drugs we use to fight infections.

Tackling antibiotic resistance, though, is hard.

"It is a complex phenomenon," says Professor Jennifer Doudna, founder of the Innovative Genomics Institute at UC Berkeley. "It's not a disease, it's a biological property that emerges over time, so there's no standard model to deal with it."

A biotechnology pioneered by Doudna offers a possible solution. Doudna is the Nobel Prize–winning co-inventor of CRISPR gene editing, a technique that allows scientists to make targeted changes to the DNA sequences of all living cells.

The technique exploits the adaptive immune system found in bacteria that helps them recognize and fight viral infections. This immune system works by using enzymes to cleave and capture small pieces of the virus' DNA, which the bacteria then store. The bacterium uses this record to create proteins that can identify the virus if it returns and snip its DNA accordingly to destroy it. CRISPR gene editing hacks this snipping process by asking it to cut DNA to order. Think of it like a precise pair of genetic scissors. Once a piece of genetic information has been cut out, new genetic information can be inserted in its place, making a specific gene edit.

Cheap and quick to use, it is opening up possibilities across everything from agriculture to medicine, where it promises to help cure hereditary diseases, blood disorders,

"IT'S A COMPLEX PHENOMENON, IT'S NOT A DISEASE, SO THERE'S NO STANDARD MODEL TO DEAL WITH IT"

Jennifer Doudna, founder, Innovative Genomics Institute at UC Berkeley

and even cancers. Between 2019 and 2022, gene editing companies, most of which are startups, raised more than $5 billion in investment. In 2023, the FDA approved the first CRISPR-based medical treatment, and the wider market for CRISPR genome editing is expected to grow to $28.8 billion by 2030.

To understand how CRISPR could be used to tackle antibiotic resistance, we need to understand how that resistance arises in the first place. Like all living things, bacteria evolve in response to environmental pressures through natural selection. Faced with an effective antibiotic, advantageous mutations may include the ability to produce enzymes that neutralize the antibiotic, or the development of cell wall "pumps" to expel the antibiotic before it does any damage. Our heavy reliance on antibiotics accelerates this process. According to a 2021 study, global human antibiotic consumption went up 65 percent between 2000 and 2015.

The problem is exacerbated by improper use. When we take a course that is too short or too weak, for example, we expose bacteria to antibiotics without actually killing them off. The most resistant bacteria might survive, and they will grow and multiply, creating a strain of resistant bacteria that may spread.

Worse still, bacteria readily swap bits of DNA among related and unrelated species in a process known as horizontal gene transfer. This means they can pass their immunity on to other kinds of bacteria. This often happens via small circular DNA molecules known as plasmids, which pass between cells during physical contact.

New solutions such as those potentially unlocked by CRISPR would be extremely valuable. Scientists are examining two primary approaches.

"One general strategy that seems promising is targeting the genes or mutations that enable microbial resistance to antibiotics, making the antimicrobials that we already have more effective," says Doudna. That's vastly preferable to "constantly having to develop new ones in a never-ending arms race with bacteria."

In May 2023, researchers targeted the resistance gene for Gentamicin, a common antibiotic, which reversed the resistance in infected cells and protected others from

"BETWEEN 2019 AND 2022, GENE EDITING COMPANIES, MOST OF WHICH ARE STARTUPS, RAISED MORE THAN $5 BILLION IN INVESTMENT"

developing it. In theory, you can re-sensitize entire bacterial populations to antibiotics and stop the resistance genes from spreading. “Horizontal gene transfer is an important mechanism in spreading resistance,” says Doudna. “So it’s likely also the key to stopping its spread.”

The second general strategy is to neutralise the bacteria directly. You can simply cut specific regions of its chromosome, by programming the CRISPR enzymes to target them, circumventing the need for antibiotics altogether. In 2021, scientists in Canada used this approach to eliminate a harmful bacterium from the gut.

Still, it may be years before CRISPR-based therapies can be used widely. One challenge is getting the mechanism inside all the bacterial cells that you wish to target, and doing so safely. We also need a better understanding of the specific genes that enable resistance to antibiotics, and to ensure that only those genes in the target bacteria are edited. A more fundamental step will simply be to show that these kinds of CRISPR therapies work not only in the lab, but in humans, and that itself will be a long road.

“This is a challenge that will be addressed over time, not solved all at once,” says Doudna. “We’ll see small victories before we win the battle.”

Meet the expert

Jennifer Doudna is the Nobel Prize–winning co-inventor of genome editing technology CRISPR, and Founder of the Innovative Genomics Institute at UC Berkeley

FRONTIERS: AUGMENTED WOOD

COULD 'AUGMENTED WOOD' BE THE FUTURE OF CONSTRUCTION?

It's natural, it's renewable—and potentially as strong as steel

ood is mankind's oldest building material, but seldom do we use it. You certainly don't see many tall buildings made out of wood—the superior strength and relative inexpensiveness of steel and concrete have sidelined its usefulness.

Timothée Boitouzet, the founder and CEO of Parisian Startup Woodoo, says that to save our planet, this must change. "Wood is the only construction material that grows by itself and it is one of the only construction materials that absorbs C02 rather than emitting it," Boitouzet says.

Construction is responsible for around 25 percent of all greenhouse gas emissions, across its supply chain, and this number is rising. Around 2.5 billion more people will live in cities by 2050, and to accommodate them we're going to need to build—a lot.

But this requires vast amounts of energy. The chemical and thermal combustion processes involved in the production of cement, a key ingredient of concrete, accounts for around eight percent of global CO2 emissions. The steel industry accounts for approximately another five percent.

What's more, construction materials require us to mine the planet's precious resources. And then, once they've served their purpose, they come to account for around one third of the world's waste.

In a bid to find sustainable workarounds, scientists and climate conscious entrepreneurs are turning to biology.

"WOOD IS THE ONLY CONSTRUCTION MATERIAL THAT GROWS BY ITSELF AND IT IS ONE OF THE ONLY CONSTRUCTION MATERIALS THAT ABSORBS C02 RATHER THAN EMITTING IT"

Timothée Boitouzet, founder and CEO, Woodoo

Recent advances in biotechnology have enabled us to tap into nature to develop novel bio-based materials across a range of fields and use cases. Examples include bio-concrete, a mix of concrete and bacteria that can self-heal as cracks develop; and engineered mycelium, a root-like network of fungus that can be used in place of leather.

The accelerating drive towards corporate and national climate goals has ignited interest in the field. A recent report estimated that the biomaterials market will be worth $81.64 billion by 2028.

Among the range of biomaterials attracting attention right now, wood-based innovations represent a major category. A number of researchers and businesses are exploring how to reinvent wood, from turning it transparent as an alternative to glass, to making it into a liquid for 3D printing.

One such drive is focused on making wood better suited to construction.

In its natural form, wood is combustible and it rots. Its mechanical strength is also not high enough for tall buildings, which need to support tremendous loads. You can overcome this with massive wooden sections, but at the cost of interior space. Wood is also vulnerable to moisture and temperature variations, and in tall structures this can lead to issues such as warping and shrinking. Over time this can compromise the building.

To overcome these limitations, architects are using natural wood fibers with adhesives and other additives, or woods that have been treated with chemicals or heat. Cross-laminated timber, a popular type of engineered wood produced by layering timber sections of wood at right angles, has been used to build an 85.4-metre-high tower in Norway.

Another way to improve wood is to adjust it on a cellular level, which is the approach taken by Woodoo, a startup founded in 2017. The two main components of wood are lignin and cellulose. While cellulose is the scaffold, lignin is the “glue” between fibers. But the bonds it creates are weak, and they become weaker due to humidity and ultraviolet radiation. In tall buildings, wood loses its rigidity, and the structure sways.

“THE BIOMATERIALS MARKET WILL BE WORTH $81.64 BILLION BY 2028”

Boitouzet's process removes that lignin by placing the wood in a reactor, where it is submerged in an alkaline solvent at a high temperature. This causes the lignin molecules to detach, and these are washed away.

A bio-based polymer is added, which takes the lignin's place, and—when fixed under pressure to create strong, new chemical bonds with the cellulose—a new material that the company calls "augmented wood" is produced.

This can take a variety of forms, depending on the polymer. One Woodoo product (called "Solid") is all about durability: The company says it has the strength of steel and a rigidity 23 times greater than concrete. It also has the benefit of being weather-proof, light, strong, dimensionally stable and easy to machine.

The idea is that Solid could be a bioreplacement for the concrete, steel, and aluminum used in construction. Boitouzet intends to target horizontal structural applications first, as the bulk of those conventional materials are used to create flat surfaces such as floors and ceilings. Solid's carbon footprint is 229 times lower than aluminum, 149 times lower than steel, and 21 times lower than concrete, based on a predictive life cycle analysis.

In April 2023, Woodoo raised $31 million to bring its products to market, but that's not easy. The construction industry is difficult to penetrate because it requires different regulatory approvals in each territory.

Woodoo's materials are, however, readily available and easy to integrate in construction systems because they don't require industry professionals to adopt new methods. There are also indications that building codes and regulations might be accepting of it. California, for instance, has recently approved cross-laminated timber for up to 18-story construction, and New York has approved it for buildings of up to 85 feet tall.

Boitouzet believes this makes it a no-brainer. "On one hand you have a super emissive material that is non-renewable," he says. "And on the other you have a material that has stored C02 and it grows next to your house."

Woodoo has recently started its regulatory process in France and believes the process will take around 18 months. For now, the company must ensure its manufacturing processes are scalable and that its products

"IT HAS THE STRENGTH OF STEEL AND A RIGIDITY 23 TIMES GREATER THAN CONCRETE"

can approximate the price of the materials they aim to replace. First, they intend to compete with aluminum, because it is relatively expensive. Later, once costs have fallen, they will take on concrete, which is a far cheaper material.

One pressing question is: What will happen to the augmented wood after the buildings have been dismantled? If it's not going to be reused there needs to be a plan, because otherwise the carbon it stores will be released back into the atmosphere. "Solid is mechanically recyclable and could be ground to be sold as a bio-based composite at the end of the life cycle," Boitouzet says.

"Everyone in the building industry is now looking for bio-based and low-carbon materials at a cheap price, and it's difficult to crack," Boitouzet says. "We can't keep building with the same polluting materials. This is the problem that we need to solve for the planet."

Meet the expert

Timothée Boitouzet is the founder and CEO of sustainable construction biomaterials startup Woodoo, based in France.

FRONTIERS: ANTI-AGING

WELCOME TO THE GOLDEN ERA OF REJUVENATION SCIENCE

Start-ups and academics are making notable progress in tackling the aging process. Will they succeed?

magine a world where we can slow down, stall, or perhaps even *reverse*, our biological clocks. Where a 22-year-old can look and feel that way for longer and a 65-year-old can return their mind and body to that age once again. Scientists believe that this is no longer a preposterous suggestion.

Right now, we are in the midst of a golden age of longevity research. Huge sums have recently poured into this space, most conspicuously from Silicon Valley billionaires. Alongside traditional players such as pharmaceutical companies and research institutions, an array of headline-grabbing startups have emerged, and a notable anti-aging industry is coalescing. In 2022, an estimated $5.2bn was invested into 130 longevity companies; the market is forecast to be worth $44.2bn annually by 2030.

"Our understanding of aging has come of age," says Professor Dame Linda Partridge, founding Director of the Max Planck Institute for Biology of Ageing in Cologne, and a Professorial Fellow at the UCL Institute of Healthy Ageing. "We can target its mechanisms to keep healthy as we get older, and it's now one of the hottest topics in pharma."

Among humanity's great successes is the extension of human life. In 1900, the average life expectancy was 32 years, but now it's more than 70. We've achieved this through technologies such as seat belts and life jackets, but also vaccines and medicines that enable us to avoid

"OUR UNDERSTANDING OF AGING HAS COME OF AGE. IT'S NOW ONE OF THE HOTTEST TOPICS IN PHARMA"

Dame Linda Partridge, founding director, Max Planck Institute for Biology of Ageing

and treat infectious and chronic diseases.

But in doing so we've highlighted how much our bodies degrade over time. The symptoms of age include brittle bones and weak muscles, as well as the increased risk of diseases such as dementia and cancer.

"So what's increasing—and it really is a problem—is a period of disability, ill health, outright disease, and multimorbidity in late life, and it's something that we need to tackle," says Partridge. "We need to squash that period of bad things happening at the end of life so people stay functional, healthy, and happy for longer."

To this end, scientists have been investigating how to control aging, and specifically whether we can address not only its symptoms, but its causes. There was little hope until 1993, when scientists discovered that you can extend a worm's lifespan by disabling a single gene. The worms appeared to be healthy until the end, meaning their aging had been slowed rather than their lives simply extended.

Out of this work came a realization of "how plastic, how malleable, the aging process is," says Partridge. Its impact was to trigger a flurry of research into the cellular processes that cause aging in humans and various methods that could be used to tackle them.

"I think what has changed has been a real molecular, cellular, and mechanical understanding of the underlying processes that are affected by the things that we all know about, like diet and exercise," says Partridge. "We might be able to manipulate them in other ways, with drugs or with cell technology."

One discovery has been that the biological clock in cells can be turned back. By adding a cocktail of four proteins, typical human adult cells can be converted into youthful stem cells, which look and act like those in a newly formed embryo. In 2022, scientists used this approach to rewind the biological clock of human skin cells by around 30 years, according to molecular measures.

Still, we're a long way off being able to use this on humans. According to Partridge, cellular rejuvenation might theoretically be useful for treating certain diseases, but before it can ever be used to wind back a human's biological clock it must be shown not to be harmful. "The

"THE BIOLOGICAL CLOCK IN CELLS CAN BE TURNED BACK"

process needs to be very safe if a lot of people are going to undertake it," she says. And that's assuming the therapy can actually be administered in practice.

That's why Partridge believes we may have more immediate success with another major strand of current longevity research: Identifying existing drugs that can also be used to target the causes of aging. New computational techniques that encompass molecular simulations, genomics, and machine learning are proving powerful in helping prioritize drug-repurposing candidates.

Take the cancer drug dasatinib, for instance, which when administered with quercetin, a molecule found in colorful fruit and vegetables, has been shown to stimulate apoptosis. This is the process whereby the body clears out "senescent" cells, which are cells that have stopped dividing. Senescent cells seem to promote the onset of age-related diseases and there's evidence that removing them can slow the aging process. Of the current wave of anti-aging startups, many of those that are not focused on cellular reprogramming are looking at developing treatments that target senescent cells.

Or consider rapamycin, an immunosuppressant drug that has demonstrated a secondary ability to increase life expectancy. The drug targets the body's nutrient-sensing systems, causing them to believe it is in starvation mode and activating the life-extending processes that help humans survive on few calories.

"Drug repurposing is a real opportunity at the moment, and there is a lot of work going on," Partridge says. "Existing drugs that target things that we know go wrong during aging can often be used at much lower doses with benefits to health."

If truly effective anti-aging treatments emerge, they are going to face numerous ethical and social questions. One common concern is that unless we can ensure they're made available to all, they will accentuate the wealth divide.

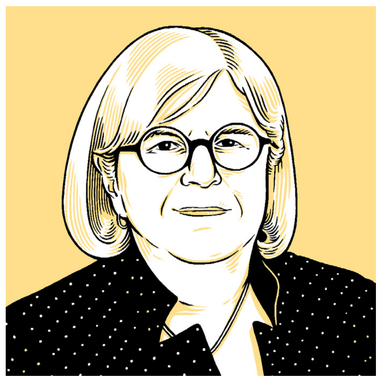
Yet if we do make them widely available, they will accelerate population growth to the detriment of the global ecosystem. Some therefore feel they shouldn't be available to anyone.

For now, that's a conundrum for down the road. "What

"WE NEED TO KNOW MORE ABOUT HOW THESE DRUGS AFFECT HUMANS, AND THAT'S CHALLENGING"

the science of aging is telling us is that if you target mechanisms of aging, then you can target multiple things that go wrong with aging simultaneously," she says. "We may know that in principle, but now it's about proving it in practice."

Meet the expert



Dame Linda Partridge is a geneticist studying the biology and genetics of aging and age-related diseases. She is the founding director of the Max Planck Institute for Biology of Ageing in Cologne, and a Professorial Fellow at the UCL Institute of Healthy Ageing.

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