New Sieves on the Block

The development of sustainable covalent organic framework membranes enables more efficient filtration of chemical agents in industrial processes.

Chemical separation processes are notorious for their high-energy consumption and environmental impact. Despite these challenges, they remain essential to a wide array of industries, from pharmaceuticals to wastewater treatment.

Recognising the need for more sustainable and efficient solutions, scientists from NTU's School of Chemistry, Chemical Engineering and Biotechnology (CCEB) have pioneered the development of new membranes for more sustainable filtration methods. The new membranes tackle the inherent limitations of conventional polymeric membranes.

"In a typical plant, separation processes consume between 40 and 60 percent of the total energy and capital costs. To achieve sustainable and green manufacturing, innovation in low-energy separation via membrane technology is essential," explained NTU Professor Rong Xu.

The use of chemical filtration systems resembles cooking. Ingredients can be added to recipes to alter flavour or properties, or even speed up reactions. Items such as the common colander can strain pasta or rinse vegetables much like filters do in industrial systems.

Filters isolate molecules in chemical liquids making them an energy-efficient tool for separation.

"In chemical production, processes such as distillation and extraction isolate and purify compounds to create high-value products. However, these processes are energy and resource intensive," remarked Xu.

Separation anxiety

While kitchen sieves and colanders have been perfected over centuries, their industrial equivalents still have room for improvement.

"If they let molecules pass through easily, they cannot selectively separate specific ones. But, if they only let a limited number of molecules through, more energy may be required for the process."

In a study published in the May 2024 journal *Angewandte Chemie International Edition*, Xu's team proposed using covalent organic frameworks (COFs) as a solution for creating effective and energy-efficient separation membranes.

COFs are a class of porous crystalline materials composed entirely of light elements such as carbon, nitrogen, oxygen and hydrogen. These elements form strong covalent bonds, creating a chemically and thermally stable molecular network with well-defined pore channels. They allow certain chemicals to pass through while providing a large surface area.

"Whether it's delivering drugs, capturing carbon dioxide or sensing disease biomarkers, COFs are fascinating materials with a multitude of uses," declared Xu. "They are a perfect example of how, through a chemical sleight of hand, simple and light elements can come together to form strong and stable structures."

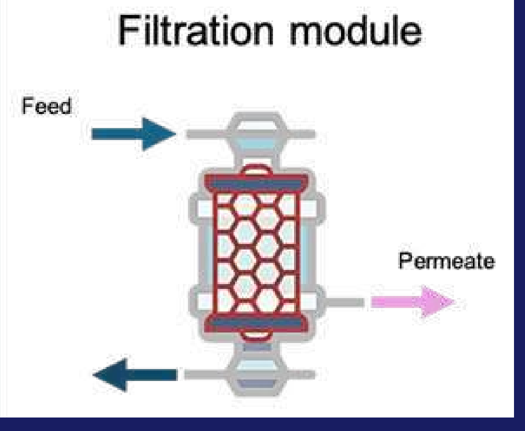
According to the researcher, the industry generally favours filtering materials through hollow fibre membranes. This geometry provides a high surface area relative to size and can be easily scaled up. Unfortunately, applying COFs to the inner surfaces of these tubes is not an easy task.

"Conventional methods are time-consuming and use liquids containing COFs to coat the curved surfaces inside the filter tubes. The very nature of liquids often results in an uneven coating, which in turn affects separation performance. This makes these filters economically unfeasible for industrial use," detailed the professor.

Xu saw the need to innovate a more practical fabrication protocol.

The filtration module is used to test the performance of the newly developed COF membranes using a cross-flow filtration configuration.

In contrast to traditional dead-end filtration, where the feed flows directly onto the membrane surface, cross-flow filtration directs the feed solution parallel to the membrane. This approach minimizes buildup by continuously sweeping away particles that would otherwise accumulate on the membrane surface.



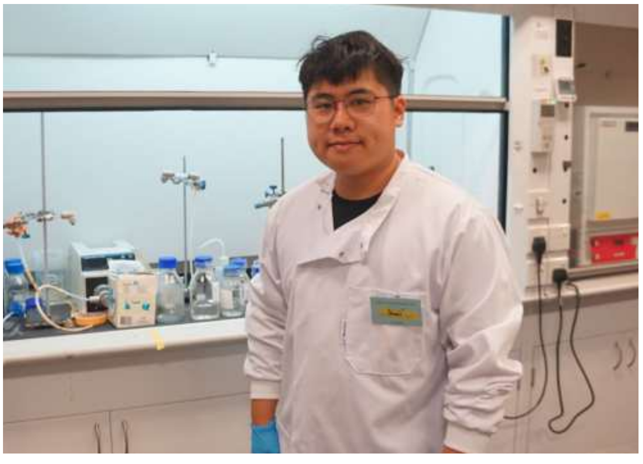
> *We need to understand that polymeric membranes commonly used in filters come with trade-offs," explained Xu.*

The team posited that introducing the COF monomers in a vapour form could allow them to diffuse through the tube, and thus, deposit onto its inner surface gradually, steadily and uniformly. This approach allowed the scientists to control the rate at which the monomers reach and coat the inner surface of the filter tube.

The researchers first coated the inner surface of a filter tube with a thin layer of polydopamine, a material that helps other substances adhere. They then placed the tube in an environment where COF-forming molecules were introduced as vapours. When these vapours contacted the polydopamine-treated surface, they reacted to form a solid COF layer that bonded tightly to the substrate.

"Our novel vapour/vapour-solid interfacial (V/V-S) method allows the fabrication of ultrathin, crystalline COF membranes in a single-step, eight-hour process," shared Xu.

When tested in an organic solvent nanofiltration system, the membrane demonstrated a methanol permeance of about 200 litres per square metre per hour per unit pressure — a high flow rate that highlights its efficiency and suitability for industrial filtration.



↑ *First author and researcher Samuel Siow, PhD*

Additionally, it can selectively filter molecules smaller than various desired sizes by tuning the pore size of the COFs. It further maintained filtration for over 80 hours without any loss in stability or function.

Versatility at its core

The team's V/V-S method is also versatile. It can be adapted to create other types of COF membranes with different pore sizes and chemical properties.

"This is important — we wanted to develop a protocol that isn't limited to just one application. Every industry has its own separation processes, each involving a wide range of chemicals," said Xu.

This means the researchers can bring sustainable filtering solutions to a broader array of separation challenges.

The team prepared membranes ranging from 100 to 500 nanometres in thickness by adjusting the number of growth cycles during the fabrication process. They demonstrated that one of the membranes can separate glycyrrhizic acid, an active pharmaceutical ingredient, from dimethyl sulfoxide, a harsh solvent that would normally corrode conventional polymeric membranes, to a filtration rate of up to 98 percent.

"The pharmaceutical industry relies on many separation processes, many of which guzzle huge amounts of energy. Our lab's new technique shortens the time needed to produce energy-efficient COF membranes that remain stable and resistant to organic solvents," stated Xu.

Xu and her team envision a future where sustainable COF membranes play a key role in driving industrial efficiency and environmental responsibility across various sectors.

The team has embarked on a project to further develop the technology for a wider range of COFs and substrates. Having acquired funding through NTUitive, NTU's commercialisation arm, a prototype membrane module for organic solvent separation is currently under development.

"In particular, we are keen to take our R&D further and explore the large-scale fabrication of COF membranes to help build a more sustainable pharmaceutical industry," said the professor.

Landfills are Trash for the Atmosphere

The development of a more accurate emissions estimation method reveals that landfills release far more methane than standard calculations capture.

Carbon dioxide receives a lot of attention as the number one climate threat, allowing methane, the second most abundant greenhouse gas, to slip under the radar.

In a study published in the February 2024 edition of Nature Sustainability, researchers at NTU's School of Civil and Environmental Engineering (CEE) concluded that methane emission estimates from landfills are significantly underestimated, sometimes by figures of up to 200 percent.

> *Not every landfill behaves the same way," stated the researcher.*

An underestimated impact

Methane gas comes in several forms with around 40 percent occurring naturally. When it comes to human-source methane, landfills make up around 20 percent, a rate half of what the energy sector and agriculture industry each produce.

"Landfills are the third-largest anthropogenic source," explained NTU Associate Professor Fei Xunchang. "But we suspect methane emissions from landfills may be far greater than current estimates suggest."

The discrepancy in landfill methane predictions versus actual values boils down to having a convenient one-size-fits-all estimation method, according to the researchers.

The current standard estimation technique, as recommended by the Intergovernmental Panel on Climate Change (IPCC), uses a first-order decay model. These types of models assume that the rate at which organic waste decomposes, and subsequently generates methane, decreases over time alongside the material itself.

↑ *Postdoctoral Research Fellow and CEE Researcher Yao Wang*

That model's bottom-up accounting method relies on two factors: the amount of organic waste in a landfill and how long it has been there. It uses a decay constant to estimate the rate at which the waste decomposes.

The problem is that the constant was determined by a few lab tests and field measurements taken two to three decades ago, according to Fei.

Our waste, under the surface

Beneath the surface of surplus produce, cardboard boxes, worn-out sneakers and other remnants of daily life in a landfill, chemistry and bacteria run the show. In a compact, oxygen-starved environment, bacteria break down organic matter anaerobically, releasing methane as a byproduct.

Calculating how quickly they do so is not as simple to predict as the nuance-lacking constant reflects.

"Not every landfill behaves the same way," stated the researcher.

He cited location, waste composition and climate conditions as influencing decay rates. For instance, landfills in tropical, humid countries produce methane at vastly different rates than those in cooler, drier climates.

A new model for old rubbish

Just as regulatory landscapes and climate science evolve, so must equations formulated two decades ago, asserted the professor.

The team got to work to do just that – update method emission estimates. Instead of relying on a fixed decay constant, the researchers tailored this constant to each landfill based on three factors: waste composition, moisture and temperature (CMT).

"We built this approach by drawing on an extensive dataset of methane measurements. There were 195 field measurements across 18 countries and 80 laboratory tests across 12 countries," Fei explained. "This gives us a model that reflects the diversity of real-world landfill conditions, which in turn provides a more accurate picture of methane emissions on a global scale."

The team then applied the model to predict the cumulative methane emissions from 2010 to 2030 for 12 major landfills across different climate zones. That is when they found the IPCC-recommended model had underestimated emissions by as much as 200 percent in some landfills.

Cleaning up the easier wins

Overlooking the compound's potency represents a missed opportunity, as methane emissions are easier to mitigate than carbon dioxide. Additionally, better data will enable policymakers to pinpoint where methane reduction efforts will yield the most returns.

Fei described addressing methane as yielding "faster benefits" than carbon dioxide as methane emissions have a relatively short lifespan, breaking down in about 12 years rather than the centuries required by its carbon dioxide counterpart. This means results will be impactful earlier.

↑ *Associate Professor Fei Xunchang*

> *"We increasingly view methane reduction as a strategy for 'buying time' on the climate crisis," declared Fei.*

Furthermore, changes in carbon dioxide emissions require systemic shifts in energy and industry. Meanwhile, methane from landfills offers a relatively economical, near-term opportunity to slash greenhouse gases, especially in developing regions where landfills are abundant but often lack proper regulation.

"Take, for instance, high-emitting landfills that receive waste from megacities," mused Fei. "With CMT-adjusted data, local authorities could take targeted actions, such as implementing methane capture technologies or enhancing landfill cover materials, to reduce emissions during peak production periods."

Taking out the trash for cash

Fei also highlighted the potential economic benefits of generating power from landfill gas. "Each year, converting up to 50 million tonnes of methane to 300 billion kWh of electricity could save about US$50 billion in energy costs," he added.

For regions like Southeast Asia and Latin America — where rapid population growth meets limited waste-management infrastructure — the CMT method could inform sustainable landfill management practices and attract funding for much-needed waste management reforms.

Fei's team believes there are more improvements that could be made in the IPCC-recommended model. The methane oxidation factor, correction factor and recovery rate all currently rely on obsolete default values and could be updated for better accuracy. The researcher also suggested establishing a standardised information recording mechanism. The measure would improve data quality and provide a strong foundation for effective climate policies.

"We increasingly view methane reduction as a strategy for 'buying time' on the climate crisis," declared Fei. "It's really important that we quantify methane emissions at the highest possible resolution."

First Quantum Recoil Observation Set to Change X-Ray Tech

Quantum recoil, theorised over eight decades ago and experimentally proven for the first time just two years ago, is paving the way for highly accurate X-ray imaging technology with benefits across sectors - from healthcare to manufacturing.

For over 80 years, the scientific community has understood the concept of quantum recoil and its implications, even though it had never been observed.

Researchers from NTU's School of Electrical and Electronic Engineering (EEE) changed that when they published research in the journal *Nature Photonics* in January 2023. The team was the first in the world to demonstrate the phenomenon through experiment, an event that paves the way for its use in practical applications.

It was in Professor Wong Liang Jie's lab that the researchers demonstrated Nobel laureate Vitaly Ginzburg's theory that when an electron loses speed after disturbing atoms, it transfers part of its energy and momentum to the photons (light particles) it emits.

This transfer occurs because, like electrons, photons also carry both energy and momentum. When photons are emitted, this energy and momentum exchange leads to a shift in the photon's energy. It turns out, the researchers were not even looking for it when they found it.

"It was a serendipitous discovery," confided Wong. "We were studying the generation of compact, high-brightness, tunable X-rays and realised our results were not matching the predictions of classical theory."

Wong's team had been directing electrons at ultrathin materials boron nitride and graphite. The materials were each a thousand times thinner than a strand of hair.

As the electrons struck the surface, the researchers measured the emitted X-rays using an energy-dispersive X-ray spectrometer.

The team investigated why the values were not as predicted and that is when they understood both sets of experiments confirmed the observation of quantum recoil.

The work also revealed that quantum recoil can be so enormous that a classically predicted X-ray photon can be emitted as an extremely low-energy photon. Additionally, it can be tailored by controlling the electron energy, the target material's atomic composition and tilt angle, and the emission order.

Wong would later be recognised as one of the 10 2024 Falling Walls winners in Physical Sciences for his contributions to X-ray photonics.

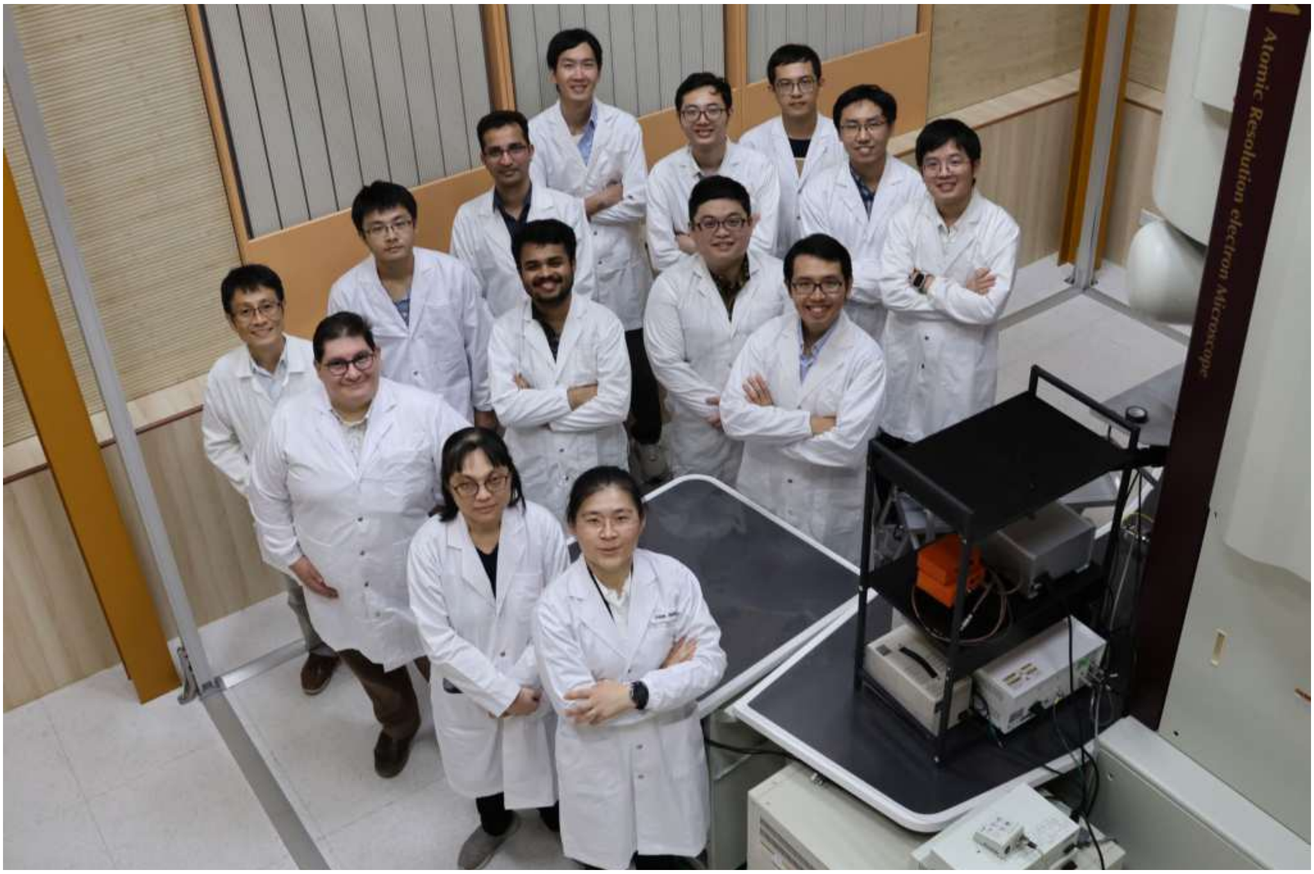
Demonstrating this phenomenon experimentally has long been challenging due to limitations in materials engineering.

"To realise quantum recoil is observable, the bombarded surfaces need to have atomic patterns or 'grooves' spaced less than one nanometre apart — and they have been challenging to fabricate," said Wong. The materials Wong's team looked at had naturally occurring nanoscale structures in layers just one atom thick.

It's the little things that count

"By accounting for quantum recoil, we can design compact devices that generate specific X-ray energies with greater precision," stated Wong. "This level of control implies that we can customise X-rays to suit a range of imaging needs."

According to Wong, the work can lead to X-rays needing less power, providing enhanced resolution and becoming safer for the operator or even the subject, who overall could get a lower dosage of radiation.



↑ *Associate Professor Wong Liang Jie and his team with a scanning electron microscope used in their quantum recoil experiments.*

While occasional X-rays pose minimal risk, repeated exposure over time can increase the likelihood of cellular damage and elevate the risk of radiation-related health issues, including cancer.

Wong sees the improved X-ray tech as potentially transforming X-rays in three major areas: semiconductors, health care and security, like airport luggage screenings.

Reduced radiation could make the use of X-rays more accessible in security applications while the ability to analyse biopsy samples in greater detail is likely to improve diagnostic accuracy and patient outcomes.

The competitive semiconductor industry can benefit from tunable X-ray inspection tools that provide highly precise scans of chip layers, preventing defective chips — such as those with microscopic air bubbles — from leaving the fab.

“It’s not just finding flaws in chips, but flaws that would elude current X-ray tech,” explained the professor. “Further, X-rays are generally used for quality assurance and failure analysis in many areas of manufacturing beyond semiconductors.”

When it comes to commercialisation of the technology, both local and global companies are already taking notice. There have been agreements for prototypes and partnerships. Wong also revealed he had developed a proof of principle experiment demonstrating the advantages of tunable X-ray imaging technology.

Some progress has been made in X-ray technology since its invention over 125 years ago, but according to Wong, the fundamental principle — the use of electromagnetic radiation to create images of internal structures - has remained unchanged.

“It’s time to take advantage of all the new scientific discoveries made in recent years and improve this tech,” he concluded.

X-ray Team Continues Scan for Next Big Breakthrough

Since first observing quantum recoil, Wong’s team has furthered their quest for safer, sustainable, and more efficient X-ray imaging systems.

Specifically, the researchers have demonstrated that van der Waals heterostructures, customizable layerings of atomically thin materials held together by weak forces, could produce tunable two and three colour X-ray emission with controllable energy and intensity. These findings show that by carefully designing these materials at the atomic level, X-ray beams can be customized for specific tasks.

Their research has also forayed into water-window X-rays, a special type of X-ray used in biological imaging and soft X-ray microscopy, which allow for clear images of cells without needing to add dyes or stains. The team demonstrated they could also generate this type of X-rays by bombarding van der Waals materials with free electrons, using record-low electron energies.

Furthermore, the team was able to derive and demonstrate the fundamental scaling laws of the X-ray generation process, showing that their proposed water-window X-ray source could be scaled up to produce a sufficient number of X-rays for imaging applications.

Brewing Sustainable Composites with Coffee Grounds and Fungi

Coffee grounds and fungi take root in a strong, 3D-printed living composite with self-healing and adhesive properties.

Coffee sparks inspiration for many, as evident by the more than two billion cups of joe consumed every day.

The byproduct of the delicious elixir is more than just a jolt of energy - it's also the six million tonnes of coffee grinds that end up in landfills or air-polluting incinerators.

> *Coffee waste improves both the growth and density of the fungi material.*

While the fate of its solid remnants rarely crosses the minds of most, Professor Hortense Le Ferrand at NTU's School of Mechanical and Aerospace Engineering (MAE) has spent quite a lot of time pondering coffee grinds, alongside other organic wastes, as a growth substrate for fungi used in 3D printing.

One of the focuses of Le Ferrand's lab is combining composite materials from harvested natural resources, such as mycelium, with digital fabrication methods.

The team sees the transition to these sustainable approaches as crucial for both economic resilience and environmental sustainability in an era of climate crisis and dwindling resources.

"The motivation for the work was to provide extra nutrients to the mycelium, while participating in the circular economy," explained Le Ferrand. "We tried with other wastes like orange and banana peel, and coffee grounds worked the best."

Mushroom for improvement

Mycelium is the vegetative network of fungi. It is to fungi what roots are to plants and is commonly visible as fuzzy, sprawling threadlike strands, called hyphae. They can be found on mouldy food, or in the lab's case, decaying wood.

The material is more than just an unwelcome sight on old food or wood. It has a surprising array of uses.

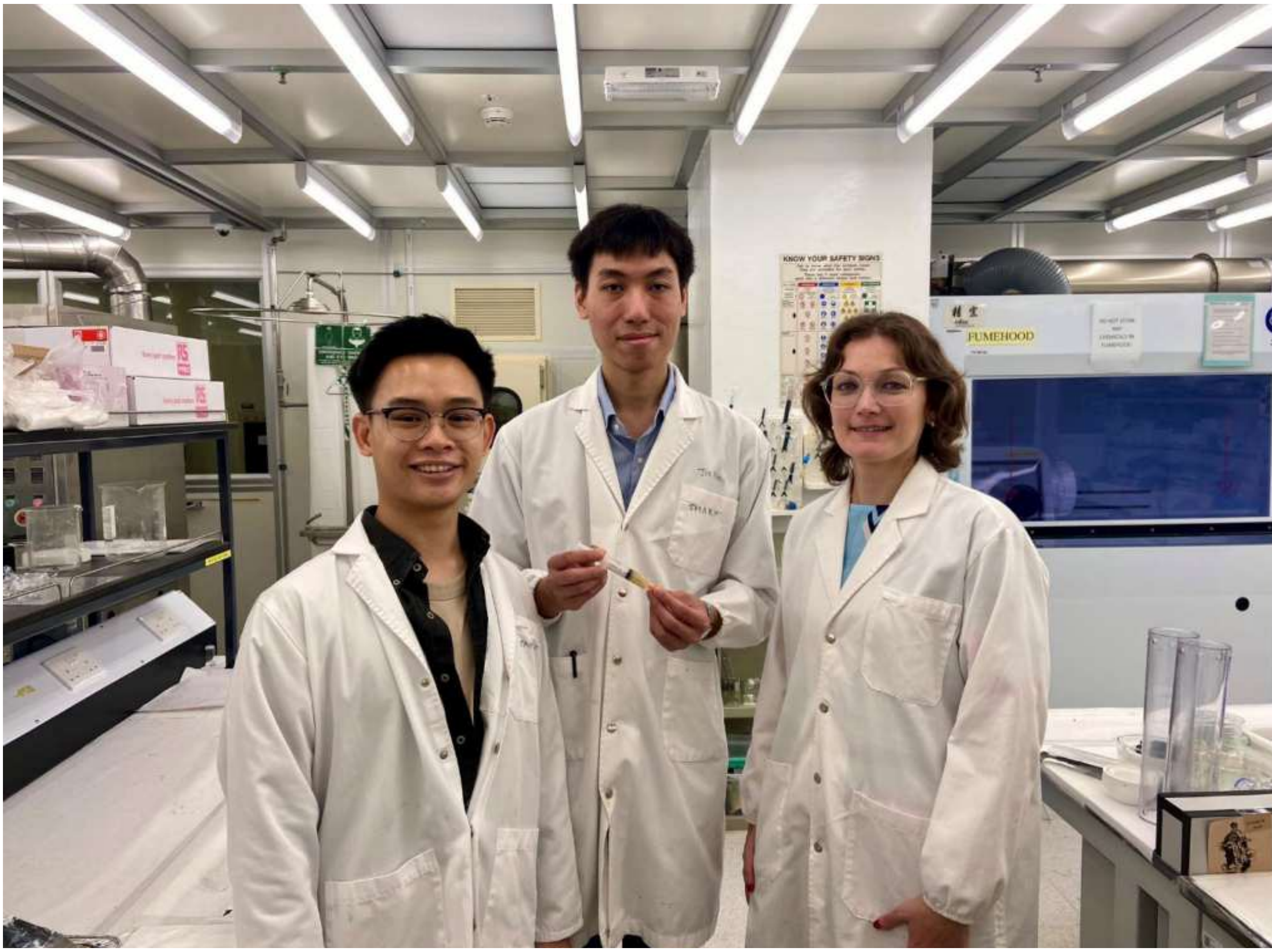
When grown on solid lignocellulosic biomass — coffee grounds in this case — the hyphae of fungi bind with the particles to form a tightly knit network, resulting in a mycelium composite that can be used to make a range of materials, from packaging to textiles and even sound-proofing sheets.

Coffee waste improves both the growth and density of the fungi material.

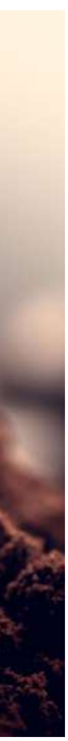
Print it up

Traditionally these composites are grown in a mould but fabricating and designing such moulds can be complex and wasteful. They also make it difficult to achieve the porosity fungi requires.

"Mycelium grows at solid-air interface. If we can control the porosity better, we can grow mycelium better and get better properties," reasoned Le Ferrand.



↑ *Pictured left to right: Eugene Soh, Project Officer; Jia Heng Teoh, Research Fellow; and Principal Investigator, Hortense Le Ferrand*



Her team used direct ink writing to develop the composite. This form of 3D printing uses smaller-than-usual nozzles to enable the extrusion of materials in precise ways, allowing for more design freedom.

For the ink, the researchers concocted a mixture combining mycelium from oyster mushrooms with agar - a growth medium that improves the ink's texture and viscosity - along with malt and peptone, which provide extra nutrients to the mycelium.

Malt and peptone spur the growth of mycelium, which enables the fungi to take hold of the medium before other bacteria have a chance to compete.

"And because bacterial contamination is no longer an issue, we don't need a highly sterile or specialised environment for the printing process," stated Le Ferrand.

Using this protocol, the team printed a sample block with the optimised ink and left it for 28 days to let the mycelium work its magic.

Waste materials brought to life

The researchers returned to find a flourishing mycelium network, which doubled the compressive strength of the sample block compared to a control with little mycelium growth. It was also stronger than typical mycelium gels.

"We believe this added strength comes from the synergistic networking between the coffee grounds and mycelium filaments," offered Le Ferrand. "While not intended for structural applications, the material's softness and nutrient-rich composition make it appealing for uses like plant substrates or animal feed, where its biodegradable nature offers added ecological benefits."

With a bit of moisture, the composite can also "self-heal," or recover from minor structural damages. Since the mycelium is kept alive in the presence of water, it can continue to grow.

"To demonstrate this, we placed two printed blocks on top of each other to replicate a large block that had been cut in half. After some time, mycelium filaments from the contact surfaces connected and fused the blocks together," added Le Ferrand.

This also means that the ink could act like a natural glue.

"In another experiment, we applied the ink between two jigsaw pieces made of wood and plastic-based filaments. As anticipated, the mycelium filaments spread towards the jigsaw pieces in search of nutrients, joining them into a single unit," Le Ferrand explained.

"An interesting application could be using the ink with a 3D printer capable of printing different types of materials, where mycelium growth acts as a glue to reduce delamination," she mused.

More studies, however, are needed to assess the strength of the mycelium glue and determine if it shrinks over time, which could reduce its integrity.

There is still much to explore in the development of mycelium composites, particularly in enhancing properties such as flame retardancy and water resistance, experimenting with different waste materials and fungal species, or adapting to varying environmental conditions like temperature and humidity.

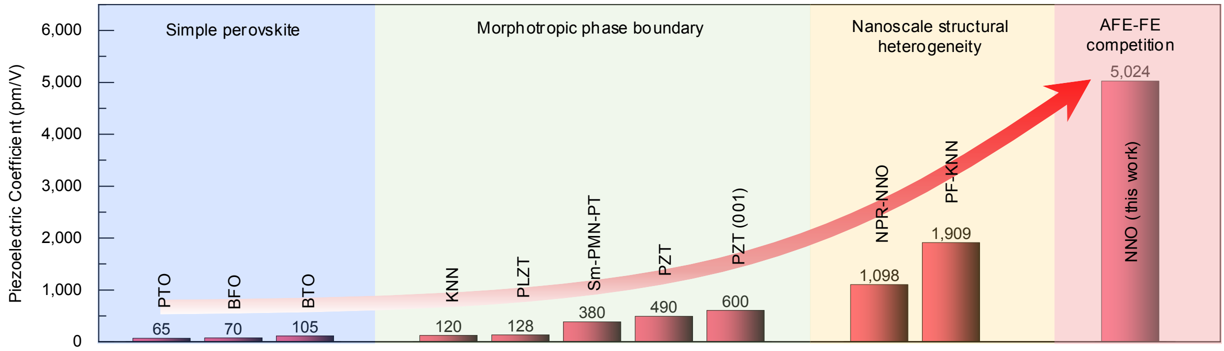
The lab has already made progress in changing the material's properties by varying the nutrient content provided. The mycelium can even "tell" it to grow more in certain regions only.

"Varying the nutrient content allows for either the inhibition or promotion of exploration and bridging of mycelium in different sections, the control of mycelium density in three dimensions and the fabrication of patterned surfaces, wrote her team of their research in the July 2024 edition of *International Journal of Bioprinting*.

Material Science to Bring Step Change to Mobile Networks

Researchers make unprecedented gains in material electromechanical performance by leveraging structural instability from competing antiferroelectric and ferroelectric phases.

Over the past few years, digitisation has surged at an extraordinary pace, transforming industries and everyday life.



↑ *The types of thin films and corresponding design strategies used for creating piezoelectrics have evolved over the years. However, the team's use of ferroelectric and antiferroelectic phases in sodium niobate (NNO) more than doubled popular existing methods, enabling a potential leap in the energy efficiency of modern systems and making new technologies possible.*

> *More than just a step forward in electromechanical performance, it represents an exponential leap — one that could transform communications infrastructure and help meet the ever-growing demands of the digital age.*

The most apparent hallmarks of this explosive growth include the likes of 5G, cloud computing and AI. Those technologies are possible thanks to the existence of faster speeds and more reliable infrastructure. These requirements of modern hyperconnectivity are only made possible by fundamental scientific advancements, like those n how energy.

A recent breakthrough at NTU's School of Materials, Science and Engineering (MSE) demonstrated a significant and much-needed leap in piezoelectric response. Their work increased a material's ability to convert electric energy into mechanical energy at an unprecedented pace.

More than just a step forward in electromechanical performance, it represents an exponential leap — one that could transform communications infrastructure and help meet the ever-growing demands of the digital age.

It starts at the atomic level

Piezoelectric materials are substances that generate an electric charge in response to mechanical stress and conversely deform when subjected to an electric field. It is a useful trait for materials when it comes to designing acoustic filters, sensors, actuators, and energy-harvesting applications.

This dual property arises from their crystalline structure, which lacks a centre of symmetry, as ions seek electrostatic balance.

The team's research focused on enhancing the piezoelectric coefficient in materials for the development of next generation filters.

"These next generation filters will enable improvements in 5G and 6G wireless networks in the near future," detailed Professor Lam Yeng Ming, a co-lead in the research.

Although she sees her team's improvement on the piezoelectric response in this material as most useful in the telecommunications industry, she noted that their applications extend beyond this sector. One of those applications is microelectomechanical systems MEMS, or devices that integrate mechanical and electronic components on a single chip.

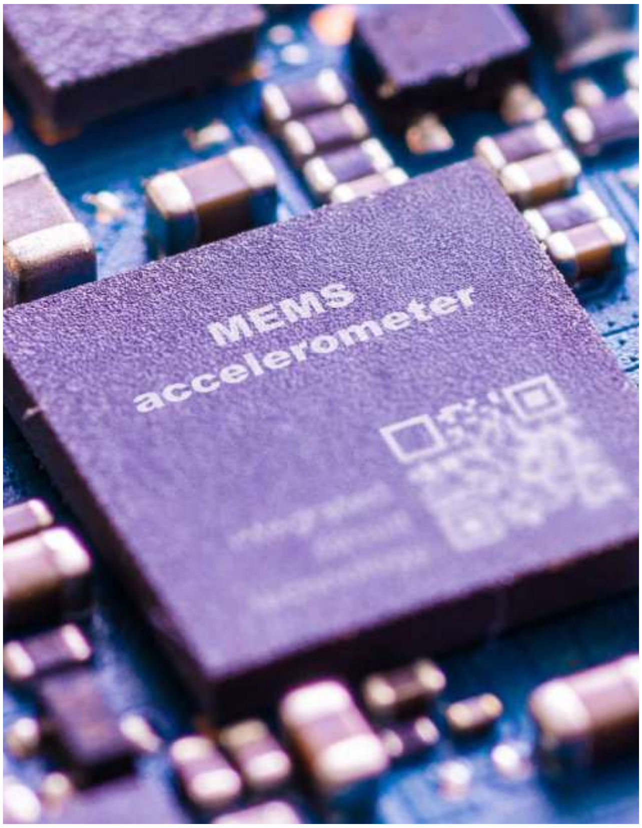
MEMS are found in healthcare applications, such as ultrasound imaging; in automotive systems for vehicle stability, traction control, navigation, and even airbag deployment; and consumer electronics, such as fitness trackers.

But when it comes to the telecommunications industry, dramatically better filters could facilitate the reduced latency and stable frequencies that modern networks demand.

Making use of displaced charge

To improve the performance of piezoelectric materials, it is imperative to understand how the structure of the materials impacts properties.

The go-to materials have evolved over the years, from quartz, which dominated in the early 20th century, to the ceramic compound Lead Zirconate Titanate (PZT), the engineered polymer Polyvinylidene Fluoride (PVDF), and polymer-modified Potassium Sodium Niobate (PF-KNN).



Traditionally, there are two paths to enhancing piezoelectric response in materials. One method used morphotropic phase boundaries (MPBs), where different material structures coexist, allowing flexibility in how materials respond to electric fields and strain. The other method relied on nanoscale structural variations, which created local distortions to boost energy conversion.

Each material has its advantages, as do their methods of enhancement. For instance, one material might have a more adept piezoelectric effect, the other more flexibility.

Similarly, MPBs are challenging to maintain because they require precise composition, while nanoscale variations can lead to material instability or inconsistency.

Improving the materials through these methods has not only been ongoing, but there are some limitations to the improvement in performance.

"Traditional strategies to enhance their performance, such as balancing material phases or introducing nanoscale imperfections, have been effective but face inherent limitations, restricting their potential in demanding applications," wrote the researchers in the September 2024 edition of Nature.

This meant that the team, which was co-led by NTU Associate Professor Huajun Liu and largely deployed by PhD student Baichen Lin, needed to be creative to find ways to optimise the materials.

"As materials scientists, we know how to control crystal structures to achieve specific properties," said Lam. "Here, we created extreme structural instability in thin films, allowing antiferroelectric orthorhombic and ferroelectric rhombohedral phases to coexist."

The team focused on the dynamic interaction between two types of phases in thin films of sodium niobate ($NaNbO_3$). Those phases are antiferroelectric (AFE), when the material's positive and negative charges naturally align, and ferroelectric (FE), when the material's charges align in opposite directions.

This method leverages electrostatic balance by optimising structural instability that allows the piezoelectric material to respond more efficiently to electric fields.

Breaking through paradigms

The researchers grew the $NaNbO_3$ on strontium titanate ($SrTiO_3$) substrates, which helped stabilise the coexistence of AFE and FE phases.

When an electric field was applied, the AFE dipoles realigned into an FE configuration, where all dipoles aligned in the same direction. The shift dramatically increased polarisation, which boosted the material's ability to convert mechanical energy into electrical energy.

Using MPB on PZT can yield a typical piezoelectric effect of up to 600 pm/V, nanoscale structural variations on another material, PF-KNN, up to around 1900 pm/V. But the $NaNbO_3$ provided a value multiples of those, a value that exceeded 5,000 pm/V.

The $NaNbO_3$ could also deform by about 2.5 percent, an amount 2.5 to 5 times greater than typical materials. The effect was even greater at lower frequencies.

This means the thin films are not only much more efficient than traditional piezoelectrics, but they can also handle much larger deformations and work better at lower frequencies. This makes them ideal candidates for applications where high energy conversion efficiency and large mechanical strain are required.

"This breakthrough offers a new pathway for designing high-performance materials, advancing next-generation energy and communication technologies," asserted the researchers.

Meanwhile, they continue to explore the limits of their approach, this time with a roadmap for exploring ferroic systems.

The researchers used a JEOL GrandARM aberration-corrected transmission electron microscope to capture images at atomic resolution.

The microscope can distinguish individual atoms as its image resolution stands at 0.078 nanometers, or 1/100,000 the width of a hair.

The microscope is housed at NTU's Facility for Analysis, Characterisation, Testing, and Simulation (FACTS) and often made available to external researchers and collaborations.