Issue 40 | March – April 2024

A*STAR RESEARCH

POWERING A GREEN TOMORROW

The A*STAR innovations steering Singapore's sustainable energy initiatives

page 08

BLAZING NEW TRAILS

Eight researchers in A*STAR's NRF class of 2024

page 18

THE STUFF OF SUSTAINABILITY

Creating a foundation of energy-efficient materials

page 28

A*STAR RESEARCH

www.research.a-star.edu.sg

*A*STAR Research* is a publication of the Agency for Science, Technology and Research (A*STAR) — Singapore's lead government agency for fostering world-class scientific research.

*A*STAR Research* is published bimonthly, presenting research highlights and feature articles. All articles are first published online on the *A*STAR Research* website and available free to all readers. Register online to receive our monthly e-newsletter by email.

*A*STAR Research* is published for A*STAR by the custom media publishing unit of Wildtype Media Group Pte Ltd.

ISSN 2010-0531

The Agency for Science, Technology and Research (A*STAR) is Singapore's lead government agency dedicated to fostering world-class scientific research and talent for a vibrant knowledge-based economy.

A*STAR actively nurtures public-sector research and development in biomedical sciences, physical sciences and engineering, and spurs growth in Singapore's key economic clusters by providing human, intellectual and industrial capital to our partners in industry and the healthcare sector.

A*STAR currently oversees the following research institutes, consortia and horizontal technology coordinating offices, and supports extramural research with universities, hospital research centres and other local and international partners:

- A*STAR Infectious Diseases Labs (ID Labs)
- A*STAR Skin Research Labs (A*SRL)
- Advanced Remanufacturing and Technology Centre (ARTC)
- Bioinformatics Institute (BII)
- Bioprocessing Technology Institute (BTI)
- Experimental Drug Development Centre (EDDC)
- Genome Institute of Singapore (GIS)
- Horizontal Technology Coordinating Offices (HTCO):
  - Agritech and Aquaculture (A2)
  - Artificial Intelligence, Analytics and Informatics (AI³)
  - Epidemic Preparedness (EP)
  - Robotics
  - Social Sciences and Technology (SST)
  - Urban and Green Technology (UGT)
- Institute of Sustainability for Chemicals, Energy and Environment (ISCE²)
- Institute of High Performance Computing (IHPC)
- Institute for Infocomm Research (I²R)
- Institute of Molecular and Cell Biology (IMCB)
- Institute of Microelectronics (IME)
- Institute of Materials Research and Engineering (IMRE)
- National Metrology Centre (NMC)
- Singapore Immunology Network (SIgN)
- Singapore Institute for Clinical Sciences (SICS)
- Singapore Institute of Manufacturing Technology (SIMTech)
- Singapore Institute of Food and Biotechnology Innovation (SIFBI)

Contents

Issue 40 | March – April 2024

Contents

Issue 40 | March – April 2024

EDITORIAL NOTES

In 1982, the world consumed around 87,000 terawatt-hours of energy in a year: equal to nearly 53 billion barrels of oil. Four decades later, that annual figure had more than doubled. With advancing economies and population growth pushing the world's energy needs ever higher, there's a growing need to reform the energy infrastructures our societies run on.

Our cover story, 'Powering a green tomorrow (p. 08)', takes a look at cutting-edge A*STAR research in sustainable energy technologies across the spectrum of energy generation to its utility. We highlight the ongoing exploration of next-generation solutions such as catalysts for hydrogen conversion, carbon-based electronics and fusion energy systems.

In a related double feature, 'The stuff of sustainability (p. 28)', we turn the spotlight to the role of materials science in a greener energy future. A*STAR National Science Scholar (PhD) recipients Rebecca Khoo and Kang Rui Garrick Lim discuss their research journeys in various aspects of the field, including improved greenhouse gas capture and efficient chemical manufacturing.

This issue also includes a special extended feature that highlights this year's recipients of the National Research Foundation Investigatorships and Fellowships. In 'Blazing new trails (p. 18)', we speak to the eight A*STAR researchers awarded these grants about the challenges they aim to tackle in their respective fields.

Beyond those pages, we provide updates on new findings and innovations coming out of A*STAR's diverse research institutes in areas from non-invasive treatments for retinal degeneration to animal-like underwater robotics. For more on these, turn to 'Eyeing vision-saving breakthroughs (p. 04)' and 'Jellyfish robot makes a big splash (p. 34)'.

For more of the latest developments from A*STAR researchers, visit our website at **research.a-star.edu.sg**. You can also stay up-to-date by following us on Twitter/X at **@astar_research**, LinkedIn at **A*STAR Research** and Telegram at **A*STAR Research**.

On the cover
A battery's silhouette forms a doorway towards a future powered by elements of a sustainable energy ecosystem.

SIGN UP FOR OUR NEWSLETTER

Join the *A*STAR Research* mailing list and stay updated with the latest research stories from A*STAR!

OPHTHALMOLOGY

Eyeing vision-saving breakthroughs

A polymer-based drug delivery innovation can replace invasive eye treatments for retinal diseases.

We have the retina to thank for the gift of sight—the thin tapestry of light-sensitive cells and nerves at the back of the eye captures light and transforms it into the vivid imagery of our visual world. However, retinal neovascular diseases such as diabetic retinopathy disrupt this; poor blood flow triggers the abnormal growth of blood vessels in the retina, leading to vision loss.

The complex anatomy of the eye creates a tricky drug delivery challenge—current treatments for retinal conditions usually require invasive intravitreal injections to access the affected tissues. Going to the clinic for these injections can be a hassle, and may be associated with sight-threatening complications.

"Topical drugs can revolutionise the treatment paradigm of retinal diseases," commented Xinyi Su, Executive Director at A*STAR's Institute of Molecular and Cell Biology (IMCB). Su's team has been pioneering a polymer-based delivery system for administering medications that counteract abnormal vascular growth in the retina.

In partnership with Xian Jun Loh, Executive Director at A*STAR's Institute of Materials Research and Engineering (IMRE), the researchers adopted a nanomicelle (nEPC) approach—tiny drug-bearing vessels designed to traverse corneal barriers to reach the retina.

Together with researchers from the National University Hospital, National University of Singapore, Singapore Eye Research Institute and Singapore University of Technology and Design, Su's team loaded nEPCs with an antiangiogenic agent, aflibercept, and tested their nanomicelles' potency in experimental eye models.

> "We hypothesise that these anti-angiogenic effects may be derived from the inhibition of vascular endothelial proliferation—a key aspect of angiogenesis."

Photo credit: bady abbas / Unsplash

The nEPCs proved adept at ferrying aflibercept to the retina and enhancing drug concentrations in the affected tissues. This thwarted the formation of blood vessels and mitigated vessel leakage in mice models of retinal disease.

Promisingly, the nanomicelle system showed biocompatibility with human cell line models, suggesting a less invasive and promising alternative to current treatments.

Su emphasised that the unique polymer used in the nanomicelle formulation may have its own intrinsic properties that suppress vascular proliferation or growth—biological processes implicated in retinal disorders.

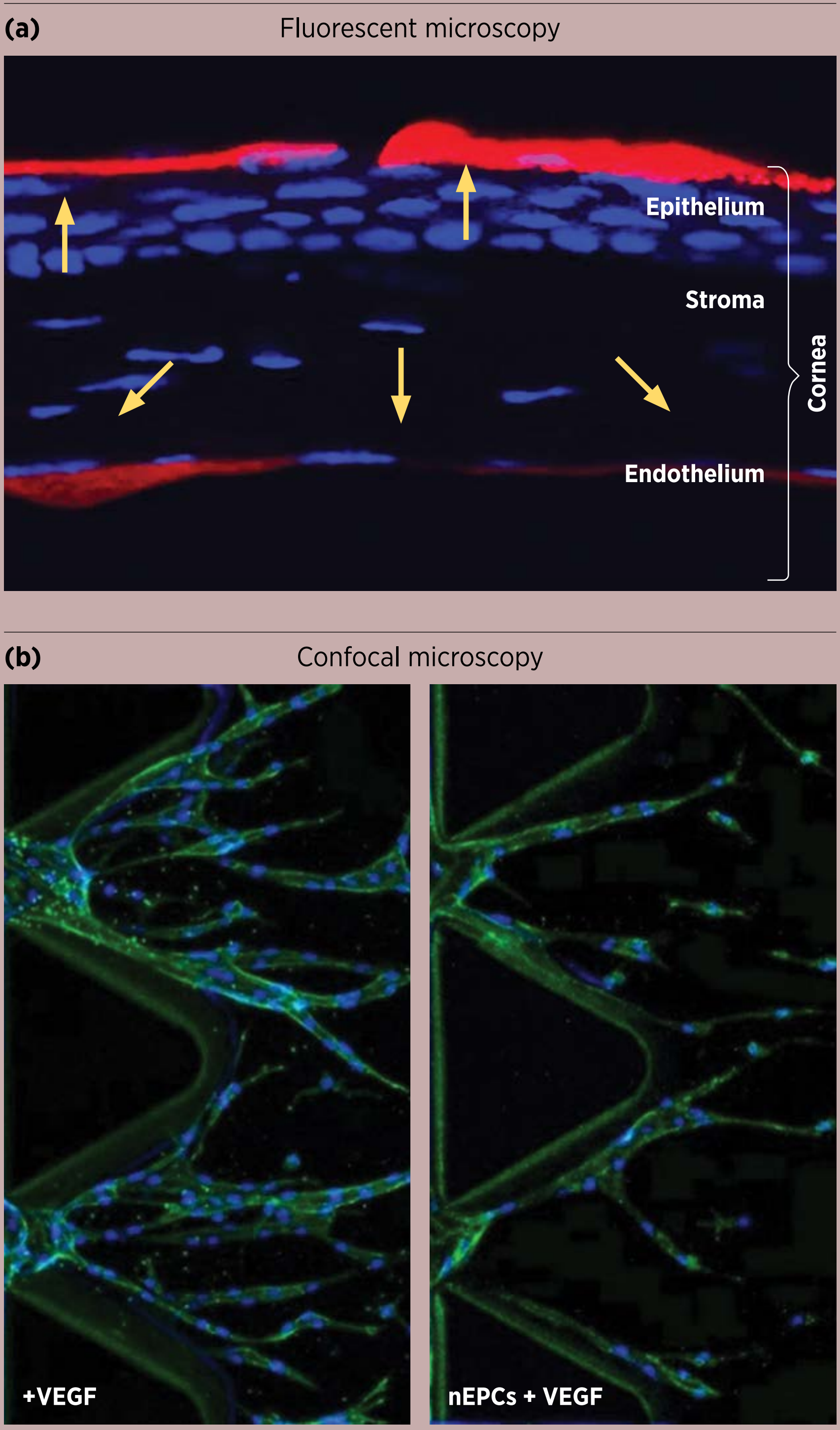
"We hypothesise that these anti-angiogenic effects may be derived from the inhibition of vascular endothelial proliferation—a key aspect of angiogenesis," said Su, adding that the team plans to investigate these pathways in future studies.

For now, the team is accelerating efforts to commercialise their new technology with a new venture, Vitreogel Innovations, to advance the nEPC polymer towards clinical applications. ★

Researchers
Xinyi Su, IMCB
and Xian Jun Loh, IMRE

IN BRIEF
Nanomicelles designed to penetrate corneal barriers effectively deliver antiangiogenic drugs to the retina to reduce unwanted blood vessel growth and leakage in experimental models.

1. Zhao, X., Seah, I., Xue, K., Wong, W., Tan, Q.S.W., *et al.* Antiangiogenic nanomicelles for the topical delivery of aflibercept to treat retinal neovascular disease. *Advanced Materials* **34** (25), 2108360 (2022).



Microscopic images of nEPC action in eye cell and tissue models. (a) nEPCs loaded with aflibercept (red) visibly penetrate a mouse cornea when administered topically. (b) nEPCs inhibit the formation of vascular structures (green outlines with blue nuclei) on a 3D cell culture chip of human vascular endothelial cells, despite the cells' exposure to vascular endothelial growth factor (VEGF).

GENETICS

Unfolding RNA origami reveals cell secrets

A*STAR researchers develop a new method to study RNA's intricate folding patterns within a single cell, revealing fresh insights into how cells develop and function.

From the same sheet of paper, origami's intricate folds can create diverse forms: a hopping frog, a gliding plane or a rolling ball. Likewise, molecules of ribonucleic acid (RNA) can be folded into a range of shapes with different properties. These structural variations are thought to influence how RNA regulates a myriad of cellular processes by controlling the molecule's stability, localisation and activity.

However, unlike origami, the secrets of RNA folding and their links to RNA function can be more difficult to unravel. "Current approaches to RNA structure studies need tens of millions of cells as starting materials," said Yue Wan, a Principal Investigator at A*STAR's Genome Institute of Singapore (GIS).

These limitations have hindered the study of RNA in rare cell types and heterogeneous cell populations from tumours, or biological samples with limited material.

In collaboration with GIS Junior Principal Investigator Jiaxu Wang and Senior Scientist Roland Huber from the Bioinformatics Institute (BII), Wan's group devised new approaches to study RNA structure at the single-cell level. They aimed to gain insights into the determinants of cell identity and how RNA structure contributes to cellular functions and diversity.

This work led to the development of single-cell structure probing of RNA transcripts (sc-SPORT), a new method of RNA structural analysis designed to simultaneously map RNA secondary structure and gene expression at a single-cell resolution.

> **"Beyond RNA expression, its RNA structure provides an added layer of information on cellular identity."**

Unlike conventional approaches, sc-SPORT determines RNA structures in individual cells by chemically modifying fragments of unfolded RNA; isolating and sequencing those fragments; and analysing DNA copies to understand how the related RNA folds influence cell functions. This approach proved remarkably sensitive, enabling researchers to use single cells as starting material for sc-SPORT.

Using sc-SPORT to examine human embryonic stem cells, Wan and colleagues discovered that their RNA had mostly uniform structures, suggesting they had consistent roles in the early stages of cell development. However, those structures became more diverse as the same stem cells differentiated into neuronal precursor cells—a crucial step towards becoming fully developed neurons.

This variation in RNA folding patterns highlights a complex layer of gene regulation that becomes more pronounced as stem cells become specialised.

"Beyond RNA expression, its structure provides an added layer of information on cellular identity," said Wan, adding that sc-SPORT could aid studies on rare cell types—cancer stem cells, organoids, embryo cells and short transit cells among them—of which very limited samples tend to be available.

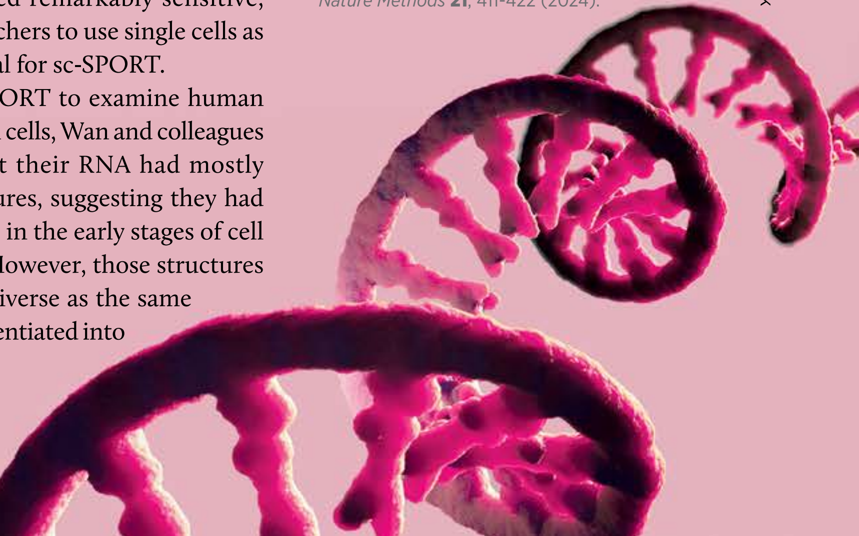
Moving forward, Wan's team plan to optimise sc-SPORT to scale up the number of cells it can analyse per run. They also aim to combine sc-SPORT with spatial omics to develop a spatial RNA structure sequencing approach, allowing scientists to track RNA structures in the context of intact tissue. ★

Researchers
Yue Wan and Jiaxu Wang, GIS

IN BRIEF
The sequencing technique sc-SPORT chemically tags and sequences unfolded fragments of RNA to link RNA folding patterns to cellular functions. This approach revealed that RNA folding becomes more diverse as stem cells differentiate into specialised cells.

1. Wang, J., Zhang, Y., Zhang, T., Tan, W.T., Lambert, F., *et al*. RNA structure profiling at single-cell resolution reveals new determinants of cell identity. *Nature Methods* **21**, 411-422 (2024).

Photo credit: Christoph Burgstedt / Shutterstock



DERMATOLOGY

Breakaway yeasts instigate the itch

A newly discovered protein-cutting enzyme may be responsible for inflammatory skin conditions triggered by yeast species.

We often think of our skin's microbiome as predominantly bacterial. Surprisingly, yeasts such as *Malassezia* also thrive on warm, moist, greasy and nutrient-rich human skin. While typically harmless, *Malassezia* can sometimes flip from friend to foe, triggering dermatological conditions from dandruff to dermatitis.

"In individuals with healthy skin, the skin barrier is usually intact, which allows the skin to function properly as a protective barrier defending against the external environment," said Thomas Dawson, Deputy Executive Director at the A*STAR Skin Research Labs (A*SRL).

Dawson explained that when this barrier is compromised, *Malassezia* can infiltrate deeper layers of skin. There, they secrete many compounds including protein-digesting enzymes called proteases, which lead to itchy, inflammatory flare-ups.

Historically, researchers have met hurdles in trying to connect the dots between *Malassezia* protease genes and the exacerbation of skin conditions—the yeast is difficult to genetically modify and grow in the lab for experimental analyses. Using a novel approach, Dawson teamed up with collaborators from the National University of Singapore; National Skin Centre, Singapore; University of California San Diego, US; and University of Zürich, Switzerland to study the gene expression profiles of *Malassezia furfur*, a more experimentally accessible model organism for studying the yeast's impact on skin health.

First, the team took skin samples from patients with atopic or seborrheic dermatitis, as well as from healthy volunteers. Gene expression analyses revealed that individuals with dermatitis showed a marked uptick in the expression of *MGSAP1*, a protease gene.

The researchers then disabled a similar yeast gene called *MFSAP1* in *M. furfur* and observed changes in the way the yeast cells stick together and grow on lab-grown human skin. They found that the absence of *MFSAP1* in a mouse model resulted in significantly less skin inflammation, as indicated by reduced swelling and fewer inflammatory cells, compared to the wild-type *M. furfur*. This confirmed the team's hypothesis that the Mfsap1 enzyme is involved in the host inflammatory response.

"Mfsap1-mediated modifications of the cell surface and the external environment can enable the fungal cells to become more hydrophobic, contributing to a shift from free-floating to adherent cells," explained Joleen Goh, the first author of the study.

Goh added that these newly gained insights explain how the yeast interacts with the skin environment, which can enable targeted treatments for inflammatory skin conditions.

"Future treatment of *Malassezia*-associated conditions can be coupled with enzyme inhibitors and antimycotics in infection control to improve clinical outcomes," Dawson and Goh said. Their group plans to study how *M. furfur* attaches to medical devices like catheters, which can endanger high-risk patient groups such as newborns and the immunocompromised receiving lipid emulsions. ★

"In individuals with healthy skin, the skin barrier is usually intact, which allows the skin to function properly as a protective barrier defending against the external environment."

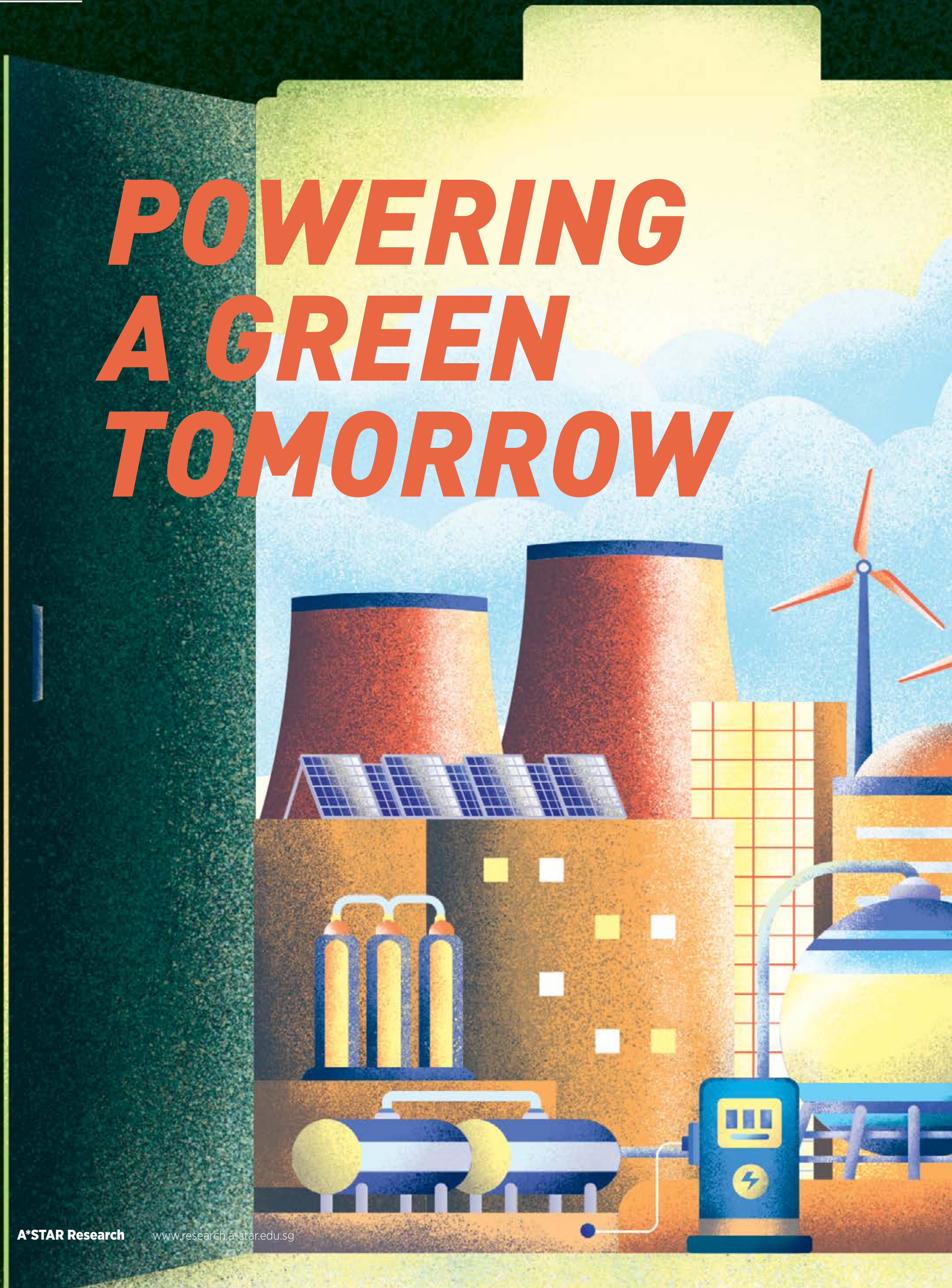
Photo credit: Kateryna Kon / Shutterstock

Researcher
Thomas Dawson, A*SRL

IN BRIEF
The Mfsap1 enzyme, produced by the skin yeast *Malassezia furfur*, is significantly more active in patients with atopic dermatitis and seborrheic dermatitis than in healthy individuals, indicating its potential role in these skin conditions.

1. Goh, J.P.Z., Ruchti, F., Poh, S.E., Koh, W.L.C., Tan, K.Y., *et al*. The human pathobiont *Malassezia furfur* secreted protease Mfsap1 regulates cell dispersal and exacerbates skin inflammation. *Proceedings of the National Academy of Sciences* **119** (49), e2212533119 (2022).

POWERING A GREEN TOMORROW



From production to storage and usage, A*STAR research institutes are tackling challenges in sustainable energy to meet the needs of the 21st century.

We're living in an era marked by an unprecedented pace of technological change, with the proliferation of artificial intelligence, digital connectivity and other tools reshaping the way we communicate and innovate. However, these advances are not without their costs—they are power hungry, and they rely on energy-intensive systems. Yet in an era of anthropogenic climate change, it's become increasingly clear that traditional energy sources, particularly fossil fuels, cannot be relied on to meet these needs in a sustainable manner.

Singapore stands at the forefront of global efforts to address the energy crisis head-on, with an ambitious goal of achieving net-zero emissions by 2050. Keng Hui Lim, Assistant Chief Executive of the A*STAR Science and Engineering Research Council (SERC), highlighted the nation's broader strategies to achieve the sustainability targets it has set for itself, which emphasise a transition to clean energy sources, greater energy efficiency, and the establishment of a circular economy's foundations.

"A*STAR has aligned our research focus on sustainable energy solutions to meet these targets and overcome the challenges of developing advanced low-carbon alternatives and technologies," said Lim.

Lim added that several national initiatives—including those propelled by the agency's research programmes—are already in progress. These include the National Hydrogen Strategy, launched in 2022, which invests in multidisciplinary research to overcome technological barriers in switching to green hydrogen production.

A*STAR's innovation engine is geared to address these complex, high-value challenges, drawing on the cross-disciplinary expertise and resources of various institutes such as the Institute of Sustainability for Chemicals, Energy and Environment (ISCE^2), the Institute of Materials Research and Engineering (IMRE), the Institute of Microelectronics (IME) and the Institute for High Performance Computing (IHPC).

Speaking on the comprehensive roadmap devised to hit Singapore's sustainability goals, Lim emphasised plans for close collaboration between A*STAR researchers, government agencies, industry stakeholders and policymakers to facilitate the national switch to green energy. "We have also strengthened our Innovation & Enterprise (I&E) team to facilitate industry engagement and commercialisation efforts," Lim said.

CATALYSTS FOR CHANGE

The portability of fossil fuels can be hard to replicate. Light, energy-dense and easy to transport, they remain a convenient form of energy for vehicles and other systems where weight efficiency matters. However, hydrogen gas offers a promising alternative, as it holds more energy per unit of weight than gasoline, yet produces a clean byproduct when burned: water.

Electrolysis is a key chemical process in hydrogen energy systems: it extracts hydrogen from water, which can then be used in fuel cells to generate power without emitting harmful pollutants. Shibo Xi, a Senior Scientist at ISCE^2, leads pioneering work in developing catalysts to give hydrogen production reactions a much-needed boost.

"Our biggest obstacle is the lack of insights into the mechanisms of hydrogen evolution reaction (HER) catalysis," said Xi, who stressed the importance of gaining an atomic-level understanding of catalyst structures to address issues around their performance, cost and durability.

Xi's team uses synchrotron radiation-based techniques to characterise materials in sub-nanoscale detail, bridging theoretical knowledge with practical applications. Using X-ray Absorption Fine Structure (XAFS) analyses, the researchers are gaining crucial insights into how a catalyst's local structure affects its function, guiding the creation and optimisation of more potent variants tailored to specific applications.

"Our iterative process of characterisation, analysis and synthesis forms a feedback loop that drives the development of more effective catalysts for energy applications," said Xi.

Through local and international collaborations, the team's breakthroughs include a novel energy-efficient method to enhance water-splitting into hydrogen and oxygen using an exceptionally active electrocatalyst. Working with researchers at the National University of Singapore, they uncovered a novel electron transfer pathway in nickel-oxyhydroxide-based catalysts which could be triggered by light.

"Another discovery, made with the City University of Hong Kong, was an exceptionally active and stable electrocatalyst for HERs in acidic environments, using single-atom platinum anchored on transition-metal dichalcogenide (TMD) nanosheets with atypical crystal phases," Xi added.

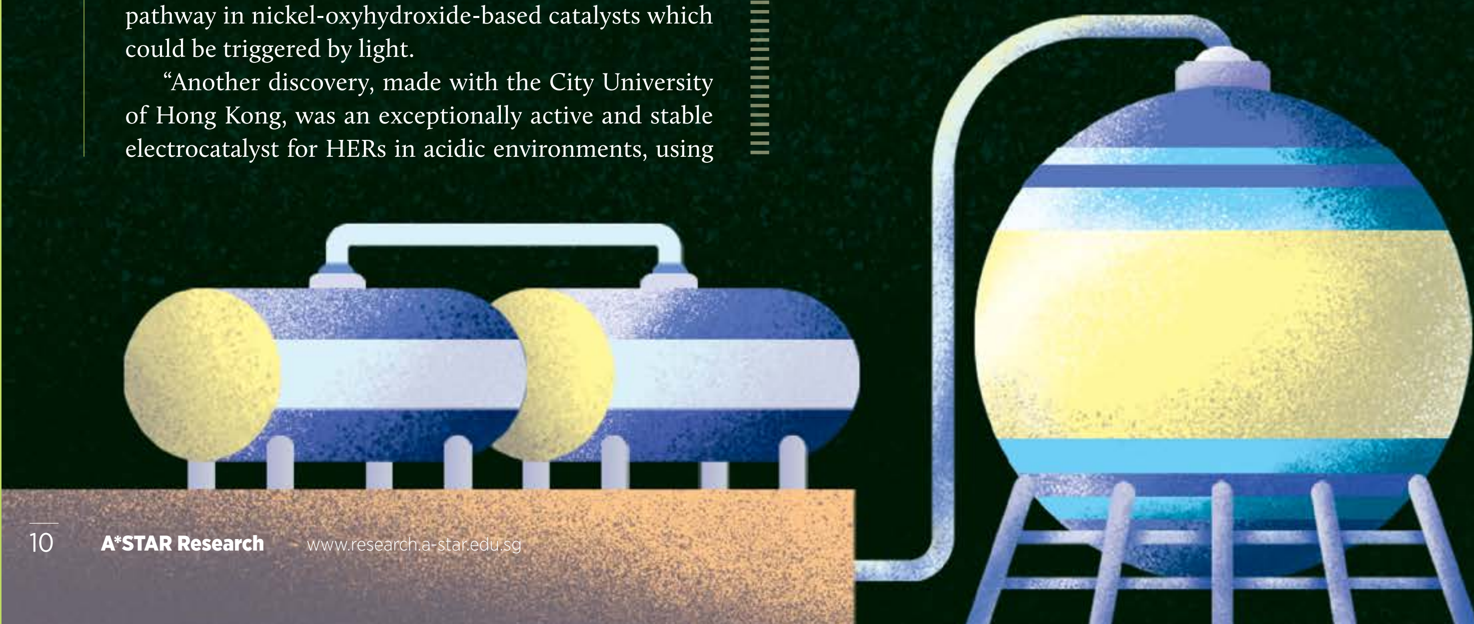
POWER BANKS

The growing use of clean electricity sources like solar and wind is encouraging, yet the intermittent nature of these sources can be challenging for power systems that operate around the clock. Energy storage technologies allow us to integrate renewable energy into the grid by storing energy during low-demand periods and releasing it when demand peaks. However, lithium-based technologies, which work for electric vehicles and consumer devices, are too expensive and volatile to use in power grids used by entire cities.

At IMRE, Principal Scientist Zhi Wei Seh is leading the charge in revolutionary battery technologies by creating a new wave of safe, high-energy-density and cost-effective multivalent-ion battery designs.

Focusing on magnesium, zinc and aluminium—elements with superior energy storage capabilities and availability compared to lithium—Seh's team has generated a suite of anode, cathode and electrolyte materials suited to these new chemistries. "We used theoretical computations and machine learning to accelerate the creation of practical batteries for portable electronics, electric vehicles, grid storage and more," said Seh.

Seh's lab has pioneered the first anode-free magnesium metal battery, boasting an energy density five times greater than traditional magnesium batteries. Furthermore, their discovery of a unique electrolyte additive has improved the kinetics and surface chemistry of magnesium anodes, achieving the highest recorded current density for such designs to date.



CIRCUITS FOR HEALTH

Beyond energy generation and storage, its consumption also plays a pivotal role in the quest to reduce greenhouse gas emissions. "As a regional hub for microelectronics design, manufacturing and supply, Singapore has a unique position in this area," said Yuan Gao, a Principal Investigator at IME. "Microelectronics plays a vital enabling role for devices that consume less power, with applications across many sectors."

Biomedicine is one particular sector of interest, as energy-efficient, portable device designs drive exciting innovations from ultrasensitive diagnostic sensors to brain-machine interfaces. At IME, Gao's team works to design intelligent sensor interface integrated circuits with biomedical applications. Blending power and energy efficiency, these circuits underpin wireless devices like micro electro multiphysical systems (MEMS) sensors for real-time remote patient monitoring and implantable medical devices such as pacemakers.

Such medical devices rely on sensors capable of continuous operation without frequent battery changes or recharges; this means a need for circuits that can intelligently collect, manage and transmit accurate data while minimising power usage.

Gao's team are developing next-generation electronics to surmount these challenges. These include sensitive, user-friendly electroencephalogram (EEG) sensors to streamline brain activity monitoring for seamless brain-computer interfaces and facilitate mental health studies. Another device, called a hysteretic buck converter, aims to improve power management in rechargeable lithium-ion batteries in wearable patient-monitoring devices.

"One of our ongoing projects in collaboration with IMRE and a local startup is to develop a sweat-based biochemical sensor for long-term health monitoring," said Gao. "Another project involves the use of novel MEMS devices to develop a near-zero power sensor node, which provides long-term environmental monitoring without frequent battery changes."

BLACK GOLD

It takes energy to make use of energy. Much of what makes up today's energy infrastructure—from cables and circuit boards to solar panels and wind turbines—relies on minerals mined from the earth's depths in energy-intensive processes, generating carbon emissions and degrading environments in the process. To researchers like Lili Zhang, Division Director of Emerging Technologies at ISCE[2], a more viable alternative to these costly materials might lie in carbon itself.

"The use of carbon-based materials for electronic components like electrodes offer a 'three birds with one stone' solution: they can enhance device performance, introduce alternative waste treatment options, and reduce the carbon footprint from manufacturing processes," said Zhang. "Waste-derived carbon can be used to design flexible, functional materials with well-controlled structures and properties that are not only cost-effective and scalable, but can also outperform current materials."

To turn trash to carbon treasure, Zhang's team has explored diverse waste streams including plastic waste, end-of-life tyres, chemical plant byproducts and factory wastewater. These have turned up valuable resources such as high-quality carbon materials, hydrogen, fuels and chemical feedstocks like light olefins.

While carbon-based electronic materials still have challenges to surmount—safety, durability and environmental impact among them—research by Zhang and colleagues is exploring innovative designs with enhanced electrochemical properties, paving the way for the next generation of high-performance supercapacitors.

Highlights from Zhang's lab include the development of a unique three-dimensional MnO_2 network, specifically structured to create a highly stable energy storage device with remarkable capacitance and exceptionally high specific power. In a successful collaboration with international colleagues, Zhang and her team have

> **"As a regional hub for microelectronics design, manufacturing and supply, Singapore has a unique position in this area."**
>
> — Yuan Gao, Principal Investigator at A*STAR's Institute of Microelectronics (IME)

also engineered MXene films with enhanced energy density and mechanical resilience, thereby improving supercapacitor performance.

The team is also transforming waste management by developing an eco-friendly process to recycle discarded tyres into high-quality commercial-grade carbon at reduced energy, environmental and financial cost. Using a novel detergent, they efficiently eliminate contaminants from waste tyres, yielding pure carbon black suitable for diverse industrial uses.

"In collaboration with IMRE, we've also been able to use waste plastics to develop multiwall carbon nanotubes (MWCNTs), which have been used in applications ranging from plant hormone sensors to ultrahigh performance concrete," Zhang added.

A FUSION FUTURE?

Like a microcosm of the sun, fusion energy offers a potential source of virtually limitless low-carbon power, free from the constraints of geography. However, to bring a commercial fusion energy system to life, there are two significant hurdles to overcome: to tame a fusion core, and to build a vessel that can hold it.

These avenues of research are currently being explored in tandem by A*STAR teams that draw on the joint expertise of researchers such as Valerian Hall-Chen, Group Manager of IHPC's Plasma Physics and Energy Group, and Andrew Ngo, Division Director of IMRE's Composites and Structural Division.

"While some consider the core and its vessel as separate problems, these challenges are deeply intertwined," said Hall-Chen, also Technical Lead of the A*STAR Fusion Taskforce. "In fusion machines, when plasma from the core interacts with the vessel's tungsten coating, tungsten is sputtered back into the plasma; if tungsten comprises more than 1/10,000th of the plasma, it cools the core rapidly, which exerts immense forces on the vessel walls."

To help tackle the multifaceted challenges around fusion plasma and its interactions with both core and vessel, Hall-Chen and colleagues are delving into the physics of fusion plasmas, aiming to understand the complex behaviour and conditions needed to optimise fusion reactions.

There are formidable hurdles to measuring and interpreting fusion plasma data due to the extreme temperatures involved. These conditions cause electrons to ionise, forming a plasma that necessitates precise control to maintain stability. "To achieve terrestrial fusion, one has to achieve temperatures many times hotter than the centre of the sun," said Hall-Chen.

Future fusion systems will demand diagnostics resilient to intense neutron radiation, necessitating robust, multi-purpose tools that minimise structural weaknesses while accurately measuring and controlling plasma to prevent costly disruptions. Hall-Chen and colleagues are working with established institutions to optimise plasma scenarios and develop durable diagnostic tools.

"Collaborating with teams at UCLA and leveraging their expertise in microwave diagnostics has been instrumental in advancing crucial research on turbulence," said Hall-Chen, adding that this facilitates the design of more affordable fusion energy systems.

Materials research also plays a critical role in advancing the physical vessels where fusion reactions occur, as researchers expect future fusion energy systems to have even harsher environments than in today's experiments. Ngo emphasised the importance of materials in experimental reactors, where they must withstand high temperatures and thermal cycles; strong forces; bombardment by energetic neutrons; as well as corrosion and erosion.

According to Ngo, for the transition to operational fusion energy systems, materials must prioritise safety, efficiency and longevity. This necessitates innovations in tritium permeation barriers, resistance against harsh conditions and corrosion protection to maintain reliable system performance.

"To achieve terrestrial fusion, one has to achieve temperatures many times hotter than the centre of the sun."

— Valerian Hall-Chen, Group Manager, Plasma Physics and Energy at A*STAR's Institute of High Performance Computing (IHPC)

With a track record in developing robust materials for the aerospace industry, including high-performance (e.g. ultra-strong) alloys and functional (e.g. anti-corrosion) coatings, Ngo's team is dedicated to pushing boundaries in fusion materials. "We see these challenges as opportunities to leverage our capabilities," Ngo said.

Ngo's team has made several breakthroughs, notably developing a thick, crack-free tungsten coating with excellent adhesion to substrates, which showed promising results in reactor-simulated conditions. "Post-test results show no visible damage to the coating, signalling its promise as plasma-facing material," Ngo said.

Looking ahead, Ngo highlighted the future exploration of compositionally graded alloys (CGAs), high entropy alloys (HEAs) and multi-principal element alloys (MPEAs), which combine multiple elements' strengths to achieve superior properties over traditional materials. As part of the Singapore Standards Council, Ngo also aims to enhance the safety, competitiveness and environmental sustainability of the fusion energy sector by developing new standards and guidelines that align with advancements in materials and technology.

EVOLVING ECOSYSTEMS

At A*STAR, strategic energy research programmes intersect with advanced manufacturing and digital technologies to offer tangible solutions to longstanding issues: decarbonising major sectors such as transportation and manufacturing, establishing a resilient renewable energy grid and reducing the environmental footprint of consumer goods.

A*STAR SERC Assistant Chief Executive Keng Hui Lim highlighted A*STAR's Accelerated Catalyst Development Platform as an exemplary initiative in advancing industrial ecosystems. Powered by machine learning, the award-winning platform streamlines the creation of cleaner industrial processes for applications such as carbon utilisation, surpassing conventional methods and accelerating catalyst screening up to 10 times with enhanced accuracy.

Other notable achievements include the Singapore Housing and Development Board's adoption of the Integrated Environmental Modelling tool—developed by IHPC and the Institute for Infocomm Research (I^{2}R)—for sustainable urban planning, as well as support for cost-saving in infrastructure projects such as EV chargers and advancements in power grids. "IHPC has also made strides in developing energy-efficient cooling solutions tailored for data centres operating in hot climates," Lim added.

Furthermore, researchers from the Singapore Institute of Manufacturing Technology (SIMTech) and the Advanced Remanufacturing and Technology Centre (ARTC) have devised computational tools to precisely track and measure carbon footprints by integrating Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methodologies. "These tools can aid companies in making better assessments for environmentally sustainable technologies, production and investment," explained Lim.

With future prospects in mind, A*STAR researchers are not only addressing current knowledge gaps but also scaling technologies for large-scale deployment, aligning with national decarbonisation objectives. "Promising lab-scale projects will require a facility to testbed potential prototypes for development," said Lim, who mentioned plans for the Low Carbon Technology Translational Testbed (LCT3) facility in ISCE^2.

Lim also stressed the importance of enhancing partnerships with academic institutions, industry leaders, and government agencies, both at home and abroad. One such partnership between ISCE^2 and industry partners aims to identify low-carbon biofuels, such as ethanol, biodiesel and sustainable aviation fuel, which offer significant national economic value. Moreover, A*STAR experts are actively serving as technical advisors on several national working groups, including the Ammonia Working Group, contributing to policymaking and planning.

"Through innovation, collaboration and a commitment to excellence, A*STAR's roadmap holds the promise of shaping a sustainable and prosperous energy future," said Lim. ★

CANCER

Cancer-killing complexes charge ahead

Specially-designed nanocomplexes prove effective in targeting and killing cancer cells, including those resistant to traditional treatments.

If you've received numerous scam calls, you're more likely to resist answering calls from unknown numbers. Likewise, cancer cells often develop resistance to current treatments such as chemotherapy, rendering them less responsive over time.

"As these resistant cancer cells are hard to kill, they often need higher drug amounts or multiple drugs to treat, which can cause severe side effects," said Yi Yan Yang, Institute Scientist at A*STAR's Bioprocessing Technology Institute (BTI).

Additionally, hurdles such as the poor solubility of drugs, their inability to sufficiently concentrate in tumours, rapid clearance from the body, and the unwanted side effects on healthy cells can further complicate cancer drug development.

Yang's team had previously developed a group of promising anticancer agents capable of killing both drug-susceptible and drug-resistant cancer cells. They found that these macromolecules—known as guanidinium functionalised biodegradable polycarbonates—prevented cancer metastasis in mice without causing resistance. However, higher doses led to toxicity at the injection site due to the positively charged guanidinium groups.

In their follow-up study, the team turned to negatively charged carriers, which they hypothesised may form complexes with positively charged anticancer drugs to neutralise their charge, making them safer for patients while enhancing their targeting of cancer cells.

Collaborating with researchers from A*STAR's Bioinformatics Institute (BII) and Institute of Molecular and Cell Biology (IMCB), as well as the IBM Almaden Research Centre, US, the team formulated next-generation nanocomplexes that were functionalised with carboxylic acid or benzoic acid. Next, they evaluated the impact of these treatments on the growth of both drug-susceptible and drug-resistant human breast cancer cell lines, as well as toxicity and efficacy in mouse models.

Yang and team discovered that the nanocomplexes significantly reduced the growth of both types of human breast cancer cells, including those resistant to drugs. By fine-tuning their formulations, the researchers also improved the treatments' longevity and safety profiles.

Impressively, they found that the treatments reduced tumour size in mice by 32 to 56 percent without harming vital organs like the liver and kidneys.

Yang said that the results highlight how nanocomplexes can offer a novel method for treating cancer by overcoming drug resistance, underscoring the critical role of drug delivery systems in enhancing treatment effectiveness and safety.

"Our anti-cancer polycarbonates may prevent or delay the development of cancer metastasis and drug resistance," Yang remarked.

Aiming to move from bench to bedside, the team is forging collaborations with partners in industry and academia to further develop their technology for clinical use. ★

"Our anti-cancer polycarbonates may prevent or delay the development of cancer metastasis and drug resistance."

Researcher
Yi Yan Yang,
BTI

IN BRIEF

Negatively charged biodegradable polycarbonate carriers combined with cationic anticancer polycarbonate significantly improved drug delivery to tumours, reduced toxicity and showed potent efficacy against drug-resistant breast cancer cells.

1. Leong, J., Tay, J., Yang, S., Yang, C., Tan, E.W.P., *et al.* Nanocomplexes of biodegradable anticancer macromolecules: Prolonged plasma half-life, reduced toxicity, and increased tumor targeting. *Advanced Healthcare Materials* **12** (19), 2201560 (2023).

Photo credit: goodbishop / Shutterstock

Photo credit: GinoMM, Pamwik / Wikimedia Commons

BIOTECHNOLOGY

Sustainably engineered scents inspired by nature

Researchers develop a novel and more efficient bioprocess for synthesising a highly valued chemical from plants that is used by the fragrance industry.

Soon, we'll be able to stop and smell the roses (even without the flowers). Biotechnologists have developed ways of synthesising natural products—such as the chemicals that give flowers their unique and recognisable scents—under controlled and scalable industrial conditions. The process, known as metabolic engineering, is said to be a more sustainable way of attaining natural compounds for food, cosmetics and pharmaceuticals.

"Many natural products are obtained through natural extraction, which would require significant natural resources such as water and land," explained Xixian Chen, a Junior Principal Investigator at A*STAR's Singapore Institute of Food and Biotechnology Innovation (SIFBI).

For example, up to 3,500 km^2 (or about five times the land area of Singapore) of agricultural land space is required to extract 10 tonnes of cis-α-irone—a sweet, woody-scented chemical from iris plants that's highly prized by the perfume industry.

Traditional methods to produce cis-α-irone have several shortcomings—they are generally slow, still rely on iris plants as a starting material, and involve complex enzymatic reactions, many of which have yet to be characterised.

"Until today, experts have no idea exactly how nature makes cis-α-irone; it's still quite challenging to perform gene discovery for such compounds that are naturally present at very low concentrations," said Chen.

Chen and colleagues hypothesised that a method heavily used in organic chemistry—retrosynthesis—could help unlock novel ways of producing cis-α-irone. In collaboration with Isabelle André's team from the Toulouse Biotechnology Institute in France, the researchers built an artificial pathway with a promiscuous methyltransferase (pMT) for the synthesis of cis-α-irone, and focused on improving pMT's activity and specificity.

First, they analysed the crystallographic structure of pMT to identify specific amino acid residues that could be critical in improving the enzyme's efficiency.

Next, they synthesised different variations of pMT with mutations at these key residues and performed computational simulations to gain insights into the interactions between mutated residues and cis-α-irone. Finally, the optimised pMT enzyme was used to convert glucose into cis-α-irone in specialised bacterial cells using precision fermentation.

By enhancing the pMT enzyme's performance, the researchers achieved a 10,000-fold increase in its activity and a 1,000-fold increase in its specificity, thereby producing significantly higher cis-α-irone yields.

"This has led us to rethink many natural pathways that have room to be improved upon in terms of carbon yield and performance," said Chen, adding that their approach could mark a new era of sustainable metabolic engineering across many industries.

The team is currently collaborating with A*STAR's in-house robotics platform, SPARROW (SIFBI PARallel RObotic Workstation), and the Centre for Frontier AI Research (CFAR) to further fine-tune these and other enzymatic pathways. ★

Researcher
Xixian Chen, SIFBI

IN BRIEF

Custom-engineered enzymes and refined production methods that use specialised bacterial cells help to improve the yield and reduce the carbon footprint of cis-α-irone production.

1. Chen, X., T, R., Esque, J., Zhang, C., Shukal, S., *et al*. Total enzymatic synthesis of cis-α-irone from a simple carbon source. *Nature Communications* **13**, 7421 (2022).

BIOMEDICAL ENGINEERING

Skin patch works up a healthy sweat

A new colour-changing paper patch detects trace levels of multiple biomarkers found in sweat, offering a cost-effective wearable tool for real-time health monitoring.

Those beads of sweat trickling down your back during a cardio session, or after savouring some spicy cuisine, aren't just about cooling off. An emerging area of diagnostic research suggests that sweat—which contains electrolytes, metabolites and hormones—hold valuable clues about our health. From metabolic function to nutritional status, sweat can provide similar information that blood tests do, but without painful needle pricks involved.

According to Le Yang, Group Leader at A*STAR's Institute for Materials Research and Engineering (IMRE), technologies that support health monitoring through non-invasive biochemical analysis can aid both clinical-level diagnostics and personal health tracking, with the potential for smartwatch integration. However, current wearable devices for biofluid analysis often involve complex fabrication processes, high costs, and a lack of user comfort and simplicity.

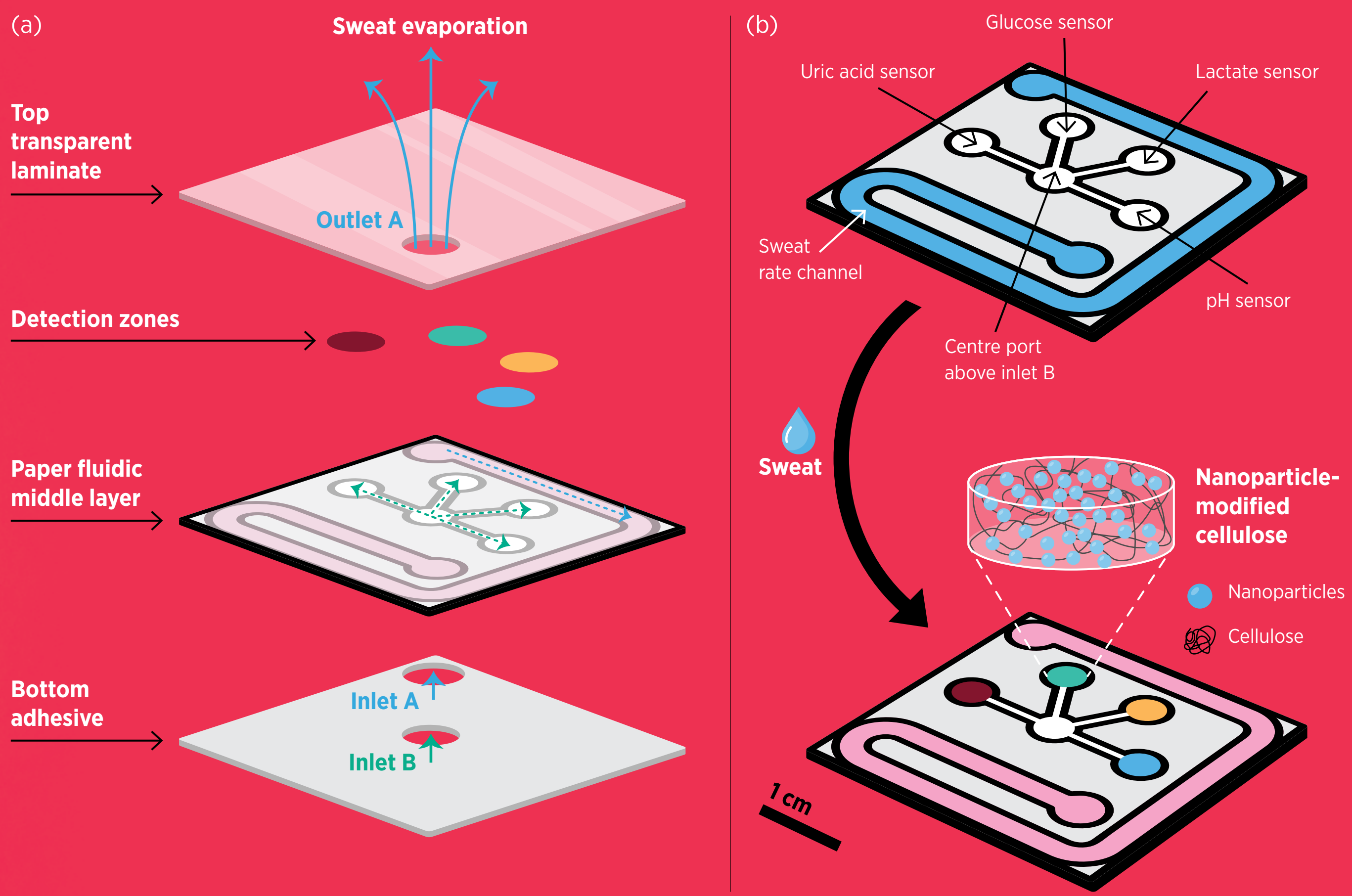
With collaborators from A*STAR's Institute of High Performance Computing (IHPC) and Nanyang Technological University, Singapore; Yang, Xinting Zheng, Xiaodi Su and IMRE colleagues set out to develop a new design for biofluid analytical devices. Their solution: a paper patch that can attach to the skin's surface and absorb sweat, change colours depending on the presence of key biomarkers, and produce unique patterns readable by a smartphone camera.

"Each detection zone on the patch elicits a change in colour intensity, or develops a new colour, which corresponds to biomarker concentrations or overall pH."

"When placed on sweaty skin, sweat enters the patch through two holes at the bottom, then flows through the paper's pores into four detection zones," said Zheng. "Each detection zone on the patch—which contains a combination of enzymes, nanoparticles and organic dyes—elicits a change in colour intensity, or develops a new colour, which corresponds to biomarker concentrations or overall pH."

The sensor patch employs a unique ceramic-based ink to control where sweat flows in the patch. Developed by the team, the ink can be printed directly onto a cellulose substrate (i.e. paper) to form sweat-wicking channels akin to COVID or pregnancy test kits.

Photo credit: Anna Shvets / Pexels



The wearable, colour-based sensor patch designed to detect sweat biochemical markers and monitor sweat rate. (a) An expanded view of the sensor patch and the sweat flow directions in the patch. (b) The colour-based sensor layout and nanoparticle modification of detection zones in the paper fluidic middle layer.

"Compared to conventional wax-printed patterns, our ink has several advantages: it creates an impervious barrier for sweat, can be printed at a higher resolution, and is more resistant to high temperatures and destructive chemicals," said Zheng.

The researchers carried out extensive optimisation on their patch prototypes using real and artificial sweat, fluid dynamics simulations, as well as comparisons with commercial benchtop testing kits. These eventually yielded promising results: their sensor patches demonstrated high recovery rates (99.4 to 103.7 percent) for sweat pH and three sweat metabolites (glucose, lactate and uric acid).

"When we tested the optimised patch on-body with volunteers, we were excited to find it was user-friendly and tallied with readings from commercial kits," said Yang. "Many commercial sweat analysis technologies need users to exercise to produce enough detectable sweat, but this patch only needs a tiny droplet."

With groundwork laid for non-invasive, simple and scalable real-time monitoring of sweat biomarkers and sweat rate, the team has filed a patent for their design. "In our upcoming work, our wearable sensors will enable continuous real-time monitoring, and be stable and sensitive enough for reliable long-term use," said Yang. ★

Researchers
Le Yang, Xiaodi Su and Xinting Zheng, IMRE

IN BRIEF
By using colour-changing fluidic patterns, a skin-attachable paper patch detects pH, glucose, lactate and uric acid concentrations in sweat *in situ* with high accuracy.

1. Zheng, X.T., Goh, W.P., Yu, Y., Sutarlie, L., Chen, D.Y., *et al.* Skin-attachable ink-dispenser-printed paper fluidic sensor patch for colorimetric sweat analysis. *Advanced Healthcare Materials* **13**, 2302173 (2024).

BLAZING NEW TRAILS

Eight A*STAR researchers stand among the latest scientific pioneers supported by the National Research Foundation Singapore's 2024 Fellowship and Investigatorship programmes.

Why do our body's defenses sometimes turn against us? What would store enough energy to power our cities? How does the same genetic code make a diverse world of cells? Can we make carbon-based chemicals part of a sustainable future?

These questions, and their consequential answers, are among several that will be investigated by eight exceptional A*STAR researchers with the support of the Singapore National Research Foundation (NRF)'s 2024 Fellowship and Investigatorship awards.

Each year, the NRF provides opportunities for researchers of all nationalities to explore new frontiers in science through these two schemes. Now in its 16th year, the NRF Fellowship supports early-career scientists as they conduct independent projects with high odds of research breakthroughs, while the NRF Investigatorship, in its own 9th year, supports principal investigators with an established record of leadership in their fields as they pursue high-risk, groundbreaking discoveries.

The NRF class of 2024 includes three NRF Investigators and five NRF Fellows from a range of A*STAR's research institutes. In this issue of *A*STAR Research*, we speak to these awardees about the scientific questions they hope to answer, and the impacts that their answers might have on our world.

9TH NRF INVESTIGATORSHIP (NRFI)

For research leaders in pursuit of high-risk, groundbreaking work

QI-JING LI

Research Director,
Institute of Molecular and Cell Biology (IMCB)

One of the human body's many defence mechanisms, T cells protect the body against cancer cells and cells infected by pathogens. A key part of the T cell toolbox is a group of proteins called T cell receptors (TCR)—found on each T cell's surface, they help detect alarming antigens and trigger an immune response.

Early in his career, Qi-Jing Li's work focused on identifying how T cells distinguish between cells that belong (self) and cells that don't (non-self), and how this mechanism was built during T cells' development. Li's team discovered a rheostat, microRNA miR-181a, that modulates T cell sensitivity and drives self-versus-non-self recognition. Li would bring this expertise forward into immuno-oncological trials; while he initially focused on analysing data from other trials, he moved on to conducting trials and generating new human data.

In 2021, Li and colleagues discovered a novel subset of effector T cells that appear in several tumour types and present as exhausted T cells. They found that the descendants of these cells appeared in distant healthy tissue before cancer cells migrated there. Liberating the seemingly 'exhausted' cells to healthy tissues led to the formation of long-standing memory cells that could defend against potential cancer metastasis.

Li and his team intend to further explore the mechanisms behind generating distant resident memory T cells and how they can be harnessed, through cellular engineering, to prevent breast cancer metastasis. With the support of the NRFI, Li aims to establish a research programme at A*STAR dedicated to developing patient-centric therapies.

"I aim to explore and validate clinically viable, immediately actionable methods to halt metastasis before it begins. My ultimate ambition is to harness the full therapeutic potential of these preventive strategies, significantly advancing immune-oncology and improving patients' lives."

NIRANJAN NAGARAJAN

Associate Director,
Genome Institute of Singapore (GIS)

The development of antibiotics in the early 1900s was a cornerstone of modern medicine. Today, we face the growing problem of antimicrobial resistance where many of our existing treatments are no longer effective.

To give us an edge in the race against evolving pathogens, Niranjan Nagarajan and his team work to understand and remodel the genetics of microbial communities to enlist them as allies in combatting colonisation by pathogens.

But first, the team has to accomplish the challenging task of analysing large amounts of DNA and RNA sequencing data. One problem the team is working on is genome assembly, where fragmentary 'reads' are obtained from DNA and pieced together to obtain the genomes of target microbes. Nagarajan compares the process to solving a large puzzle with millions of pieces to find an answer that has never been found before.

Over time, he hopes to expand the lab's work beyond metagenomics and computational biology towards culturomics and metabolic modelling. Ultimately, Nagarajan's team aims to build a collection of strains, genomic information and modelling capabilities that can harness microbial communities to solve challenges across infectious diseases, food production and sustainability.

"I am passionate about my field because it is one of humanity's grand challenges. We hope that our work will not only contribute to meaningful solutions, but also recalibrate our relationship with the microbial world that we live in."

ZHI WEI SEH

Principal Scientist,
Institute of Materials Research and Engineering (IMRE)

Decades ago, batteries kept car radios going; today, batteries keep cars on the go. Thanks to lithium-ion (Li-ion) technologies, batteries now power smartphones and city buses. However, even Li-ion batteries have their shortfalls: they rely on costly rare metals, are less energy-dense than liquid fuels, and are generally impractical for energy storage at a home- or city-wide scale.

Zhi Wei Seh's investigations revolve around new battery chemistries that overcome Li-ion's current theoretical energy limits. To Seh, multivalent-ion batteries—which use more common metals—are promising candidates for high-energy, low-cost Li-ion alternatives. However, many gaps remain in our fundamental understanding of how to design around them, as they lack the decades of research experience that informs Li-ion development.

By exploring structure-property relationships and constructing prototypes, Seh aims to uncover universal design principles for multivalent-ion batteries based on magnesium, zinc and aluminium, with the goal of creating a unified framework to guide their general development. Through theory computations and machine learning, they are accelerating the development of practical batteries for portable electronics, electric vehicles, grid energy storage and other applications.

"I hope to build better batteries to support humanity's sustainability efforts. I believe the true measure of success is not the number of papers or citations to your name, but rather whether your work will make a real impact on future generations."

16TH NRF FELLOWSHIP (NRFF)

For early career scientists in pursuit of independent research

LESLIE BEH

Principal Investigator,
Institute of Molecular and Cell Biology (IMCB)

As the driving force behind most biological functions, RNA acts as a blueprint for the synthesis of proteins. However, this blueprint can be modified through molecular and cellular processes that later impact the instructions that are passed along. While such modifications have been identified, their significance and functions remain largely unknown.

Leslie Beh—whose previous research includes identifying and engineering new DNA-modifying enzymes—now works to accomplish a similar goal with RNA. Beh and his team at IMCB hope to illuminate the roles RNA modification plays in human health and disease.

To do this, Beh's lab will harness synthetic messenger RNA (mRNA) harbouring different modifications at specific positions. These site-specifically modified mRNAs will be used in quantitative assays to determine how the position, number and type of modifications influence biological functions.

Looking ahead, Beh's team hopes to publish their findings from mechanistic studies of RNA modifications and CRISPR-Cas systems.

"The NRF Fellowship has enabled me to undertake high-risk, high-impact research in epitranscriptomics. I'm excited to dive into this field with fresh experimental approaches and perspectives."

"The NRFF is a preliminary endorsement of the value of formal methods research and my ability to pursue it."

— Yong Kiam Tan, Research Scientist, Institute for Infocomm Research (I^{2}R)

KENNETH LAY

Principal Investigator,
*A*STAR Skin Research Labs (A*SRL)*

Our skin is a fortress that protects our delicate organs from a harsh environment. Within that fortress, stem cells act not only as bricklayers, but also watchmen: in addition to replacing the millions of skin cells we shed each day, they also work closely with our immune cells to ward off microbes, toxins, radiation and other external dangers around the clock.

Kenneth Lay aims to build a research programme that will shed more light into the biology of skin stem cells, as many mysteries remain over how these cells respond to signals from both the outside world and the microenvironment around them. How these skin stem cells respond can mean the difference between stem cells that help or hurt; in particular, their working relationship with immune cells can determine whether they maintain a healthy skin barrier or trigger inflammatory skin diseases such as atopic dermatitis and psoriasis.

Lay hopes to unearth new insights into how skin stem cells function in healthy and diseased skin, which would pave the way towards harnessing their remarkable regenerative capacity and modulating them for better patient outcomes.

"I see the NRF Fellowship as a vote of confidence and an empowerment to realise my vision of improving lives through scientific discoveries; mentor and train new generations of scientists; and drive Singapore's growth as a world-leading biomedical research hub."

WAN RU LEOW

Scientist,
Institute of Sustainability for Chemicals, Energy and Environment (ISCE^2)

Petrochemicals are the lifeblood of modern society; everything we consume begins in some way from petrochemical refining. It's an especially critical industry in Singapore, where 1.5 million barrels of crude oil are refined daily. However, current petrochemical refining processes not only need high temperatures, but often burn a large portion of their feedstocks. As a result, the industry generates large amounts of carbon dioxide, accounting for around half of Singapore's carbon emissions profile.

To figure out how to cut the industry's carbon emissions without compromising our modern quality of life, Wan Ru Leow aims to create novel technologies that transform how chemicals are made. At ISCE^2, Leow and her colleagues are focusing on the dynamic reaction interfaces formed by electrocatalysts and their immediate vicinities.

By better manipulating such interfaces to achieve specific target reactions, Leow hopes to not only expand the repertoire of achievable electrochemical reactions for industrial processes, but also pave the way for cleaner, more benign chemical reactions powered by renewable energy. Building on these discoveries, Leow also intends to foster industrial partnerships to co-develop pilot-scale prototypes that can make real-world impacts on decarbonisation.

"My goal is to build niche technologies that eventually provide platforms for broader applications such as carbon capture or waste valorisation. The NRF Fellowship provides a great starting platform to establish photoelectrochemical capabilities new to ISCE^2 and Singapore, and enables fundamental investigations into critical challenges in sustainability."

TIM STUART

Senior Research Scientist,
Genome Institute of Singapore (GIS)

In 2003, the Human Genome Sequencing Consortium announced it had decoded an essentially complete human genome, accounting for 92 percent of the full sequence. Nearly two decades later, the Telomere-to-Telomere (T2T) consortium announced they had filled the gaps in that code.

While researchers can now easily read DNA sequences, much remains unknown about how a single DNA sequence, when "read" by our cells, can lead to different biological functions, and even the formation of entirely different cells. To explore the relationship between sequence and function, and how it can be manipulated for precision gene therapy, Tim Stuart aims to engineer synthetic DNA regulatory elements that direct gene expression in specific cell types.

With colleagues at GIS, Stuart plans to expand on existing genomics methods, such as single-cell epigenomics, to develop expertise in building deep learning models for DNA sequences. The team's work aims to advance capabilities in DNA sequence engineering and ultimately enable novel therapeutic applications that can target specific cell states in the human body—in what could be a gamechanger for precision healthcare.

"It's an exciting time to be in genomics: DNA sequencing costs are falling fast, all kinds of new molecular methods are being developed rapidly, and all in parallel with massive improvements in artificial intelligence (AI) and computation. I'm sure that many opportunities for interesting and exciting science will present themselves in the coming years."

YONG KIAM TAN

Research Scientist,
Institute for Infocomm
Research (I^2R)

Every system has its flaws: whether a factory, a hospital or a corporation, it's always reassuring to know that a system is regularly audited for potentially harmful issues based on professional standards and best practices. Computer systems are no different; as we increasingly rely on them in many aspects of our lives, there's a growing need for tools to confirm that they work as intended.

Yong Kiam Tan's fascination with formal methods—the rigorous analyses of computer systems using mathematical tools and techniques—began during a summer research internship as an undergraduate at Cambridge University in the UK. For Tan, the field is entering an exciting era, as formal methods tools have become more widely adopted to verify the correctness of software and hardware in safety- and mission-critical settings.

Today, Tan's research focuses on making formal methods produce more reliable verification results; as with any other software, formal methods tools are susceptible to bugs of their own. Tan aims to tackle this by "verifying the verifiers"; using formal methods to rigorously analyse formal methods tools. Working with collaborators at A*STAR and Nanyang Technological University, Singapore, Tan will also seek opportunities to apply formal methods in practice together with experts in adjacent areas, such as cybersecurity and AI.

"The NRFF is a preliminary endorsement of the value of formal methods research and my ability to pursue it. I hope to live up to that endorsement, and to introduce students to the fascinating world of formal methods through teaching and mentorship." ★

WASTE MANAGEMENT

Plastic and ash: from trash to treasure

A common waste material from municipal incinerators shows potential as an effective catalyst to upcycle waste single-use plastics into valuable chemicals.

We're grappling globally with a persistent plastic predicament. Our heavy reliance on non-biodegradable single-use plastics, coupled with inefficient recycling processes, means that a lot of plastic still ends up languishing in landfills or choking up sensitive environments.

Today, conventional plastic recycling involves mechanically breaking down specific types of plastics into small pellets that can be turned into new plastic products. A promising alternative approach called pyrolysis uses high temperatures and powerful catalysts to chemically transform waste plastics, upcycling them into a wider range of valuable materials such as fuels and chemical feedstocks.

However, plastic pyrolysis faces its own technical hurdles: its crucial catalysts need to be regularly replaced due to issues such as coking, where built-up carbon residues block active sites, and poisoning, where other chemicals deactivate their catalytic properties.

To tackle this dilemma, a joint team of researchers from A*STAR's Institute of Materials Research and Engineering (IMRE) and the Institute of Sustainability for Chemicals, Energy and Environment ($ISCE^2$) have been on the hunt for next-generation catalysts for pyrolysis.

"Considering the disadvantages of traditional options such as zeolites and metal oxides, we sought an inexpensive inorganic alternative that is readily available, continuously produced and exhibits significant catalytic efficacy," said Jason Lim, Group Leader of IMRE's Sustainable Supramolecular Materials Lab.

Co-led by Lim and Enyi Ye, Group Leader of IMRE's Nano+ Lab, the team earmarked incineration fly ash (IFA), a byproduct from municipal waste incinerators that typically ends up in landfill. While IFA is rich in catalytic compounds like calcium hydroxychloride (CaClOH), its potential as a catalyst for pyrolysis had been largely ignored till now.

Using IFA, the researchers explored pyrolysis of three widely-used plastics—polyethylene (PE), polypropylene and polystyrene—in their pure forms, as well as samples of everyday plastic waste. In a series of control experiments, they compared IFA's effectiveness versus other materials to understand CaClOH's potential role in plastic recycling.

The researchers reported that IFA significantly boosted pyrolytic conversion of virgin high-density PE (HDPE) into liquid hydrocarbons from 46.7 to 92.8 percent. They also discovered that HDPE plastics, commonly used in bottles and grocery bags, yielded the highest amount of liquid product while minimising the formation of char, a solid byproduct.

"CaClOH's amphoteric nature lets it act as both an acid and a base, giving it a unique reactivity compared to other calcium-containing basic materials like calcium oxide," said Lim. "It promotes the formation of positively-charged intermediates during pyrolysis, reducing the odds of chemical crosslinking that would normally result in waxes, and increasing the production of low-weight liquid hydrocarbons, which can be useful as fuels, solvents and chemical precursors."

The team envisions repurposing abundant, low-cost plastic waste into valuable hydrocarbon feedstocks through IFA pyrolysis to minimise landfill volume and foster a sustainable circular economy. To pave the way, the group is currently exploring other classes of catalysts for plastic upcycling.

"We would also like to stabilise post-pyrolysis IFA so it can be safely used in construction materials and other areas," added Ye. "We aim to transform IFA from a waste product into a resource with diverse applications." ★

Researchers
Jason Lim and Enyi Ye, IMRE

Xian Jun Loh, IMRE and Zibiao Li, $ISCE^2$

IN BRIEF
Incineration fly ash significantly enhanced the pyrolysis of polyethylene into useful low-weight hydrocarbons, offering a promising upcycling solution for a common class of single-use plastic waste.

1. Heng, J.Z.X., Tan, T.T.Y., Xing, Z., Ong, J.L.Y., Lin, K.S., *et al.* Unraveling the catalytic activity of CaClOH-rich incineration fly ash in the pyrolysis of single-use plastics. *Materials Today Chemistry* **31**, 101608 (2023).

Photo credit: Freepik

MODELLING AND SIMULATIONS

Bypassing silicon for light speed computing

An enhanced computational design method uses deep learning to accelerate the development of light-based computer chip technologies.

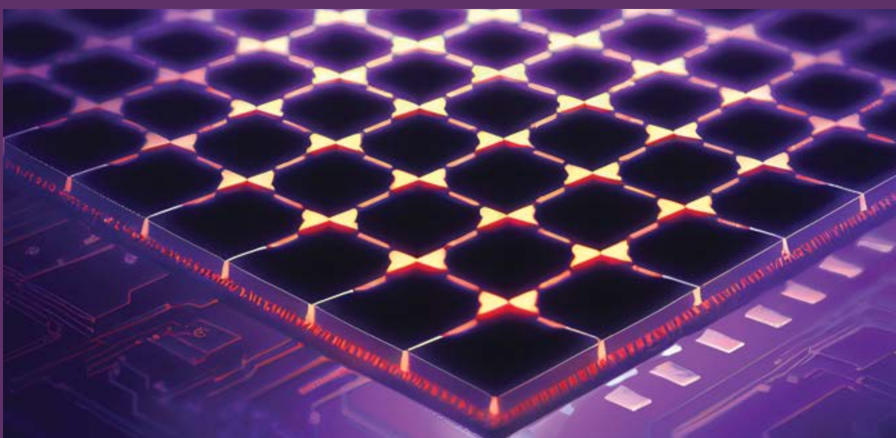


Photo credit: Alexander_Evgenyevich / Shutterstock

Phones and computers have gotten exponentially smarter and faster over the years. In the world of electronics, this growth has been partly driven by Moore's Law: an industrial aspiration to double the number of transistors on a circuit board approximately every two years.

Nevertheless, the sector is reaching a juncture where integrating additional transistors onto silicon wafers, the traditional material for circuit boards, is proving to be a formidable challenge.

Consequently, materials scientists are investigating new materials and technologies to sustain the progression of computational power without being constrained by the physical limitations of silicon.

Principal Scientist Gandhi Alagappan, and Director for the Electronics and Photonics Department, Jason Png, both from A*STAR's Institute of High-Performance Computing (IHPC), have been exploring a novel paradigm that harnesses the power of light. "In contrast to electronic chips reliant on electrons, photonic chips exploit light for data transmission, yielding swifter communication and higher capacity," noted the duo.

This photonic chip technology is similar to optical fibres used in long-distance data transfer, and according to experts, can completely revolutionise computer architecture.

While the potential of photonic circuits is vast, current chips have a much larger physical footprint compared to electronic circuits, presenting a hurdle for commercial viability. To address this, Alagappan and Png have reconceptualised the design of pivotal photonic components. Their study centred on the refinement of power dividers: integral devices that split light into discrete pathways for downstream processing.

Employing deep learning, the team enhanced inverse design algorithms—computational methods that ideate components conforming to specified functionalities and constraints.

Listing the merits of this approach, Alagappan said, "Embracing inverse design methodologies opens the door to creating innovative power dividers characterised by compactness, minimal loss, large bandwidth and importantly, suitability for large-scale manufacturing processes."

Deep learning models are advanced computer programmes that enhance the design process (which traditionally could be quite slow) by simulating how light moves through different structures. This allows for a more efficient and creative approach to design, where the computer can quickly test and refine different models.

This method proved to be particularly useful as the team successfully designed a range of power dividers that were shown to be highly efficient, compact and resilient to manufacturing variations. Significantly, the team's deep learning-based design process surpasses traditional methods in speed without sacrificing the precision or effectiveness of the final product.

Looking ahead, the researchers intend to apply their methods to other photonic components, potentially unlocking new prospects in quantum communications and optical networking. ★

Researchers
Gandhi Alagappan and Jason Png, IHPC

IN BRIEF
Using deep learning models, A*STAR researchers enhanced the design of power dividers in photonic chips, resulting in high-efficiency components that are compact and suitable for large-scale production.

1. Alagappan, G. and Png, C.E. Deep learning accelerated discovery of photonic power dividers. *Nanophotonics* **12** (7), 1255-1269 (2023).

COMPUTER VISION

'I spy' with a digital eye

A novel machine learning framework efficiently detects small objects in images, potentially boosting computer vision technologies such as self-driving vehicles and remote sensing.

Finding the proverbial 'needle in a haystack' is notoriously challenging, not just because of the target's small size, but because of the clutter around it. When creating computers that 'see' like we do, artificial intelligence (AI) researchers face a similar puzzle. To learn how to precisely pinpoint that needle, object detection algorithms often need to scrutinise high-resolution images in detail, driving up the processing power needed to train them.

This constraint has profound implications on computer vision's real-world applications. For example, to a self-driving car, a small object initially noticed by its cameras might in fact be a distant, yet rapidly approaching one.

"Small objects like debris, road signs, pedestrians and animals pose dangers for on-road autonomous vehicles," said Fen Fang, a Research Scientist at A*STAR's Institute for Infocomm Research (I^{2}R). "These need to be detected early and accurately to ensure safe travel."

However, detection algorithms can be slowed down by the difficulties of identifying small objects from limited visual cues, processing their small details, and picking them out from cluttered environments, Fang added.

To give computers a sharper, faster, and yet more efficient eye for detail, Fang's team developed a novel policy framework that combines reinforcement learning (RL) techniques with a spatial transformation network (STN) and a transformer model with a convolutional neural network (CNN). This approach trains

> **"Small objects like debris, road signs, pedestrians and animals pose dangers for on-road autonomous vehicles."**

a reinforcement learning agent to use a two-step process: a coarse location query (CLQ), followed by context-sensitive object detection.

"CLQ predicts the regions in an image where small objects are likely to be located, which enables the object detector to use high-resolution image patches for those regions, and low-resolution patches for the rest," said Fang.

Imagine a detective searching a satellite photo of a city for clues; the STN acts like their local guide, drawing a map of key districts and roads over the photo. The detective can then use the CNN-transformer like a magnifying glass, giving them more detailed, close-up views of suspicious districts. This synergistic framework not only homes in on areas likely concealing small targets, but also minimises false positive readings, which reduces the computing resources and human effort needed.

Tested across diverse image datasets—from bustling city streets to aerial vistas—the researchers' framework showed improvements in detection accuracy by up to two percent while reducing the number of processed pixels. Moreover, the new framework not only matched but outperformed current state-of-the-art methods in some cases.

"Our framework can help autonomous vehicles avoid accidents by improving their environmental awareness and predicting potential hazards," said Fang. "By identifying small objects like trees, power lines and infrastructure in aerial images, the framework could also help accurately map and monitor environments, which would support urban planning, disaster management and environmental conservation."

The team is currently reinforcing the robustness of their recently patented model by expanding its perceptual field through enriched datasets, including synthetic data made by generative AI. ★

Researcher
Fen Fang,
I^{2}R

IN BRIEF
By combining a spatial transformation network and a transformer model with early convolution, researchers develop a reinforcement learning-based small object detection framework with higher detection accuracy and lower computing requirements versus existing models.

1. Fang, F., Liang, W., Cheng, Y., Xu, Q. and Lim, J.-H. Enhancing representation learning with spatial transformation and early convolution for reinforcement learning-based small object detection. *IEEE Transactions on Circuits and Systems for Video Technology* **34** (1), 315-328 (2024).

Photo credit: Ryoji Iwata / Unsplash

COMPUTER NETWORKS AND COMMUNICATIONS

Covert whispers behind digital curtains

A new approach to secure direct communication between devices enhances privacy by preventing eavesdropping.

High-profile data breaches in large organisations frequently grab headlines, underscoring vulnerabilities in our digital era. However, it seems that even private digital conversations between friends aren't immune to security threats.

Device-to-Device (D2D) communication allows interactions between mobile devices without routing through a cellular base station, making it highly efficient for sharing data over short distances. Since D2D communication often happens over open airwaves, it can be easier for unauthorised people or devices nearby to intercept or 'eavesdrop' on these communications.

This is especially concerning for sensitive information, as there's a risk that someone might listen in without the users knowing.

"The differences in infrastructure and operational characteristics between traditional network communications and D2D communications contribute to the suitability of certain secure and covert communication approaches," noted Sumei Sun, Acting Executive Director for A*STAR's Institute for Infocomm Research (I²R). Sun emphasised the need for tailored security strategies, given the distinctive infrastructure and operational traits of D2D networks.

To find solutions, Sun's team worked with experts from Nanyang Technological University, Singapore; University of Manitoba, Canada; and Ericsson Canada Inc. to simulate a D2D communications network environment. The researchers then created a scenario like a game of strategy, where the devices in the network had to outsmart multiple eavesdroppers attempting to intercept transmissions.

For their analytical framework, the team used the established two-stage Stackelberg game model, emulating the proactive stance that devices must assume to protect against potential attacks.

"The model captures the fact that information can only be intercepted by attackers after it has been transmitted," said Sun.

Through their analysis, the team found that to keep conversations private, the strength of 'friendly' jamming signals (a masking technique used for secure communication) must be carefully adjusted. Too weak, and they could fail to hide messages; too strong, and they could block messages between devices.

The team also noted that jamming signals offer the additional security advantage of concealing the locations of transmitting devices. Overall, their new jamming-assisted covert communication method was found to outperform theoretical stealth models that simply provide a best guess on how to stay hidden.

Sun and colleagues aspire to refine their security protocols further for D2D network integration, bolstering the confidentiality and resilience of these increasingly pivotal communication systems. ★

"The model captures the fact that information can only be intercepted by attackers after it has been transmitted."

Researcher
Sumei Sun,
I²R

Photo credit: Tero Vesalainen / Shutterstock

IN BRIEF
Using a strategic mix of covert communication and friendly jamming, researchers made data transmission between devices less detectable to malicious attackers, significantly improving the security of device-to-device (D2D) communication networks.

1. Feng, S., Lu, X., Sun, S., Niyato, D. and Hossain, E. Securing large-scale D2D networks using covert communication and friendly jamming. *IEEE Transactions on Wireless Communications* **23** (1), 592-606 (2024).

THE STUFF OF SUSTAINABILITY

Serving as atomic architects, A*STAR scholars Rebecca Khoo and Kang Rui Garrick Lim are designing novel materials that can shape a more sustainable future.

Electric lines, cooking gas, petrol engines, pocket batteries; most of us may find it hard to imagine daily life in a world without these. But as we grapple with the challenges of climate change and environmental degradation, the technologies we use to generate, store, transform and utilise energy are a key force in shaping a sustainable future.

A*STAR National Science Scholar (NSS) recipients Rebecca Khoo and Kang Rui Garrick Lim are among many researchers working on cutting-edge materials with an eye on sustainability. Intrigued by the chemistry that binds together the stuff of our world, Khoo and Lim are exploring different facets of materials science that support solutions ranging from improved carbon capture to efficient chemical manufacturing.

In this interview with *A*STAR Research*, Khoo and Lim reflect on their journeys with A*STAR, share details about the projects they've enjoyed working on, and give their advice for those beginning their careers in science.

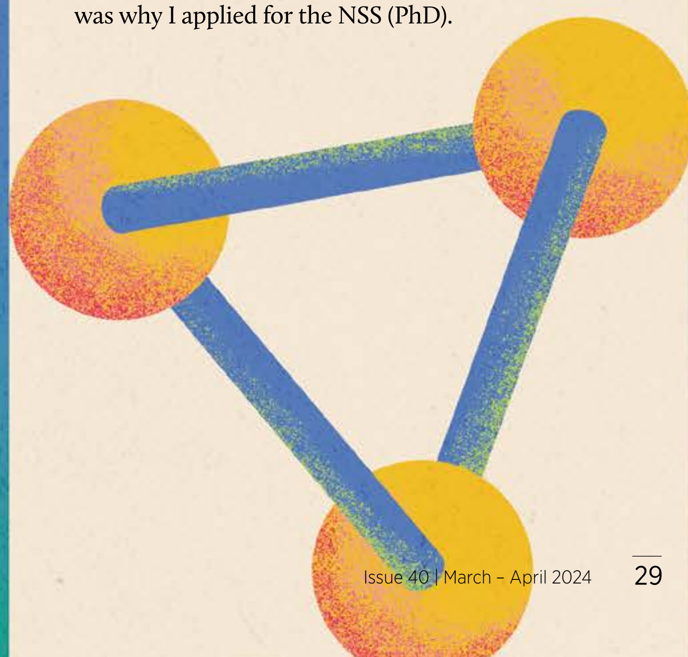
Q: WHAT LED YOU TO YOUR CURRENT RESEARCH?

RK: I became interested in materials science and chemistry during my pre-university internship with Singapore General Hospital's Orthopaedic Department, where I learned about research in biocompatible materials for joint replacement implants. This led me to pursue a chemistry degree at the National University of Singapore (NUS), where I had the chance to explore topics ranging from superhydrophobic surfaces to catalysts.

After graduation, I joined A*STAR's Institute of Materials Research and Engineering (IMRE) and had a good time working on utilising carbon dioxide (CO_2) to make novel polymers and supramolecules. From there, I applied for the NSS (PhD) to expand my horizons at the frontiers of gas capture, separation, storage and catalysis technology at the University of California, Berkeley, US.

GL: My first exposure to A*STAR was as an upper secondary school student, when I was selected for the A*STAR Science Award. I remember taking a tour of IMRE in 2009; it was my first glimpse into what a research laboratory looks like.

Since then, A*STAR has supported me throughout my eventful 15-year journey; one that spanned my undergraduate education at NUS and three research stints at IMRE. I came to realise that pursuing a career in scientific research would allow me to continue tinkering with materials and deliver real-world impact by increasing human knowledge and experience. I wanted to create that impact in Singapore, which was why I applied for the NSS (PhD).



Q: WHAT ARE SOME INTERESTING PROJECTS YOU'VE WORKED ON?

RK: For my PhD, I studied metal-organic frameworks (MOFs): these are a highly versatile class of porous, crystalline solids built from molecular building blocks. Putting them together is not unlike stacking LEGO bricks.

MOFs fascinate me—by simply blending different atomic components, these frameworks can be customised for various uses, such as greenhouse gas capture and storage; separation and purification of gaseous mixtures; and solid-state catalysis for both liquid and gas-phase chemical reactions.

At the Institute of Sustainability for Chemicals, Energy and Environment (ISCE[2]), my research is currently focused on the mechanochemical degradation and alteration of polystyrene, which aims to enable this typically non-recyclable plastic to be recycled and repurposed. Mechanochemistry is a straightforward and environmentally-friendly approach because it uses physical forces, such as impact and shear, to trigger reactions without involving a lot of harmful solvents and complicated processes.

GL: As a fourth-year chemistry PhD student at Harvard University, US, I'm working on developing new methods to prepare catalysts, which help achieve more energy-efficient chemical transformations. Catalysts drive practically all industrial chemical production; there's an urgent need to develop more efficient, selective and durable catalysts.

My research at Harvard specifically taps on colloidal chemistry as a toolbox to create a catalyst platform with multiple components and features that can be independently swapped out if needed. Such a model catalyst platform would enable researchers to isolate and investigate the independent effects of any of the catalyst's features—chemical or physical—on its resulting catalytic performance.

The project has been the subject of a Harvard press release; I'm happy that our team's efforts are gaining international attention. The catalyst platform we developed was inspired by the nanostructure of butterfly wings, and we continue to look for inspiration all around us.

"Remember that failure is not the end, but rather a learning opportunity for growth."

— Rebecca Khoo, Scientist at A*STAR's Institute of Sustainability for Chemicals, Energy and Environment (ISCE[2])

Q: HOW DOES YOUR WORK SUPPORT SUSTAINABLE ENERGY RESEARCH?

RK: In one of my current projects, I design and synthesise new MOFs for CO_2 utilisation and small molecule catalysis. MOFs show great potential as sorbents for carbon capture and storage; they can essentially soak up CO_2 like a sponge. If that potential is realised, that functionality could propel many international initiatives that aim to scale up and industrialise MOFs. I hope to play a part in advancing this field and contribute to Singapore's efforts towards achieving net-zero emissions.

GL: Before my PhD, I spent a year at IMRE developing electrocatalysts for hydrogen evolution. Prior to that, my research at NUS involved synthesising nanomaterials that could capture sunlight to be harvested as light energy. Energy capture, storage and conversion have been recurring themes in my research journey. I hope to see more young students and researchers joining us on this ride, because this endeavour is going to need all of us.

"Persevere when things do not go as expected. Behind every 'aha!' landmark experiment lies months and years of hard work."

— Kang Rui Garrick Lim, A*STAR National Science Scholar (PhD)

Q: WHAT EXCITES YOU ABOUT YOUR JOURNEY AHEAD?

RK: The present is an exciting time not just for myself, but for everyone dedicated to sustainability research. People are beginning to recognise the need for, and the significance of, sustainable practices. I hope to play my part in addressing global energy challenges and contribute to securing a viable future for generations to come.

GL: My work has brought me to different parts of the world and allowed me to engage with other researchers. I hope to continue to learn from some of the brightest minds here at Harvard during my PhD, and beyond.

Being young also grants me ample energy to experiment boldly at the laboratory bench! My PhD advisor is deeply intrigued by all things science, and I hope to bring that same infectious enthusiasm into my research.

Q: WHAT ADVICE WOULD YOU GIVE YOUNG STEM GRADUATES?

RK: Always prioritise your mental and physical well-being, and do allocate time for family, friends and leisure! Remember that failure is not the end, but rather a learning opportunity for growth.

Embrace the opportunity to ask questions—regardless of how trivial they may seem—as they will give you valuable insights. Also, be open to sharing your thoughts and opinions with supervisors, mentors and peers; you never know when it might spark innovative breakthroughs.

GL: I hope that aspiring researchers, myself included, will fondly remember what brought them to science in the first place. I learned early that scientific research is fraught with failure and rejections. The first advice my PhD advisor gave me is that science is non-linear: some days you will have much to discuss, and on other days, nothing much. Knowledge creation is difficult, and translating that knowledge into something tangible that benefits many others only compounds that challenge even further.

My hope is that students will bring cautious optimism and their unique perspective into their scientific research; work on problems that keep them up at night; and persevere when things do not go as expected. Behind every 'aha!' landmark experiment lies months and years of hard work. I hope that our budding scientists will find their own eureka moment(s) in time to come. ★

MATERIALS SCIENCE

Towards ultrathin active metaoptics

Researchers show that a new design element for nanoscale light-bending materials makes them electrically tuneable at room temperature, opening doors to new optical technologies.

For humans, an ideal temperature can mean a lot to a day's work; our productivity can struggle under stifling heat or chilling winds. For two-dimensional (2D) semiconductive materials, however, an ideal temperature might be hundreds of degrees below freezing, making it challenging to use their potent light-interaction properties in everyday devices and at ambient temperatures.

"Often mere atoms thick, 2D materials have unique light-matter interactions not seen in bulkier materials, such as strong exciton binding energy and dangling bond-free surfaces, which allow easier integration with other materials," said Jinghua Teng, Senior Principal Scientist and Senior Group Leader from A*STAR's Institute of Materials Research and Engineering (IMRE).

Using 2D materials, researchers are developing metaoptics: nanoscale device components with strong light-manipulating powers, thanks to tiny surface structures smaller than the wavelength of light itself. When light hits these structures, it bends, focuses or scatters, with changes to its colour, intensity or even polarisation. These fascinating properties mean metaoptics built from 2D materials can support new ultra-compact optoelectronics designs for advanced displays, sensors, photonic circuits, communications and more.

However, existing device designs either need large amounts of power or very low temperatures to operate; or respond weakly to optical tuning. "It's crucial to be able to dynamically control how a 2D metaoptic reflects light using electricity and at room temperature," said Teng.

To pave the way for innovative, yet practical 2D metaoptics applications, Teng and colleagues from IMRE; Nanyang Technological University, Singapore; and University College London, UK; explored a phenomenon known as exciton-trion conversion in transition metal dichalcogenides (TMDCs), a class of 2D materials.

Many TMDCs are packed full of excitons (bound states of electron-hole pairs carrying energy) and trions (charged excitons with an additional electron or hole). Studies have shown that the balance between excitons and trions in a TMDC affects how it interacts with light, and that electricity can convert excitons to trions. However, little data exists on how to electrically control that conversion in an everyday setting, as the effect is normally too weak to detect at room temperatures.

To better understand electrically-controlled exciton-trion conversion under ambient conditions, Teng and colleagues designed a vertical optical cavity using a single-molecule layer of tungsten disulphide (WS_2), a TMDC, tucked between an ionic gel and layers of aluminium and aluminium oxides. The cavity acted like a tiny echo chamber, making the dynamics between light and the metaoptic easier to observe.

"The optical cavity provides strong light-matter interactions that boost excitonic resonance and absorption in monolayer WS_2 at specific exciton energies, enhancing exciton-trion conversion in the WS_2 monolayer," said Zeng Wang, an IMRE Senior Scientist and the first author of the paper.

When the researchers applied an electric force to their device, they found it could convert nearly all energy carried by the excitons to trions at ambient temperature, causing dramatic changes to the metasurface's reflection and refractive indices.

"We showed that monolayer WS_2's optical properties are highly tuneable through electrical modulation," said Teng. "These findings could contribute to innovations in telecommunications, imaging systems and information processing, where adaptability and miniaturisation are key."

Moving forward, the team is delving deeper into applications of TMDC-based metasurfaces in new optical devices and systems, focusing on commercial applications such as lasers and sensors. ★

Researchers
Jinghua Teng and Zeng Wang, IMRE

IN BRIEF
By integrating vertical optical cavities into a monolayer WS_2 metaoptic, researchers achieve efficient exciton-trion conversion at room temperature, which allows dynamic electrical control of the metaoptic's interactions with light.

1. Wang, Z., Sebek, M., Liang, X., Elbanna, A., Nemati, A., *et al.* Greatly enhanced resonant exciton-trion conversion in electrically modulated atomically thin WS_2 at room temperature. *Advanced Materials* **35** (33), 2302248 (2023).

OPTOELECTRONICS

A quantum leap towards reshaping connectivity

A new approach to generating terahertz radiation offers a compact, tuneable and scalable solution for faster data transmission and improved imaging applications.

Imagine your home Wi-Fi network as a delivery service that transports data ‘packages’ full of emails, videos and social media content through invisible airwaves. Today’s Wi-Fi technologies make use of radio frequencies to swiftly deliver these packages.

Now picture that delivery service cruising on a highway at ultrafast speeds, carrying truckloads of data with unmatched reliability even in challenging environments. This future wireless network could harness terahertz (THz) radiation: a form of electromagnetic radiation that sits between microwaves and infrared light.

“THz radiation can penetrate non-metallic substances such as clothing, paper and plastic without the ionising dangers of X-rays,” said Wenjun Ding, a Senior Scientist at A*STAR’s Institute of High Performance Computing (IHPC). This unique property also means that beyond communications, THz radiation can unlock new possibilities in security, manufacturing and biomedical research.

However, conventional sources of THz radiation are either too weak, too large or too expensive for everyday use. To better integrate THz-based technologies into home devices like Wi-Fi routers, we need THz emitters that are compact, tuneable and low-cost, Ding added.

In a collaboration between Ding and colleagues from IHPC, A*STAR’s Institute of Materials Research and Engineering (IMRE), Nanyang Technological University, Singapore (NTU), and the Singapore University of Technology and Design, researchers examined one possible solution: a phenomenon known as the Smith-Purcell (SP) effect. When charged particles are beamed very closely and parallel to a periodic grating—a surface covered with fine, evenly-spaced grooves—some energy from those particles scatters off the grating, turning into longer-distance radiation.

Taking advantage of the SP effect, the team proposed laying two-dimensional (2D) quantum materials like graphene over a silicon-based periodic grating. At just one atom thick, the conductive graphene layer allows charge carriers, like electrons, to move freely across its surface, generating THz radiation with minimal energy loss.

In their study, the team pinpointed optimal conditions for generating THz radiation by finely adjusting the distance between an electron beam and the graphene layer. They also discovered that electrons within the graphene could became ‘hot’ or highly energetic: an effect they manipulated to enhance THz radiation intensity.

“With SP radiation, you don’t need an electron emitter to put out electrons at a minimum velocity; 2D materials can excite ‘slow’ charge carriers,” said Ding. “This approach significantly reduces the system’s complexity, making it highly suited for compact THz radiation sources.”

The team’s approach offers other exciting advantages: it’s highly tuneable, as they can adjust THz radiation frequency by modulating electron energy or changing the grating pattern. It’s also scalable enough to put on a chip, making it feasible to integrate into portable devices. “These properties could drive advancements in wireless communication, sensing and imaging,” Ding added.

Ding credited National Science Scholar Shengyuan Lu as the project’s main contributor, with experimental advice from IMRE Senior Principal Scientist Jinghua Teng and team; and IHPC Scientist Ayan Nussupbekov as its equal contributor, under the supervision of Lin Wu, an IHPC Principal Scientist II, and NTU colleagues. Moving forward, in a project led by Teng, the team is further developing the use of the SP effect in other 2D quantum materials for THz and infrared applications. ★

Researchers
Lin Wu and Wenjun Ding, IHPC

IN BRIEF
By layering graphene over finely-grooved silicon surfaces and leveraging the Smith-Purcell effect to manipulate electron energy, researchers create a potential compact, efficient THz radiation source.

1. Lu, S., Nussupbekov, A., Xiong, X., Ding, W.J., Png, C.E., *et al*. Smith–Purcell radiation from highly mobile carriers in 2D quantum materials. *Laser & Photonics Reviews* **17** (7), 2300002 (2023).

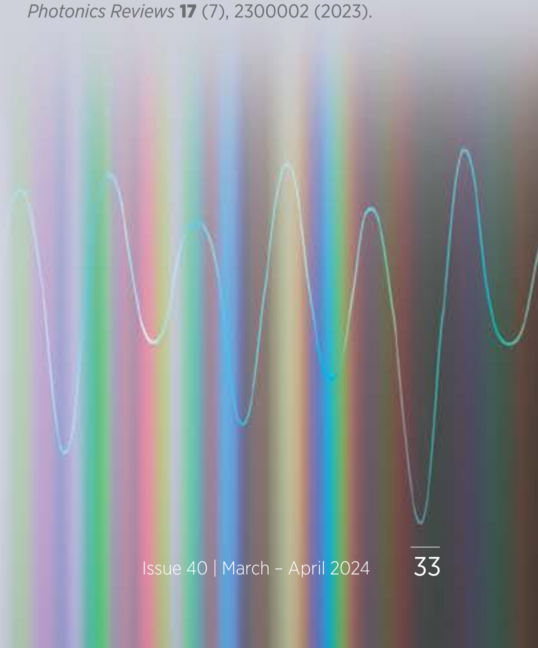


Photo credit: Vladimir / Shutterstock

MECHANICAL ENGINEERING

Jellyfish robot makes a big splash

A new transparent soft robot uses innovative materials to blend into underwater environments by mimicking the moon jellyfish's movement and appearance.

Many animals have evolved camouflage to evade both predators and prey. The moon jellyfish (*Aurelia aurita*) takes this strategy further: with its near-transparent body, the species blends into and thrives in open oceans worldwide.

Inspired by the moon jellyfish's form and function, a team of researchers from A*STAR's Singapore Institute of Manufacturing Technology (SIMTech), the National University of Singapore, and the Chinese University of Hong Kong, Shenzhen, China, have created a new 'soft' robot that not only swims like *A. aurita*, but looks just as glasslike.

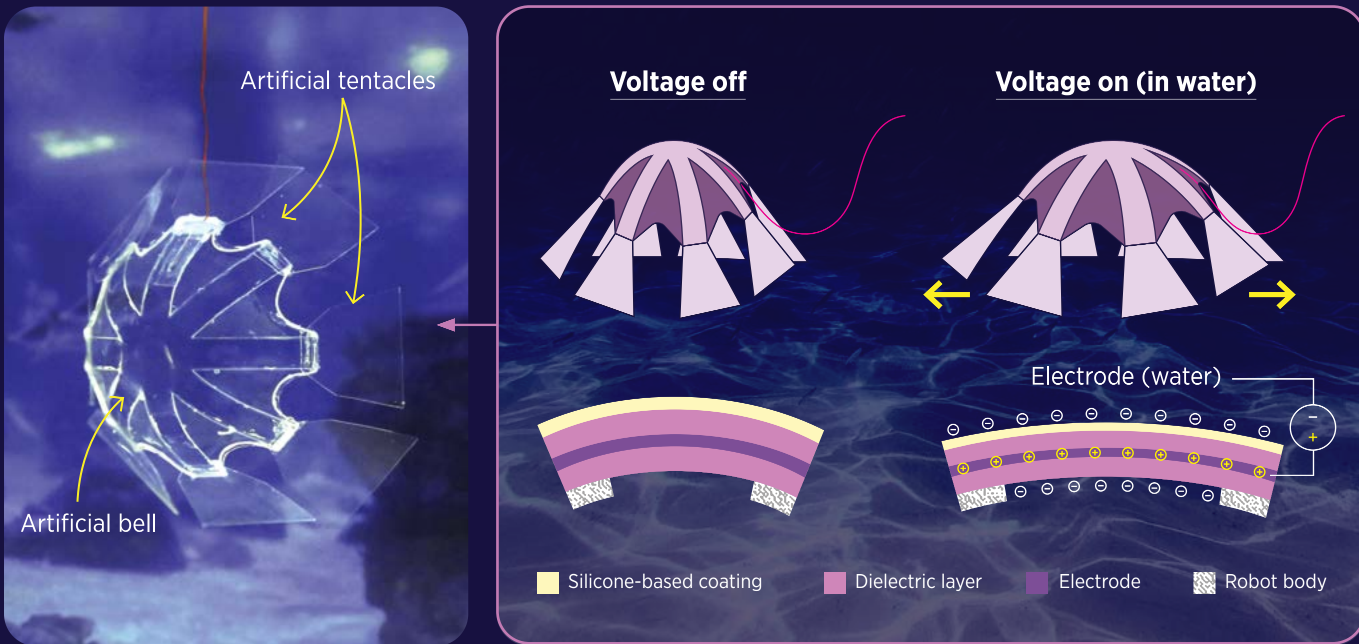
"Integrating transparency into soft robots can be valuable for many applications, such as non-disruptive underwater surveillance, allowing researchers to observe aquatic animals in their natural habitats," said Yuzhe Wang, a SIMTech Senior Scientist and first author of the study.

It's not easy to transition robots from metallic structures to soft, translucent blobs, as most conventional motors, actuators and chassis used in robotics aren't designed to be see-through. To overcome this limitation, the team aimed to develop a new type of dielectric elastomer actuator (DEA) which would be both fully transparent and able to mimic the moon jellyfish's pulsating, rhythmic motions underwater.

"DEAs stand out among other soft actuation technologies; they're flexible polymers that can deform greatly under applied voltage," said Wang. "They also have high energy density, fast response times, low weights and quiet operations. Crucially, they can be made extremely thin—DEAs can comprise just a single dielectric membrane and two layers of compliant electrodes."

Wang and colleagues examined the ability of DEAs to form thin structures with smooth surface curvatures that minimise diffuse reflections. While other jellyfish-like soft robots have previously been developed using DEAs, these DEAs

Photo credit: vichailao / Freepik



The transparent soft jellyfish robot as designed by Wang and colleagues. When subjected to an electrical current, the artificial bell opens as the membrane deforms, mimicking a live jellyfish's movements.

> **"In future, a fully-contained soft robot driven by these transparent soft actuators could house power sources, electrical circuits, microcontrollers, cameras and sensors."**

typically use opaque materials like carbon grease for electrodes.

To create a transparent and highly conductive DEA, the team developed a novel hybrid compliant electrode that combines a conductive polymer, PEDOT:PSS/WPU, with silver nanowires—a popular component in flexible electronics. The researchers then used two layers of such hybrid electrodes—each layer a mere 1 μm thick—to sandwich a transparent dielectric membrane, then sealed the three layers with a waterproof silicone-based coating.

When the team applied voltage across the DEA, it expanded its area by up to 146 percent, while only exhibiting a three percent energy loss during cyclic actuation.

Using their DEA to construct a jellyfish robot, the researchers found that the robot's bell-shaped DEA 'body' could stretch and contract like a muscle. The robot was also capable of imitating the moon jellyfish's vertical and horizontal movements in water, and had an average visible light transmittance of 87 percent across its body; many transparent and translucent deep-sea animals have a range between 50 and 90 percent.

According to Wang, their biologically-inspired robot is a breakthrough in soft robotics that could invite new opportunities in stealthy underwater surveillance, environmental research and marine education. The robot's mimicry of natural biological movements not only improved its function, but also allowed the robot to integrate into aquatic environments.

"We plan to explore enhancements to soft robot durability and robustness," said Wang. "In future, a fully-contained soft robot driven by these transparent soft actuators could house power sources, electrical circuits, microcontrollers, cameras and sensors." ★

Researchers
Hui Huang and Yuzhe Wang, SIMTech

IN BRIEF
Using highly-transparent dielectric elastomer actuators with hybrid silver nanowire electrodes, researchers develop a soft jellyfish robot modelled after *Aurelia aurita* that is capable of biologically-versatile vertical and horizontal underwater movements.

1. Wang, Y., Zhang, P., Huang, H. and Zhu, J. Bio-inspired transparent soft jellyfish robot. *Soft Robotics* **10** (3), 590-600 (2023).

NEXT ISSUE

Here's a sneak peek of the material covered in the next issue of *A*STAR Research*

CHEMISTRY

RINGING IN PROTEIN REMEDIES

A novel approach for sequencing custom-built synthetic peptide rings opens up new drug discovery possibilities.

ENVIRONMENTAL SCIENCE

PLOTTING THE PATH OF FOREVER CHEMICALS

Using virtual simulations, researchers track and predict how chemicals used in everyday objects impact human health over time.

CHEMICAL ENGINEERING

MAGNESIUM BATTERIES OFFER A BOOST

An anode-free design for magnesium batteries proves more energy-dense than current lithium-based options, offering new solutions for next-generation energy storage.

OPTICAL MATERIALS

KEEPING 6G'S AIRWAVES ON COURSE

An intelligent metasurface design allows more refined steering of terahertz waves, paving the way towards seamless multi-user 6G communications.

Agency for
Science, Technology
and Research

SINGAPORE

www.research.a-star.edu.sg