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CRITICAL FOCUS

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Microbes and the Plant-Based Foods of Tomorrow

Plant-based substitutes for cheese and meat are being widely promoted. What can the microbes provide for the future?

We often complain about our microbes, don't we? One will produce confluent colonies rather than discrete growths; sometimes a culture medium doesn't seem to work; occasionally bacteria don't take stain the way we think they should. It just happened to me. I was so surprised at what I found that I muttered aloud: "Well, I didn't expect to find you here." It was only a passing thought. To my surprise, one of the bacteria responded. "And why not?" it said. "I've as much right to be here as anything else."

Mixed bacterial culture from Vermont blue cheese, imaged at the Wolfe Laboratory of Tufts University. The yellow colonies are *Staphylococcus xylosus* and the white ones are *S. succinus*. Several species of *Brevibacterium* show as small round growths, and the white fungal colonies are of immature *Penicillium roqueforti.*

"Oh, but surely not here. What's *Lactobacillus* doing in a sample of vegan cheese?"

"Here?" retorted the microbe. "Why not here?"

I was nonplused. "Look, I expect to find you in conventional cheese, a traditional dairy product, but this is a plant-based food," I said. "Nothing here has been anywhere near the rear end of a cow. This is not cheese – it's a synthetic substitute."

"Why would you say that?"

I thought for a moment. "Obviously – food technologists take proteinaceous products from plant sources, doctor them to feel cheesy, add a few biochemical flavors and there – you're done. That's not real cheese"

"Flavored protein?"

"Exactly," I continued, warming to the task. "Just throw in some short-chain fatty acids like butyric or hexanoic, a few methyl ketones, acetoin for that buttery taste, a selection of aldehydes such as 3-methylbutanal, perhaps a hint of hexanal, and some esters. Not much, but a hint of ethyl butanoate for that slight fruity taste … and there you have it: chemical food. I could write the recipe on the back of an envelope."

The bacterium laughed. "So, you'd assemble weighed amounts of these costly ingredients and blend them all in a mixer?" I nodded. "Have you any idea of the complexity of all this, or the cost? A small bottle of some of those can cost thousands of bucks. And why would you go to all that trouble if we mi-

Cheese from Ancient Egypt was discovered in the tomb of Ptahmes dating back 3,200 years. Teams from the University of Catania, Sicily, and Cairo, Egypt, found this solid deposit that analysts showed to be made from sheep's and goat's milk. The site was unearthed in 1885, but shifting sands buried it until rediscovery in 2010.

crobes can produce the whole range easily, at no additional cost, and without effort?"

"How do you mean?" I asked.

"You're a typical scientist," said the bacterium. "Think of the process, then work out a high-tech method to impose it all on nature." I nodded. "You have been tasting examples?" asked the microbe.

"Yes, I have," I replied.

"Did you have a favorite?"

"Not really. I tried a plant-based cheddar last week," I said. "Actually, it was surprisingly good."

"Look at it from the microbe's point of view. There's no need for this hi-tech recipe approach. We can do it for you. All of us – from we lactobacilli to *Penicillium roqueforti* – have been harnessed to ferment milk for thousands of years. But, from our point of view, all we do is process the substrate. We don't care where it comes from. If you give us milk, we'll produce traditional cheese. Provide us with some alternative growth medium – an extract of plants, like soybeans and nuts, or coconut and cashews, even sweet potatoes or tofu – we aren't picky. It's all fats, proteins, and carbohydrates, like milk. We ferment it all in the same way, and the result is still cheesy. Don't think of the product as an artificial alternative; to us, it's a different kind of cheese. The fermentation is the same, which is why the results taste so similar. Our live cultures also provide the probiotics, the bite of lowered pH, all the nutritional power of dairy cheese – though we don't produce any of the cholesterol."

"Wait," I asked. "Are you suggesting that plant-based cheese is better than dairy?

The microbe shrugged – until this moment, I didn't realize they could – and said, "Dairy cheese is a much-loved, ancient tradition. We can create an alternative that's genuinely healthy, perhaps more so, and tastes surprisingly authentic. We aren't very different. The taste is not contrived by human technology; natural microbes create it. Since prehistoric times, humans have had us fermenting milk from cows, sheep, goats, even horses; all fat-rich, carbohydrate-containing fluids in which we thrive. In the modern world, you are beginning to realize that there are other substrates that work as well as milk. The result? Much closer to traditional cheeses than you seem to have realized."

The microbe had laid bare my ignorance. So I heat-fixed the slide in a Bunsen flame and ran a Gram stain. That'll teach it …

STONE-AGE CHEESE

Cheese goes back a long way. We know it was being made in Neolithic times. Microanalysts have identified milk-fat residues showing they were making cheese 7,500 years ago in Kujawy, Poland (Ford, Brian J. "Beer and Pizza: A Slice of Ancient Life," *The Microscope*, 64:4, pp. 173–185, 2016). There are some samples from Croatia that may be even older. Ancient ceramic cheese strainers have been found in Poland, still bearing detectable traces of dairy produce, and dated at over 5,000 years old. Markers of *Lactobacillus kefiranofaciens* have been detected in Neolithic pottery residues, and a remarkable example comes from 3,600-year-old kefir cheese found in the Tarim Basin in China, buried with mummies of the Bronze Age. Ancient DNA was extracted from these remarkably well-preserved curds and metagenomic sequencing was used to reconstruct nearly complete genomes of key fermenting microbes, particularly *L. kefiranofaciens*, the core bacterium in producing kefir, and associated yeasts like *Pichia kudriavzevii*. Even more exciting is the discovery of traces of cheese which proteomic analysis showed was made with sheep's and goat's milk from Ancient Egypt and dating back 3,200 years. These were found in the Saqqara necropolis, the tomb of Ptahmes, the governor of Memphis, near modern Cairo. It wasn't all good news; among the bacteria that were identified was *Brucella melitensis*, causative agent of brucellosis. That troubles us now; it troubled the Ancient Egyptians then …

The earliest records of cheese were in Sumerian texts from 4,000 years ago. Cheese was an important part of the diet of Ancient Rome. Pliny the Elder wrote of cheese in 79 AD, noting that sheep's milk yields almost twice as much cheese as goat's milk. He describes sources of rennet and describes the coagulation of curds, and lists 'twelve remedies derived from cheese' for eye issues, defluxions, and other ailments. He even reports that the Persian prophet Zarathustra, back in the Bronze Age, had lived in the desert on a diet of nothing but cheese for some 30 years, and insisted it prevented his ageing. There was a surprising range of cheeses in Ancient Rome. Pliny writes of cheeses brought from Bithynia in present-day Turkey, enormous cheeses from Liguria in today's northwestern Italy, mountain cheeses from the Alpine villages, and hard cheeses (think of Parmesan) from Switzerland.

Today there are around 2,000 different cheeses. Some (like Cambozola and Natural American Cheese) are recent inventions – but others date back further than you might think. Conciato Romano is an aged sheep's cheese packed with herbs in jars of oil and produced in a manner dating back some 2,500 years to the Samnite era, before the foundation of Ancient Rome.

There are many blue cheeses. To create a blue product, the set cheese is inoculated with *Penicillium roqueforti*, occasionally *P. glaucus*, or *P. camemberti*. Roquefort originated in Lozère in southern France, an area which Pliny the Elder described as producing fine cheeses … so does that delicious blue cheese date back that far? There's no definitive evidence that it does, though it has been produced there since before recorded time. It is produced from the milk of Lacaune sheep and still spends its early aging in the limestone caves of Cambalou.

Gorgonzola is documented from 879 AD so has been made continuously for almost 1,500 years. Gorgonzola is famous for being odorous. It is not the worst. The specialty cheese Epoisses de Bourgogne is so seriously smelly that it is generally believed that it is illegal to take it on public transport in France. Like so many popular beliefs, it isn't true, though you are recommended to seal it in a plastic bag, out of courtesy to fellow travelers. Vieux Boulogne is even more disgusting, smelling of rotting cabbage, wet barnyard, dung, old socks, or a mix of body odor and decaying vegetation. One writer noted it could be smelt 165 feet (50 meters) away.

Many cheeses, like Limburger and Muenster, are renowned for an odor like smelly feet. The likely explanation will be immediately obvious to a microscopist: the same organisms inhabit both the cheese and the feet. Bacteria like *Brevibacterium linens* metabolize proteins and fats during aging, producing compounds like methanethiol, which has a sulfurous odor, and isovaleric acid, which smells pungently like sour cheese. When someone wafts their hands and says, about one of those cheeses: 'Whew, smelly feet!'

The Bell Inn, Stilton, was first written up in 1515. It's an excellent place to sample Stilton cheese, though the cheese cannot be made anywhere near. It is named from the fact that Stilton was a major resting-place on the Great North Road to London, and has been since Roman times. The cheese was brought there, not produced.

you can compliment them on their instinctual grasp of microbial biochemistry.

BLUE CHEESE BANISHMENT

One of the great blue cheeses is Stilton, named from a village a mere bike ride from my home in Cambridgeshire. It is produced in cylindrical wheels called "truckles" from cow's milk, veined with colonies of *Penicilliun roqueforti*. Each one is about 9 inches in diameter and 9 inches (23 cm) thick and weighs about 15-20 lb (7-9 kg). My father always used to order a half-Stilton at Christmas. It would last until Easter. One popular way to serve it is to moisten the cut surface with port wine, then spoon out the cheese, rather than cutting it with a knife. Our half truckle would come out with a flourish on Christmas Day, and it was the perfect close to a fine lunch. It still is. Some $4 million worth of Stilton is imported to the States every year. If you haven't, why not try it?

The cheese was first mentioned in 1720, when a cheesemaker named Frances Pawlett was noted as making the cheese from the milk of Shorthorn cows. By 1722, it was referenced by writers including William Stukeley, and Daniel Defoe, author of *Robinson Crusoe*, and in 1723 the production process was documented by Richard Bradley, an English author who went on to publish *The Country Housewife and Lady's Director* in 1727, followed by *The Gentleman and* Farmer's Guide in 1732.

The cheese became increasingly popular, especially at the Bell Inn in Stilton, a pub still largely unaltered to this day – we were there for lunch last week. Stilton was a stopping-point on the old Roman Road reaching from London – Ermine Street, later the Great

North Road – so it became a popular place to sell the cheese and transport it south to the capital. Curiously, it is illegal to make the cheese in Stilton. The production must be in the Midlands counties (predominately Leicestershire) and, since 1996, its status has been legally protected. In Stilton you can buy it; from Stilton they used to sell it; but it was never made there. And never can be.

Fungi and bacteria are not the only microscopical organisms that live in Stilton cheese. My grandfather had given me a German toy microscope when I was 12, and I had used it to observe spore formation in the fungi, and also something much more motile – the abundant cheese mite *Tyrophagus casei* that all such cheeses harbor in the rind. Each is only 500 μm long and, under the low-power microscope, they are entrancing to study. They infest cheeses naturally, though in Würchwitz, Germany, where they make Milbenkäse, locals farm them in traditional mite houses. The flavorsome gray powder adorning old cheeses is mostly mite feces and shed exoskeletons as the mites mature. Mmmm. Delicious.

The spores of *P. roqueforti* abound in the farm buildings where Stilton cheese is produced, and the truckles are stabbed with pointed wires to ensure the mold spores are introduced into the cheese. Back in the day, the wires were traditionally made from copper, because it was believed that the greenish-gray color of the spores was verdigris, basic copper acetate $Cu(CH_3COO)_2 \cdot [Cu(OH)_2]_3 \cdot 2H_2O$ – the copper must surely be the source. Indeed, when I tried to explain the biological nature of the greenish veining to my engineer father, he told me I was obviously wrong. "They prick the cheeses with copper forks," he insisted. "And you know why? You have seen plenty of copper church spires green with verdigris. It is obvious why they use copper. Fungi? Pahh."

One Boxing Day, I thought I'd prove the point, and I invited my father to look at the fungal spores on a fragment of Stilton cheese under the little microscope. He looked, he grunted, and he wasn't impressed. Then he suddenly jolted upright – "Good heavens," he said. "What's that? Something is moving." I took a peek; a mite had wandered into view.

"Oh, that's just a cheese mite," I told him.

"A what?"

"A cheese mite, *Tyrophagus*. They're everywhere."

"Everywhere?"

I nodded. "The gray powdery dust all around the cheese? It's all cheese mite feces. And their dead bodies."

My father stared down the microscope again, aghast. Then he looked at me, and at the cheese on

Cheese mites of the genus *Tyrophagus* infest the rind of old blue cheeses. They are responsible for the flavorsome gray dust that covers the cheese, composed of mite feces and shed exoskeletons. It is considered so important that they are sometimes reared in mite houses, ready to be sprinkled on the maturing cheese.

the sideboard. He didn't say a word. He stood up, collected the cheese, walked down the garden to the stone birdbath, and set the cheese down on the path, brushing his hands together as he slowly returned to the house. Within minutes, starlings flew down, and in no time there were scores of birds, all jostling for position and pecking furiously at the delicious, mature, flavorsome cheese. We never had Stilton in his house, ever again.

THE QUIET UNNATURALNESS OF CHEESE

When we have had visitors, I have sometimes proffered a sample of vegan cheese and asked that they thought. One common response is something like: "Plastic rubbish! Like that white bread." This won't do. It isn't plastic, synthetic, created. It's a fermented food, much like any other. Another is: "Ghastly stuff, tastes like socks." The "ghastly" is an instinctive, subjective judgement; and plenty of cheeses smell like the sweatiest of socks.

The most popular response is: "This is artificial. If I eat cheese, it's going to be natural. Natural foods are the best…"

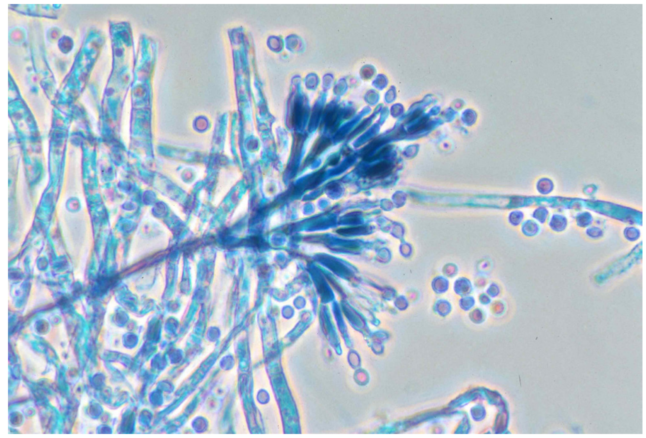
What was that? It is tempting to think that cheese is natural, but that's far from the truth. It is certainly traditional, sure, but there is nothing natural about it. Consider – you start with milk. This is the secretion of modified sweat glands on the underbelly of genetically selected cattle, intended only for their offspring. The fact that cows lactate at all is highly unnatural. Heifers are impregnated, give birth to their young, and the calves are then removed when a few days old, so that the cows are thereafter milked artificially by machine. Regular suction evacuates the udder. And so the cow continues to produce milk in large volumes. If you doubt this is unnatural, then visit a cattle farm after the calves are forcibly removed. The pitiful wailing and howling in which the cows indulge, is a response to the traumatic loss of their young. Every glass of milk represents a distressed cow. There is nothing natural about milking cattle.

Because milk is an inherently unnatural substance for humans to consume, we should not be surprised at the high proportion of people who are intolerant to it. Western Europeans and Americans of Western European descent are largely tolerant of dairy products, but East Asians, Chinese, Japanese, Koreans, Vietnamese, etc., are predominantly intolerant of lactose. The indigenous populations of the Americas are highly intolerant of dairy products, with over 90% being unable to digest milk. In the United States, about 15% of people of northern European descent are intolerant of lactose, about 75% of African Americans and Hispanic communities are intolerant, and up to 95% of Asian Americans. It should be no surprise that so many people cannot digest it. It's unnatural to consume milk, unless you're a calf.

So this unnatural fluid, obtained by unnatural means, is collected in vats ready to make into cheese. The first stage (traditional, but highly unnatural) is to separate the proteinaceous curds from the watery whey. This is done with rennet, an enzyme complex obtained from the stomach of very young ruminant animals. These little calves – too young even to have been weaned – are slaughtered and the entire abomasum, the fourth stomach, is removed. The lining is stripped off and dried and is then sliced and soaked in brine. The enzymes dissolve into the supernatant liquid which can then be evaporated to leave a powder. This is what is sprinkled into the milk and causes the curds to separate. Remember the nursery rhyme about Little Miss Muffitt, who sat on her tuffet? She was 'eating her curds and whey' – enjoying the cheese making process before it had even completed.

Animal rennet produces the finest flavors, but rennet enzymes are also produced by microbial fermentation. Fungi like *Rhizomucor miehei* can be cultured in vats to form a kind of rennet. Genetically modified *Aspergillus niger* is also used to produce chymosin, the rennet precursor in animals. Milk-coagulating enzymes, such as cardosin and cyprosin, as alternatives to rennet, are secreted by the cardoon thistle *Cynara cardunculus* and have been used in India and Portugal, though they are less reliable than rennet and they can also produce bitter tastes in the cheese.

So we have a semi-solid product from the unnatural rearing of unnatural cattle and their unnatural deprivation from the calves, being treated with



Spore formation in *Penicillium roqueforti* occurs as hyphae divide, much like a paintbrush (penicillus is Latin for "little brush"). Charles Thom of the U.S. Department of Agriculture named the species in 1906, from the French town of Roquefort, where blue cheese had been produced for centuries.

the unnaturally dried, soaked and powdered extract from unweaned calves' stomachs. The product is then salted, stacked into molds and left to dry. For a blue cheese, this is only the start. The *Penicillium roqueforti* fungus that will confer the blue veining lives naturally in decaying vegetation and dirt, where it is a principal agent of decomposition. It is widespread in forest soil or general decomposing plants and vegetation. This fungus is frequently found on decaying wood and is of common occurrence in moldy silage, spoiled grains and other forms of rotting food. Inoculating it into cheese? Entirely unnatural.

Traditional cheesemakers know that the spores are bound to settle on the rind of young cheese, and so they start stabbing the cheeses with thin metal rods. These days, they are made of stainless steel, rather than copper. The spores will be driven into the interior of the cheese where they will start to grow and induce decomposition. This is the highly unnatural process that provides the delicious piquancy of refined and mature blue cheese. Well, that and mite poop.

Natural? Cheese? It may be traditional, but cheese results from a cascade of unnatural, artificial, technical processing contrived over thousands of years by humans. Nothing like it can ever exist in nature, and we must never imagine that cheese is in any way a natural food for humans. It's not.

ANIMAL-FREE OR FANCY-FREE?

Opponents of plant-based foodstuffs say people are not ready to accept an artificial product. That is unsupportable; they already do. It's in your pizza. From the microbial viewpoint, there are endless alternative substances with a composition that is comparable with curds made from dairy. A creamy texture results when nuts are used as the raw ingredient. Cashews, almonds, and macadamia nuts are popular choices. Tofu provides a popular base for dairy cheese substitutes and sauces, while coconut milk and oil provide a balance between fat content and creaminess. Many have additions of starches, like tapioca, to optimize textures, and autolyzed yeast is often added to boost both the cheesy flavor and the B vitamin components of the product.

The resulting alternatives to cheese are generally lower in saturated fats than their dairy equivalents, though they are lower in protein. Although this point is often made as a criticism, it has no practical impact, since the average American man consumes about 100 g of protein per day, of which 10 g would typically derive from cheese, whereas the requirement is only 50 g. The products themselves are widely criticized for not tasting like dairy cheese, though – since they're different – you could not expect them to taste exactly the same, but what is surprising is how close they are to traditional cheese. The plant-based cheddar I've savored has the texture of dairy cheese, and a remarkably similar taste. The difference between real and plant-based cheddar is probably less than the difference between cheddar and Edam, or Emmenthal.

The main difference between these products and dairy cheese is the absence of casein, the primary protein in dairy milk which confers the stretch and melt properties of dairy cheese. Casein is a phosphoprotein that contains all 9 amino acids essential for human life, and it is rich in calcium as well as phosphorus. Genetic engineering now allows us to implant casein-synthesizing genes into microbes (bacteria and yeasts) so it is possible to create a plant-based substrate that is biochemically a close twin to dairy.

The best of all that I found is plant-based salad cheese. It tastes like a superbly creamy feta – in fact, I have sometimes purchased it in preference, for its reliably deep and creamy flavor is just what we need. The blue cheeses are perhaps the most interesting; the substrate may be different, but the blue-green fungus is identical, and there is no mistaking the taste of *P. roqueforti* fermentation. Daiya Foods produce a highly successful range of plant-based cheese. Though originated in Canada, they are now owned by Otsuka Holdings from Japan. Kite Hill, Miyko's Creamery, and Follow Your Heart, are based in California, Rebel Cheese (can't you tell from the name?) are in Austin, Texas. Chicago boasts several plant-based food companies – Cheeze and Thank You (run by women, and available through Whole Foods stores) and Chicago Vegan Foods are marketing high-quality alternatives to dairy cheese. The introduction of casein-producing microbial cultures will make it very hard to distinguish between traditional dairy products and the plant-based alternatives. We'd best start getting used to them.

FAMINE MISUNDERSTOOD

The search for plant-based foods is usually framed as an answer to famine. That is a myth. Currently, we are not running short of food. Half of our food is lost; it is damaged, discarded, or thrown away uneaten; but there is no shortage of food. In 1960, the index of food production per head of population was 85 – we were producing only 85 percent of the food everyone needed to be healthy. The figure rose to 90 by 1970. In 1990 it was standardized at 100 and by 2000 it was as high as 105. Today it's 130 – food supplies have increased until they far exceeded demand. This was a success story for global agriculture and a watershed for the modern world.

Famines are not generally caused by shortages of food, but by governments imposing restrictions. During the great famine in Eritrea in 1984, the Ethiopian government repeatedly rejected or restricted food aid, regarding it as foreign interference with domestic affairs. They rejected cooperation from all the major non-governmental organizations (NGOs) or from the United Nations. They exported grain, and still imported luxury goods like whisky, while aid trucks were regularly blocked. The problem was not a lack of food, but isolationist policies and economic mismanagement. The regime refused aid, using hunger as leverage and prioritizing sovereignty over humanitarian relief.

Remember Live Aid, the charitable single that aimed to help end the Ethiopian famine in 1985? The aid went initially to the regime, which confiscated food to feed their troops, to trade for Soviet arms, and to support forced resettlements as a tactic against counterinsurgency. In spite of warnings from groups like Médecins Sans Frontières, organizer Bob Geldof handed over funds that were often misused against the very people he had hoped to save. A 2010 investigation by the BBC included interviews with ex-rebels who claimed that 95 percent of the aid went to buy weapons, with only 5% benefiting the civilians. An assessment by the CIA from that era noted that aid was almost certainly diverted for military use rather than humanitarian benefit. Live Aid depoliticized the famine and portrayed it as a natural disaster, diverting attention from the fact that it was a man-made war, and it perpetuated stereotypes of helpless Africans in need of rescue by noble White communities, and indirectly helped to bolster a repressive regime without addressing the root causes.

The greatest current famine is in Sudan. Conflict and siege warfare has devastated agriculture, and displaced over 12 million people, while turning starvation into a deliberate military tactic. Aid convoys and trucks are blocked by bureaucracy. Inflation means that staple foods like sorghum, millet and wheat are unaffordable, while the collapse in vaccination protocols means that cholera and measles have now decimated the young. We do not educate people to understand these things, and the best-intentioned efforts frequently rebound and cause more harm than good. Today's famine in Sudan, which we rarely see mentioned on television or in the news online, is caused by political intransigence. They are not short of food.

Chinese agronomist Yuan Longping began his search for male-sterile rice in 1964. In 1970 he discovered a male-sterile wild rice, *Oryza rufipogon*, in Hainan, which could prevent self-fertilization and allow hybrid strains to flourish. The yields increased by almost 50 percent and some 80 million more people could be fed.

THE MICROSCOPE FEEDS THE CHINESE

The greatest famine in history was caused by ill-informed leaders enforcing uneducated principles on an unwilling population. This was the great Chinese famine of 1960, a direct result of Mao Zedong's personal policy – his Great Leap Forward. It produced the most catastrophic famine in human history. At least 40 million people died, far more than the 7 million who died in the Soviet famine of 1933 or the Great Bengal famine back in 1770 that saw 10 million starve to death. Mao Zedong forced collectivization on the communes, set impossible production quotas, diverted agricultural labor to steel furnaces, and introduced flawed policies like a sparrow-killing campaign that triggered huge outbreaks of insect pests. Food was prioritized for the cities, while starving the peasants in the countryside, where production was crucial. Any dissent or criticism was crushed.

The answer was found by a Chinese agronomist and microscopist, Yuan Longping. Everyone should know his name. He studied male-sterile rice plants using light microscopy and staining the pollen grains with iodine/potassium iodide. Viable pollen stains deep blue under the microscope, being rich in starch; aborted pollen grains from sterile rice plants appear devoid of carbohydrate. These investigations led to his discovery of a wild abortive strain of rice in 1970 that could restrict wind pollination and increase the productivity of hybrid rice. Today, his varieties are grown in over 60 countries, and Yuan's diligent microscopical research heralded an agricultural revolution.

A very different revolution took place in the USA under the leadership of Norman Borlaug, an agronomist and microscopist who worked for many years at DuPont. He later went to the Cooperative Wheat Research Production Program in Mexico, where he became preoccupied by increasing crop yields. Borlaug crossbred wheat plants to create disease-resistant strains. He also introduced short-stemmed wheat developed from a dwarf variety called Norin 10 that was originally developed by agronomist Gonjiro Inazuka of the Iwate Prefecture in Japan. The short, stubby stems could carry more weight from the ripening seed head, resulting in wheat that could produce three times as much grain.

You would think that Borlaug was hailed as a reformer, but his methods were centered on the liberal use of nitrogenous fertilizers, and he enthusiastically endorsed the widespread use of DDT as an insecticide. It turned out that Borlaug's reliance on chemical inputs led to reduced soil fertility, widespread erosion, loss of genetic diversity, and increased vulnerability to pests and water depletion. Modern western farming relies on the use of nitrogenous fertilizers, though this means that we are moving towards a hydroponic system. Soil is no longer seen as a nutritive ecosystem from which plants derive their nourishment, but merely as a means of holding growing plants upright while we irrigate them with factory-based fertilizer. Regenerative agriculture is emerging as a step back from technology (Ford, Brian J. "Our Disappearing Dirt," *The Microscope*, 69:1, pp. 25–36, 2022).

Borlaug's technologies clearly favored wealthy farmers with capital and access to credit and the market, while smallholder peasants sometimes faced high debts and land consolidation. It is also true that, by boosting food supply, his revolution encouraged population growth without addressing the underlying is-

Norman Borlaug, the chief microbiologist at DuPont in Delaware, single-handedly spearheaded the introduction of high-yielding wheat that doubled productivity and advocates claim he saved 1 billion lives. His support for chemical fertilizers and the use of DDT brought him detractors as well as supporters.

sues of poverty and food distribution, resulting in his being accused of contributing to overpopulation. In his 1970 Nobel Prize lecture, Borlaug acknowledged that his revolution bought time against the "population monster" but he acknowledged that it would not solve hunger permanently.

On the other hand, there is no doubt that his Green Revolution produced huge amounts of food that fed folk who would otherwise go hungry. His novel strains of short-stemmed wheat revolutionized Mexican agriculture, which went from being perpetually short of wheat in the 1950s to becoming an exporter of grain in the early 1960s. When these novel strains of wheat were introduced into India and Pakistan, they doubled productivity. Borlaug is claimed to have saved the lives of over 1 billion people. He remains a controversial figure: a hero to many, but to others a villain.

Will we need plant-based foods in future to avoid people starving? It's a topical point of discussion online, and there are conferences that address the issue – but it's a much older debate than you might imagine. Scholars celebrate the ideas of Thomas Malthus, who predicted that the needs of a growing population would outstrip the production of food. He published his thoughts in his book *An Essay on the Principle of Population, As It Affects the Future Improvement of Society*, published posthumously in London in 1798. It has been heralded as revolutionary and groundbreaking, though he was wrong. Malthus thought that farming methods were stuck in time, and never considered that agricultural efficiency could advance so rapidly. In his time, the world's population was just 800,000 people, and he was speculating that it might one day reach 1 billion. Today? It's 8,231,613,070 and increasing by one person every 10 seconds.

To find the earliest recorded discussions about food, agriculture, and population size, you need to go back much further, to Ancient China around 500 BC, when Confucius first advocated government policies that would ensure a balanced distribution of people across farmland. He realized the crucial importance of balancing population and resources and recognized the dangers of unchecked population growth. Confucius was the first we know who wrote of keeping population size in harmony with resources. Plato recorded similar views around 340 BC. In his books, *The Republic*, and especially in *The Laws*, he emphasized fixing an optimal and stable population that was tied to available land and resources. Plato argued for keeping the number of households constant, since that was how everyone could live decently without want.

In 1377 AD, the Tunisian philosopher Ibn Khaldun published a work entitled Muqaddimah, in which he wrote extensively on people and resources. He was the first philosopher to analyze economic cycles, the history of population dynamics, and agricultural productivity. Ibn Khaldun discussed the division of labor and cooperation, which could boost production far beyond individual efforts. For example, he showed that one person could not produce enough wheat alone, but coordinated groups of farmers and toolmakers could cooperatively produce food for many times their number.

And so the scene was finally set for the English philosopher Thomas Malthus, educated at Cambridge University, who became a professor of political economy. He argued that population grows geometrically, while food production increases only arithmetically. Famine was therefore inevitable. Malthus is regarded as a great innovator, but he was incorrect. Farming has steadily increased in efficiency and, when major famines occurred, the causes were not Malthusian. Although a failed monsoon caused drought in 1777, the Great Bengal famine was exacerbated by the East India Company forcing tax hikes upon peasant farmers and buying up supplies for their own troops. By mid-1770, rice cost 40 times as much under their regime. Colonial exploitation and outbreaks of smallpox led to the famine, not just a failure of the farms.

Similarly, Joseph Stalin precipitated the Soviet famine of 1933 by introducing shortsighted policies. Private farms were seized by the government and merged into state-controlled collectives. The peasants resisted as fiercely as they could, especially in Ukraine (the major grain producing region) but the widespread slaughter of livestock and the destruction of farming equipment led to chaos. Stalin set unrealistically high quotas for delivering grain to the state, and when quotas weren't met, the authorities confiscated seed grain, and they blacklisted villages that tried to resist. Stalin sealed the borders to prevent peasants from fleeing to find food, and he deported the wealthier and politically resistant farmers while suppressing Ukrainian intellectuals. The Soviet Union kept exporting grain while denying food to the hungry. Stalin weaponized starvation in Ukraine, and that was the cause of the famine.

The Irish Potato Famine was exacerbated by politics, too. The fungus *Phytophthora infestans*, introduced from America by trading vessels, struck the Irish potato crop in 1845, and thereafter caused devastating annual outbreaks. Half the population ate little else other than potatoes and malnutrition was everywhere. Ireland was under British rule, and the land was controlled by absentee landlords who showed scant regard for the fate of their tenants, trapped under a punitive regime. There was much talk of the disaster being heavenly retribution for the Irish holding to their Roman Catholicism, and the aid initially proposed by the Peel government in London soon petered out. British businessmen continued to export grain and livestock from Irish ports as the catastrophe unfolded around them. Jonathan Swift, the Irish writer and clergyman, satirically proposed that Irish families could solve both poverty and overpopulation by selling their children as food to the rich, proposing recipes like roast babies and fricasseed toddlers. His essay, *A Modest Proposal*, was published in Dublin in 1729 and recently inspired the Irish singer Hozier to release "Eat Your Young" in 2023.

THIRSTY HERDS EMPTY RIVERS

We have seen that famine, from Bengal in 1777 to the current catastrophe in Sudan, is caused by political intransigence, and not simply by a failure of food production. However, we are starting to look towards the day when we might start to run short. From the middle of the century, the world's population could rise to around 10 billion, and by then we will be feeling the pinch. Farming is not the problem; our greatest fear is for water shortage. We are running out of water. Neither the Colorado River nor the Rio Grande reach the sea, because of water extraction to support the population. The Yellow River in China, and the Indus River in India are the same. And meat production is an excessively thirsty industry.

A beefy hamburger sits well in the hand, but it consumed 3 tons of water to create. It takes 15 tons of water to raise a single kilogram of steak, around 2,000 gallons per pound. Sheep (and goats) require around 10,000 tons, pork 6,000 tons, chicken less than 5,000 tons. Producing livestock takes 40 percent of all the water consumed by agriculture but produces only 18 percent of the calories. That isn't sustainable. A kilogram of cheese takes 5 tons of water to produce. The plant-based alternatives consume only one-tenth as much. The quest for alternatives is not just a matter of eating healthily or showing ourselves to be trendy. We will need those alternatives – and need them soon.

TOFU TO TEMPEH

Searching for alternatives to meat has a reassuringly contemporary ring to it, but the quest to find plant-based meat substitutes dates back over 2,250 years. Tofu is a form of curd that dates back to the Han Dynasty of Ancient China some 220 BC (drawings of its production have been found in tomb art from that era). Tofu is made by soaking soybeans in water and grinding them to a paste. They are then boiled, and a coagulant is added – traditionally gypsum – which curdles the liquid and causes soft curds to form. They are then drained and pressed into blocks.

Tofu spread with the adoption of Buddhism in China, which promoted vegetarianism to avoid harming any living beings. By the 10th century, tofu was explicitly mentioned as imitation meat – called "small mutton" or "mock lamb" – to highlight its role as a viable alternative for animal products. Wheat gluten, seitan, known as mianjin or "wheat meat" in Chinese, originated around the 6th century AD. Buddhist monks developed it as a chewy, meat-like substitute that was suitable for their vegetarian cuisine. It was produced by washing wheat dough to isolate the gluten to create dense, elastic textures that were perfect for mimicking poultry, pork, or beef in alternative, plant-based meals.

Tofu has no taste. Well, it has the slightest flavor that you could be forgiven for not noticing: it is bland. This has the advantage of making it a "blank canvas" ready to absorb your favorite marinades, spices, sauces, and seasonings incredibly well. You can fry Tofu till crispy, bake it, grill it, and use it in everything from stir-fries and curries to smoothies, cheesecakes, and even scramble it, like a vegan version of eggs.

The people of Java, Indonesia, prepared a meat-like food from soy by fermenting the beans, rather than extracting curd. This is tempeh. Nobody knows when it originated; it was written about by the earliest European explorers, and is described in Javanese literature like the *Serat Centhini*, a poetic encyclopedia compiled around 1820, which describes events and culture from the 1500s. It is produced by cooking soybeans, then fermenting the resulting mass with the zygomycete pin mold *Rhizopus oligosporus*, which produces a penetrating white mycelium binding the beans tightly into a firm, compact cake. You can still see the beans in the resulting blocks, which have a nutty and earthy flavor, and a chewy, dense texture. Tempeh is a popular plant-based source of carbohydrate and protein that has served as a versatile meat alternative for – who knows? – Perhaps thousands of years.

FROM BATTLE CREEK TO THE SPACE AGE

Nobody troubled to develop meat substitutes in the Western world until John Harvey Kellogg and the Seventh-day Adventist health reform movement launched "biologic living" in Battle Creek, Michigan. It was 1876. Within 10 years, he had perfected Nuttose, a canned meat substitute processed from peanuts. In 1899 he launched Nuttolene with the consistency of cheese and he followed that in 1901 with Protose, made from peanuts with wheat gluten that provided something of a meaty texture. Most importantly, in 1895, he patented peanut butter. The Incas and Aztecs had ground peanuts to a paste for centuries, and Canadian chemist Marcellus Edson had patented a peanut paste in 1884; but it was Kellogg who bequeathed to us the jar in everybody's kitchen today.

PLANT-BASED MEAT GOES MAINSTREAM

Not until the 1950s did anyone else in the West consider making modern meat substitutes. A pioneering experimental product was developed in Britain in 1965 under the acronym CESP (standing, if I remember correctly, for Courtaulds' Extruded Structured Protein). At about that time, the British firm of Rank Hovis McDougall (RHM) began to investigate whether waste starch from cereal manufacture could be processed by microorganisms to produce edible proteins. Vegetarianism was on the rise, and RHM were keen to exploit the market.

In the U.S., plans were announced by the National Aeronautics and Space Administration (NASA) to develop food of this sort for prolonged journeys through space, and in 1968 they conducted research into hydrogenotrophic microbes (bacteria that convert CO_2 into protein-rich biomass). The idea was to turn the astronauts' exhaled CO_2 into a high-protein food source — essentially an early "meat substitute" creating single-cell proteins from air and microbes. Companies like Air Protein later revived this work in the 2010s, crediting NASA's forgotten 1960s ideas.

Large-scale investigations of possible fungal products as alternatives to meat were soon under way, and it was experiments by RHM with the mold *Fusarium venenatum* that proved to be most promising. This species of ascomycete fungus was first isolated in a wheat field in 1967 and after a decade of exhaustive testing, RHM was authorized to produce foods made from the *Fusarium* protein in 1980. The structure of the mycelium gave it a texture very like that of the striated muscle fibers in flesh. Five years later, the first retail products appeared in the shops. The production company was named Marlow Foods Ltd, after the town of Marlow, Buckinghamshire, where RHM's headquarters were situated, and production began as a joint venture between RHM and Imperial Chemical Industries (ICI) who had provided one of their fermenters that had been left unused from their abandoned single-cell animal feed research. The name chosen for the product? Quorn, named after a village of that name in Leicestershire, England. The village of Quorn did not always have that name; it was originally known as Quorndon but in 1889, as the postal service began to expand, it was often confused by delivery staff with the nearby village of Quarndon, so the postal authorities applied to have the name shortened in the interests of clarity. The village has been Quorn ever since and, since 1980, so has the fake meat.

When meals made with the Quorn protein were introduced as a meat substitute in the staff canteen of RHM, they proved to be popular, but the product went through a number of iterations before it was put on general sale. Supermarkets refused to sell the product until Lord Sainsbury agreed to market it through the Sainsbury's chain of food stores in 1994, and from then on production steadily increased. Over the next few years, it was progressively marketed across Western Europe and introduced to the United States in 2002.

The success of a novel product like Quorn has been remarkable. It is very popular with health-food fanatics, even though it is fundamentally science-based and is an entirely unnatural form of factory-made food. Once the fungus mass has been extracted from the fermentation vat, it is artificially flavored so that it can be used in meals as a substitute for beef, pork, chicken, or lamb. How curious it is that this high-tech product can become so popular with those who espouse "natural" foods; and how paradoxical that, instead of being marketed solely as a vegetarian product, its appeal to vegetarians is founded on the fact that it looks, tastes, smells, and feels like meat.

HEMOGLOBIN – IN PLANTS?

The first plant-based burger was introduced in 1981, the Garden Burger in the United States. The following year, Gregory Sam, owner of a London natural food restaurant SEED, launched one made of wheat, soy, oats, onions, and dried tomatoes. It was followed by the Boca Burger in 1993, but they all remained of niche status, being crumbly, bland patties that appealed mostly to vegetarians but failed to convert meat eaters. Beyond Meat and Impossible Foods were different: their hamburgers were made from soy protein and oils from coconut and sunflower seeds, but they had added ingredients that their predecessors lacked.

The developers, faced with a product made from components known for thousands of years, had to turn eventually to the microbe world. The look of a traditional hamburger depends on the red heme that oozes out, and they knew they'd need to incorporate heme into the product if it was to emulate minced meat. Heme is the red-colored iron-rich molecule, found in hemoglobin and myoglobin, which transports oxygen in vertebrates.

Surprisingly, there is also plant-based heme. This is not some exotic laboratory innovation, for it is naturally present in virtually every living plant. All green plants synthesize heme as it is an essential cofactor in cytochromes and peroxidases, and these phytoglobins provide a source of vegetarian heme. In most plants the levels are low, and the heme is dispersed in chloroplasts for chlorophyll precursors and in mitochondria for electron transport. But it is particularly concentrated in the bacteria that produce root nodules in legumes, where it is known (obviously) as leghemoglobin.

In 1954, a new species of yeast was discovered in California by Herman Phaff, a microbiologist born and trained in the Netherlands, before a distinguished career at UC Davis. His discovery was of a harmless methylotropic ascomycete isolated from exudates from the oak *Quercus kelloggii*. You will find this yeast called *Pichia pastoris* in many laboratories, but has recently been re-named *Komagataella phaffii*. Like most yeasts, *K. phaffii* grows well in culture, but (unlike *Saccharomyces*) never synthesizes ethanol. It is haploid, is easy to modify genetically, and secretes proteins efficiently, so it has become a go-to factory yeast.

In 2011, Patrick O. Brown, the founder and CEO of Impossible Foods, extracted heme from the nodules on soy roots, but only in small amounts. And so his team engineered the yeast by inserting the soy gene LGB2 into *K. phaffii* along with enhancements to the yeast's own heme biosynthesis pathway, and found they had a microbial culture that would produce useful amounts of botanical heme. The organism is genetically engineered, sure, but the heme it secretes is indistinguishable from the heme naturally produced in the root nodules. It could be extracted and added to the plant-based mix to produce a hamburger that looked just like the real thing, even down to oozing and sizzling on the grill.

Plant-based hamburgers were developed with botanical heme to imitate meat. They hit the headlines – then slumped. Cooking on the barbecue they looked like real meat, felt like it, bled like it, even sizzled like it. If only they had managed to make them taste like it, they would be home and dry.

Beyond Meat had a different approach, using pea protein sometimes blended with rice, while eschewing genetic modification and adding red beet juice to create the desired juicy appearance. The introduction of additives like autolyzed yeast paste added that savory umami to these novel products, so at last we had purely plant-based burgers that looked just like meat. It seemed like a PR miracle, and there was coast-to-coast publicity for these exciting new developments – realistic, bleeding burgers that were produced purely from plants. Americans were surprised at how good they looked, and how realistic they were on the barbecue. They browned. They sizzled. They even bled like a burger. But they still didn't taste like them…

The publicity proved to be hype, and Beyond Meat is currently in financial distress. Their shares lost almost 80 percent of their value this year alone and they are currently well over $1 billion in debt. Impossible Foods remain a private company, and although their sales have steadily declined, they are repositioning themselves as a health food company for athletes. The idea of the perfect emulation of a meat hamburger with plant-only ingredients remains just a dream, rather than reality.

THE VEGAN DIVIDE

One of the underlying marketing aims, rather than appealing only to vegetarians, had been to convert self-confessed carnivores. But eating pure meat has a particular appeal; in South Africa the hunters say: "Wipe its ass, cut off its horns, and chuck it on the barbecue." Sayings in the States include: "Real men eat meat" and those who are out earning dollars to feed the family are said to be "bringing home the bacon." Consuming steak is seen as manly. Yet it also brings health hazards. It may increase the risk of contracting colorectal cancer and cardiovascular disease. Meat consumption is also associated with increased risk of Type 2 diabetes and diverticular disease. Intestinal function is geared to levels of plant fiber in the diet, and 90 percent of Americans are reckoned to consume less fiber than they should. About one-fifth of older citizens suffer constipation as a result, with hemorrhoids, anal fissures, and fecal impaction as possible side effects.

Fatty meat is also a contributing factor in national obesity, with almost 75 percent of Americans being overweight. It is obviously hard to resist the huge and appetizing meals served in restaurants, with a new $70 billion industry in the supply of injectables to encourage people to lose weight. You control your weight best by deciding to limit what you eat, and I find it astonishing that people would consent to be injected with mind-altering drugs rather than simply deciding to adjust their daily diets.

Those relying on a plant-based diet may feel they are automatically healthier, though they may suffer vitamin deficiencies, notably of B12 and omega-3 fatty acids, and face higher risks of anemia and osteoporosis. Processed foods are worse: foods like frankfurters, ham, and bacon are listed as Group 1 Carcinogens, while vegan foods have also been associated with obesity, raised serum sodium, and several cancers – and many of the vegan foodstuffs are among the most intensively processed foods we know.

The answer – a sensible combination of all foods that people choose for themselves – seems to be elusive. In response, the pharmaceutical industry is content to charge people some $10 a day to obtain something they could do for themselves, at no cost at all. An edition of The Simpsons, an American animated sitcom created by Matt Groening, (series 36 episode 13) is amusingly devoted to the effect of a mythical hunger-reducing medication they call Othinquic on reducing everyone's weight. Believe me, it's not a pretty sight.

CHICAGO - WINDY CITY

They called Chicago the Windy City because of the high-pressure marketing that lay behind the city securing the World's Columbian Exposition of 1893. I can think of another reason: Chicago currently hosts so many innovative companies processing beans to make plant-based foods.

Upton's Naturals have been based in the city for a decade, making seitan-based bacon, chorizo, and jackfruit pulled burgers imitating pork. Aqua Cultured Foods are in the city's West Loop and produce fungi-fermented whole-cut alternatives to shrimp, calamari, scallops and tuna. The Vegan Copacker in Elk Grove Village is developing new plant-based brands, while the Fresh Factory specializes in plant-based manufacturing and packing. Good2Go Veggie manufacture groundbreaking plant-based foods from Shock'N Shrimp to Blaz'N Bacon, while Nature's Fynd are creating fermented fungus-based breakfast patties and cheese-style spreads, and TiNDLE are conducting research into plant-based chicken substitutes. Few cities can match Chicago for novel plant-based enterprises.

MUSCLE FIBERS MEET THEIR MATCH

One of the main problems with plant-based foods is texture. You might manufacture a product that matches meat for composition, but it lacks the feeling of meat in the mouth. Striated muscle has a fine, fibrous nature and the cells of the tongue can detect this. One of the advantages of Quorn, when it was launched in the 1960s, was that the hyphae comprising the mycelium have a stranded texture that seemed to emulate meat, even though being ten times finer under the microscope.

In the United States, food scientists were trying a different approach, namely, conferring a fibrous, meat-like texture to structureless plant proteins. The initiative was pioneered by William T. Atkinson, research scientist at Archer Daniels Midland (ADM) in Chicago. The company was founded in 1902, extracting oil from linseed yet, in 1965, Atkinson announced a revolutionary new product – textured vegetable protein (TVP). He extruded vegetable protein through tiny spinnerets, which conferred the essential fibrous texture. ADM secured approval for TVP to be permitted in school meals in the 1970s, and in 1991 created the first soy-based patty. Cargill in Minnesota, specializing in grain, oil-seed products and biofuels, have become the largest privately-owned company in the world, and are now researching plant-based foods.

Researchers at the Fraunhofer Institute in Munich, Germany, are developing ways to process pulses into a range of plant-based foods. After decades in the doldrums, alternatives to meat and dairy produce are suddenly in demand around the world. Trained microscopists play a key role in the research.

Universities are active in the field, too. In the U.S., University of California, Davis, is a major player, so is Purdue, NC State, and the University of Minnesota. European centers of research include the Technical University of Munich and the prestigious Fraunhofer Institute in Munich, also the University of Hohenheim, all in Germany; at Wageningen University, Netherlands; and at the University of Reading in the U.K. Funding has dramatically increased in recent years; plant-based alternatives and microbial foods are now key sectors of research.

PLANT MILKS: OLDER THAN YOU THINK

Then, along came the attorneys. It had to happen. The European Union decided to define "milk" as the mammary secretions of mammals. Now the British Supreme Court is about to rule that an oat milk product could not be promoted as a drink for the "post-milk generation." You might be wondering why the British courts are following the European Union, after all the controversy over quitting Europe. I'm wondering too. We all are.

What those lawyers missed is that the term "milk" is not confined to dairy. Coconut milk has been known for 5,000 years, and walnut milk likely dates back as far in North America. Hickory nuts have been pounded to make a milk substitute by the Powhatan people, since prehistoric times, and rice milk has been popular in China for over 3,000 years. Soy milk has been known for some 2,000 years, while almond milk dates from the year 800 (and there is a detailed recipe published in Baghdad in 1226). Oat milk is one that's new. This brand, Oatly, was invented in 1994 by brothers Rickard and Björn Öste at Lund University, Sweden, and they are now being told that it cannot be described as a drink for the "post-milk generation." After over 5,000 years of history, they can't even say something isn't milk! Meanwhile we have so many products that sound like dairy but aren't. Peanut butter, coconut milk, cream sherry, shea butter…

They tried it in the U.S. earlier this year with an attempt to introduce similar controls. This was a bill by Senator Tammy Baldwin. It was a contorted acronym: "Defending Against Imitations and Replacements of Yogurt to Promote Regular Intake of Dairy Everyday" – DAIRY PRIDE. It aimed to limit the use of dairy descriptors for plant-based items, just as in Europe and the U.K., but the bill was stalled; it is going nowhere. The American approach has been so much more sensible, because it respects history.

MICROBIAL DREAM TEAM

Fifty years ago, I wrote that we'd have limitless food if we turned to microbes in culture, grown in vast vats (Ford, Brian J. *Microbe Power, Tomorrow's Revolution*, New York: Stein & Day, "Food from the Microbe," p. 41, 1976). It hasn't happened. The bulk of our plant-based meals are processed from the same foods people have used for thousands of years: soybeans, grains, and rice. The only successful food made from cell cultures is Quorn, yet so many will inevitably follow.

Yet it is microbes that underpin the industry. In ancient times, tempeh was produced with *Rhizopus*, and today we use autolyzed yeast to confer umami to a range of plant-based foods. It is cultured yeasts that have allowed us to produce vegetarian heme in large amounts, and which generate the B vitamins present in meat that are important to vegans. Microbes enhance protein digestibility, they can reduce levels of the phytates, lectins, tannins, and other compounds that can restrict the update of nutriment from foods. We have long used domesticated microbes to produce yogurts, kimchi, and sourdough bread, and fermented foodstuffs have been prized since prehistoric times.

When we consider the future, plant-based foodstuffs offer one overwhelming advantage: their greatly reduced environmental impact. The production of plant-based foods as alternatives to meat releases only 5 percent of the emissions and consumes less than 1 percent of the land. The savings are immense. I predict that there will come a time, within 50 years, when we look back to the mass production of dairy cheese and beefsteak with astonishment and regret.

It will be like coal-burning factories and leaded petrol; it seemed necessary at the time, but that time … will have passed. ■