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Technology and Innovation for Bioeconomy Transition in Asia and the Pacific



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Asian and Pacific Centre for Transfer of Technology



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ASIAN AND PACIFIC CENTRE FOR TRANSFER OF TECHNOLOGY
C-2, Qutab Institutional Area
Post Box No. 4575
New Delhi 110 016, India
Tel: +91-11-6901-3710
E-mail: apctt.techmonitor@un.org
Website: http://www.apctt.org

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Foreword

The transition towards a sustainable bioeconomy is gaining momentum across Asia and the Pacific as countries seek innovative solutions to address climate change and environmental degradation while creating new opportunities for sustainable economic development. By harnessing biological resources, technological innovation and circular approaches, the bioeconomy offers significant potential to support more resilient and resource-efficient economies.

This regional commitment was reinforced at the eighty-second session of the United Nations Economic and Social Commission for Asia and the Pacific (ESCAP) in April 2026, with the adoption of resolution 82/2, *"Supporting the transition towards a sustainable bioeconomy in countries in Asia and the Pacific."* The resolution underscores the importance of science, technology, innovation and regional cooperation in advancing a sustainable bioeconomy.

In line with this regional priority, the Asian and Pacific Centre for Transfer of Technology (APCTT) continues to promote technology transfer, knowledge exchange and capacity-building in this area. APCTT will convene an international conference on **"Technology and Innovation for Climate Resilient Agriculture and Bioeconomy"** in Changsha, China, in December 2026, providing a platform to exchange experiences and explore technological solutions for sustainable agricultural and industrial transformation.

Against this backdrop, the present issue of the *Asia-Pacific Tech Monitor* brings together four articles exploring different dimensions of the bioeconomy transition. The first examines innovation ecosystems for bio-based materials and circular business models in Bangladesh. The second assesses the potential of oil palm residues for bioenergy, carbon capture and sustainable aviation fuels in Southeast Asia. The third explores emerging microalgal technologies for biological carbon capture and industrial transformation. The final article examines intellectual property, genetic resource governance and commercialisation readiness, drawing on Australia's experience.

Together, these contributions highlight the importance of connecting technological innovation with supportive policies, effective technology transfer and regional cooperation. We believe this issue will provide valuable insights for all stakeholders and contribute to ongoing efforts to advance a sustainable and inclusive bioeconomy across Asia and the Pacific.

Preeti Soni
Head, APCTT

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Technology Market Scan

ASIA-PACIFIC

AUSTRALIA

ARENA backs domestic electrolyser manufacturing

The Australian Renewable Energy Agency (ARENA) has committed up to A$49 million to Hysata to establish an electrolyser manufacturing facility at Port Kembla, New South Wales. The A$98 million project, matched by private capital, is supported through ARENA's Future Made in Australia Innovation Fund.

The 8,500-square-metre facility will produce electrolysers and core components, including membranes and electrodes, with an initial capacity of 50 megawatts a year, scalable to 200 megawatts with round-the-clock operation. Hysata's capillary-fed electrolyser requires 41.5 kilowatt-hours of electricity per kilogram of green hydrogen, which the company reports is about 20 per cent more efficient than competing technologies.

Source: pv-magazine-australia.com

CHINA

Renewable energy plan targets 2030 expansion

The National Development and Reform Commission and the National Energy Administration released the 15th Five-Year Plan for Renewable Energy Development on 23 July 2026. The plan targets about 3.5 billion kilowatts of installed renewable capacity by 2030, including more than 2.8 billion kilowatts of wind and solar, with wind and solar supplying 30 per cent of national power generation.

At least 370 gigawatts of new capacity is to be built across seven major wind and solar bases in northern China between 2026 and 2030. Supporting measures include grid-forming inverters for new projects, concentrated solar power as long-duration storage, hybrid wind-solar-storage configurations and expanded inter-provincial transmission. Third-party estimates put industrial investment across the value chain at more than RMB 5 trillion (about $730 billion).

Source: pv-tech.org

INDIA

Cabinet approves Semicon 2.0 programme

The Union Cabinet approved Semicon 2.0 on 15 July 2026 with an outlay of Rs 1,27,500 crore, providing long-term policy support for the country's semiconductor sector. The programme has six components: chip design and intellectual property, semiconductor equipment and materials, fabrication plants (silicon, compound semiconductor and display), assembly, testing and packaging, research and development towards more advanced nodes, and talent development.

Under the first phase of the India Semiconductor Mission, 12 manufacturing units with a cumulative investment of Rs 1.64 lakh crore and 24 chip design projects have been approved, with the first fabrication plant expected to be commissioned in 2028. Training programmes have now reached 315 universities.

Source: pmindia.gov.in

INDONESIA

Five-layer strategy to build AI capacity

Indonesia aims to become a developer of artificial intelligence rather than merely a user, Deputy Minister of Communication and Digital Affairs Nezar Patria said in Yogyakarta on 13 August 2026. He outlined a

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five-layer approach to developing the national AI ecosystem covering energy, infrastructure, chips, talent and applications.

In the near term, the country is focusing on the application layer, adapting existing open-source foundation models through post-training to deliver solutions in health, agriculture and education. Over the longer term, Indonesia intends to use its critical mineral reserves and industrial down streaming to integrate into global semiconductor supply chains. The ministry is drafting a National Roadmap for AI Development to strengthen regulation, encourage cross-sector collaboration and attract investment across all five layers.

Source: en.antaranews.com

JAPAN

Plan for sovereign AI and robots

The Government of Japan has adopted a strategy to develop a home-grown AI model and deploy 10 million AI-equipped robots across 18 sectors by 2040, as part of efforts to address labour shortages caused by an ageing and shrinking population. Around $6 billion will be directed to developing a domestic AI model through Noetra, a consortium that includes SoftBank and Sony, with about 44 companies expected to participate.

The strategy focuses on 'physical AI' — the application of AI in autonomous vehicles, factory robots and service robots — across sectors ranging from automotive and electronics to logistics, food manufacturing and medical services.

Source: thestar.com.my

MALAYSIA

Solar tender mandates battery storage

The Ministry of Energy Transition and Water Transformation launched the sixth round of the Large Scale Solar programme (LSS6), seeking 2.65 gigawatts of solar photovoltaic capacity, of which 2.5 gigawatts is to be co-located with 1.25 gigawatts of battery energy storage. The tender is divided into three packages, with bidding held in July and August 2026 and commercial operation required by the end of 2029.

Source: energy-storage.news

PAKISTAN

Space Centre advances, security framework approved

Pakistan's Central Development Working Party cleared the Rs 37 billion Pakistan Space Centre project on 6 August 2026 and referred it to the Executive Committee of the National Economic Council (ECNEC) for final approval. The Centre aims to build domestic capacity for satellite design, assembly, integration and testing.

In August, the federal cabinet approved the Pakistan Information Security Framework 2026, establishing unified baseline security standards with central oversight. The Minister for Information Technology also announced a target of $25.1 billion in information and communications technology exports by 2030.

Source: fnpk.org

PHILIPPINES

First offshore wind auction rescheduled

The Department of Energy has set a new timeline for the country's first offshore wind auction, the fifth round of the Green Energy Auction Programme (GEA-5), which offers 3.3 gigawatts of fixed-bottom

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offshore wind capacity. The auction was suspended on 4 July 2026 and is now indicatively scheduled for 1 December 2026, with post-auction processes to be completed by 30 June 2027.

The recalibration aims to align the auction framework with infrastructure readiness, permitting requirements, port and environmental costs, grid connection and potential supply chain disruptions. Projects are expected to begin operations between 2028 and 2030.

Source: offshorewind.biz

REPUBLIC OF KOREA

Fund to build sovereign frontier AI

The Ministry of Science and ICT announced on 8 September 2026 that it will invest 4.7 trillion won ($3.49 billion) to develop a domestically built frontier AI model comparable to leading global systems. The investment will be managed through an independent fund and will form part of the ministry's 9.4 trillion won AI budget request for 2027.

Minister Bae Kyung-hoon stressed the need for a sovereign frontier model to preserve technological independence amid intensifying global competition in AI. Detailed project arrangements are yet to be finalised.

Source: koreaherald.com

THAILAND

Committee to govern data centre growth

The Cabinet approved the establishment of a Data Centre Business Policy Committee on 5 August 2026. The committee will propose policies, standards and approval frameworks for data centre operations and assess their impact, taking into account the economy, clean energy use, energy security, electricity and water efficiency, urban planning and public safety.

Thailand currently has no dedicated data centre legislation, and the new committee signals closer government oversight of a sector that has attracted substantial investment amid rising demand for AI computing.

Source: bakermckenzie.com

VIET NAM

Digital transformation laws take effect

Three laws governing the digital economy entered into force on 1 July 2026. The Law on Digital Transformation provides the legal foundation for digital infrastructure, data governance, AI adoption and digital government. The Law on Cybersecurity, which consolidates and replaces two earlier laws, strengthens security and data governance obligations for organisations operating digital systems and online services.

The new Law on E-commerce updates rules for online marketplaces, cross-border digital trade, platform responsibilities and consumer protection, providing greater regulatory certainty for technology businesses operating in the country.

Source: vietnam-briefing.com

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Technology Scan

AUSTRALIA

Solar sleeve powers telecom towers

Victorian infrastructure services firm Decon Corporation has completed a trial of flexible solar laminate wrapped around a telecommunications monopole, in partnership with Australia's National Broadband Network (nbn). The lightweight, bendable panels were fitted to the north-facing side of a 40-metre fixed wireless tower at New Gisborne in the Macedon Ranges, about 60 kilometres north-west of Melbourne, using the company's patented mounting system.

During daylight hours, the installation can meet up to 40 per cent of the site's power demand, depending on weather conditions. Combined with battery storage and energy-saving measures, the system can keep the site running for up to 12 hours during a grid outage, maintaining connectivity for local communities. nbn stated that it will continue to evaluate the solution's performance and explore wider use of such technologies to strengthen network resilience.

Source: pv-magazine-australia.com

CHINA

Optical interconnect speeds up AI inference

Researchers at Peking University have developed an all-optical interconnect system that links standard electronic chips and combined with purpose-designed algorithms, accelerates distributed artificial intelligence (AI) inference by more than 100 times while using only about one-ninth of the usual computing resources.

The work, led by Dr Shu Haowen and Professor Wang Xingjun and published in National Science Review, connects field-programmable gate array (FPGA) chips through silicon photonic transceivers. The approach offers an alternative to the prevailing strategy of adding ever more graphics processors and building larger data centres, pointing to AI systems that deliver greater performance with lower energy and hardware demands.

Source: scmp.com

LONGi sets silicon cell efficiency record

Chinese solar manufacturer LONGi Green Energy Technology has achieved a certified conversion efficiency of 28.29 per cent for a single-junction crystalline silicon solar cell, a new world record verified by Germany's Institute for Solar Energy Research Hamelin (ISFH). The result improves on the 28.13 per cent record the company set earlier in 2026 and is its third world record of the year.

The hybrid interdigitated back-contact (HIBC) cell places both positive and negative contacts on the rear of a half-cut M10 wafer, eliminating front-side shading. Improvements include advanced surface passivation, reduced doping in the contact layers, edge passivation and laser-based crystallisation of amorphous silicon. The company reports that crystalline silicon cell efficiency has now reached 96.2 per cent of its theoretical limit, and that the technology could be adapted to heterojunction mass production.

Source: pv-magazine.com

INDIA

Low-cost reactor removes arsenic, fluoride

Researchers at the Indian Institute of Technology (IIT) Guwahati have developed a water treatment reactor that removes arsenic and fluoride from contaminated groundwater at the same time

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— two pollutants that are difficult to treat together because they compete for removal sites in conventional processes.

The rotating-anode electrocoagulation reactor replaces the stationary aluminium electrode used in standard systems with a rotating one. The rotation improves mixing, continuously renews the electrode surface and promotes the formation of aluminium hydroxide flocs that capture both contaminants. In tests, including with real groundwater samples from Assam, the system removed up to 98.2 per cent of arsenate and 91.8 per cent of fluoride within minutes, at an estimated operating cost of Rs 18–58 per 1,000 litres.

The research, led by Professor Mihir K. Purkait with research scholar Mukesh Bharti, was published in the Chemical Engineering Journal. The team is now developing a pilot-scale, continuous-flow version with sensor-based automated control for deployment in rural and community water systems.

Source: aninews.in

Nickel catalyst for affordable green hydrogen

A team at IIT Guwahati has developed a low-cost catalyst for producing hydrogen from water that could support India's National Green Hydrogen Mission. The catalyst is a coordination polymer made from an inexpensive nickel salt and an anthracene-based organic molecule, synthesised at room temperature using ultrasonic waves.

The material forms a three-dimensional network in which nickel atoms are linked through the organic framework, creating a high density of active sites and efficient electron transport for the hydrogen evolution reaction. It achieved nearly 88 per cent electrical energy efficiency in water splitting and showed long-term stability, offering an alternative to costly noble-metal catalysts. The study, led by Associate Professor Akshai Kumar, was published in the Journal of Materials Chemistry A.

Source: wionews.com

JAPAN

Magnetic braking tested for spacecraft reentry

Researchers at Tokyo Metropolitan University have built a laboratory system to test magnetohydrodynamic aerobraking, a technique that uses strong magnetic fields to manipulate the ionised gas around a spacecraft during high-speed atmospheric reentry. The approach could reduce heating and increase drag, supporting reusable spacecraft that are less dependent on conventional heat shields.

The team, led by Associate Professor Kohei Shimamura, integrated a pulsed electromagnet into an expansion tube and fired shockwaves at about 7.7 kilometres per second at miniature spacecraft models. The electromagnet generated fields of up to 1.58 tesla — 1.7 to 2.1 times stronger than earlier tests with permanent magnets — and expanded the shock layer by around 16 per cent. The findings were published in the Journal of Spacecraft and Rockets.

Source: thebrighterside.news

Atomic steps guide superconducting vortices

Scientists at the National Institute for Materials Science (NIMS) have found that atomic-scale steps on the surface of ultrathin superconductors can act as rails that guide superconducting vortices — tiny whirlpools of electrical current whose uncontrolled motion causes energy loss. The vortices moved more than 1,000 times more easily along the steps than across them.

Using electrical measurements and scanning tunnelling microscopy, the team led by Takashi Uchihashi showed that the guiding effect can be tuned through temperature and magnetic field. The results, published in Physical Review B, open a route to ultralow-power superconducting devices with more precise control of current and heat flow.

Source: eurekalert.org

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REPUBLIC OF KOREA

Molecular network filters clean hydrogen

Researchers at the Korea Advanced Institute of Science and Technology (KAIST) have developed a polymer membrane that separates hydrogen from mixed gases with high efficiency, addressing a key obstacle to the wider use of clean hydrogen. The team linked polymer chains with modular crosslinkers to form a highly connected internal network containing pores smaller than three ångströms — large enough for hydrogen but too small for carbon dioxide.

To measure how completely the network is connected, the researchers introduced a new metric, the bridge connectivity degree. Their membrane reached 73 per cent on this metric and showed markedly higher hydrogen permeability and selectivity than the starting material. The study, led by Professor Tae-Hyun Bae, was published in Nature Communications.

Source: miragenews.com

SINGAPORE

Carbon fibre waste turned into aerogels

Engineers at the National University of Singapore (NUS) have developed a method to recycle carbon fibre epoxy composite waste — widely used in aircraft, vehicles and wind turbines but difficult to recycle — into lightweight aerogels. Unlike existing approaches that recover only the carbon fibres, the process makes use of both the fibres and the epoxy.

The waste is mechanically ground into fine powder and short fibres, mixed with a cellulose-based binder and freeze-dried to create a sponge-like material with interconnected pores. The resulting aerogels provide thermal insulation and sound absorption and, when treated to repel water, can absorb large quantities of oil for spill clean-up. The research, led by Associate Professor Duong Hai Minh and published in Waste Management, is now being pursued with industry partners to assess scale-up.

Source: cde.nus.edu.sg

EUROPE

FRANCE

First photonic time crystal controls light

Physicists at École Polytechnique, working with the Collège de France and Germany's Helmholtz-Zentrum Dresden-Rossendorf (HZDR), have created the first all-optical photonic time crystal — a material whose optical properties are switched rapidly and repeatedly in time, allowing unprecedented control over light.

The team, led by Assistant Professor Yannis Laplace, built a metamaterial of micrometre-scale gold structures on an indium antimonide semiconductor and modulated it with intense terahertz pulses. This altered the material's optical response within trillionths of a second and reduced trapped light loss by about half. Published in Nature, the result could lead to new terahertz lasers, amplifiers and signal-processing technologies for future communication systems.

Source: polytechnique.edu

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NORTH AMERICA

UNITED STATES OF AMERICA

Solar desalination without harmful brine

Researchers at the University of Rochester have developed a solar-powered desalination system that produces fresh water while collecting salt as a solid, avoiding the concentrated brine that conventional plants discharge into the sea. The team, led by Professor Chunlei Guo, used femtosecond lasers to etch microscopic structures into black metal panels, causing water to spread rapidly across the surface as sunlight evaporates it.

Salt deposits are directed to the edges of the panel, keeping the active surface clean. Tests with seawater from the Pacific, Atlantic and Indian Oceans achieved near-complete solid salt extraction, while trials with water from the Great Salt Lake recovered about half of its lithium. The work was published in Light: Science & Applications and the Journal of Materials Chemistry A.

Source: sciencedaily.com

Durable catalyst cuts fuel cell platinum

Engineers at Washington University in St. Louis have developed a fuel cell catalyst that uses minimal platinum while remaining highly durable, which could help hydrogen fuel cells supply power to energy-intensive data centres and vehicles. The team designed hollow carbon spheres with ordered radial nanochannels that hold platinum–cobalt particles below five nanometres in size, even when heated to 1,000°C to form a highly ordered atomic structure.

The catalyst retained 85 per cent of its performance after 150,000 demanding voltage cycles, equivalent to roughly 25,000 hours of operation. The research, led by Professor Gang Wu, was published in Nature Nanotechnology.

Source: source.washu.edu

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Technology and Innovation for Bioeconomy Transition in Asia and the Pacific

Innovation Ecosystems for the Bioeconomy Transition: Bioplastics, Reuse Models and Circular Start-up Systems in Bangladesh

H.M.L.C. Jayawardhana[a,*], Rana Pratap Singh[b], Sattya Ranjan Bhattacharjee[a], Gubair Bin Arafat[a], Md Mahobul Islam[a], Adriana Grigoriu[b], Ramisa Rahman[a], Md Shahidul Islam[a]

Project Team – "Integrated Approach Towards Sustainable Plastics Use and Marine Litter Prevention in Bangladesh"

[a] United Nations Industrial Development Organization (UNIDO), Dhaka, Bangladesh

[b] United Nations Industrial Development Organization (UNIDO), Vienna, Austria

[a*] Corresponding author. E-mail: lashanjaya@yahoo.com

Abstract

Asia-Pacific's transition to a sustainable bioeconomy requires greater attention to plastics as a fossil-dependent material system. Using Bangladesh as an emerging industrial case, this article examines how bio-based materials and reuse models can support wider industrial transformation. It argues that progress depends on innovation ecosystems that connect technology development, transfer, demonstration, finance and market adoption. Four pathways are considered: bio-based materials and industrial biotechnology, reuse and refill business models, Plastic-Tech hubs for testing and commercialisation, and finance for start-ups and small enterprises. The article also considers digital tools and regional cooperation as supporting mechanisms. Bangladesh's experience reflects a broader Asia-Pacific challenge: renewable feedstocks and technical ideas are increasingly available, but the facilities, partnerships and financing needed to turn them into reliable products remain limited. Regional progress will hinge on strengthening the practical systems through which technologies are adapted, tested, financed and adopted by industry.

Keywords: bioeconomy; bioplastics; technology transfer; reuse systems; commercialisation; innovation finance; Bangladesh; Asia-Pacific

1. Introduction: Plastics and the Bioeconomy Transition

Bioeconomy policy in Asia-Pacific has largely centred on agriculture, food systems, forestry and renewable energy. Materials deserve equal attention. Plastics are embedded in packaging, manufacturing, healthcare, construction, agriculture and consumer markets, yet most remain dependent on fossil feedstocks. Their environmental effects are well recognised (UNEP, 2023; OECD, 2022). The industrial question is less often addressed: how can economies reduce fossil dependence without sacrificing product performance, affordability or productive capacity?

This perspective places plastics within industrial transformation rather than treating them solely as a waste problem. It directs attention to feedstocks, processing technologies, product design and business viability, while recognising that alternative materials must compete within established supply chains and demanding consumer markets.

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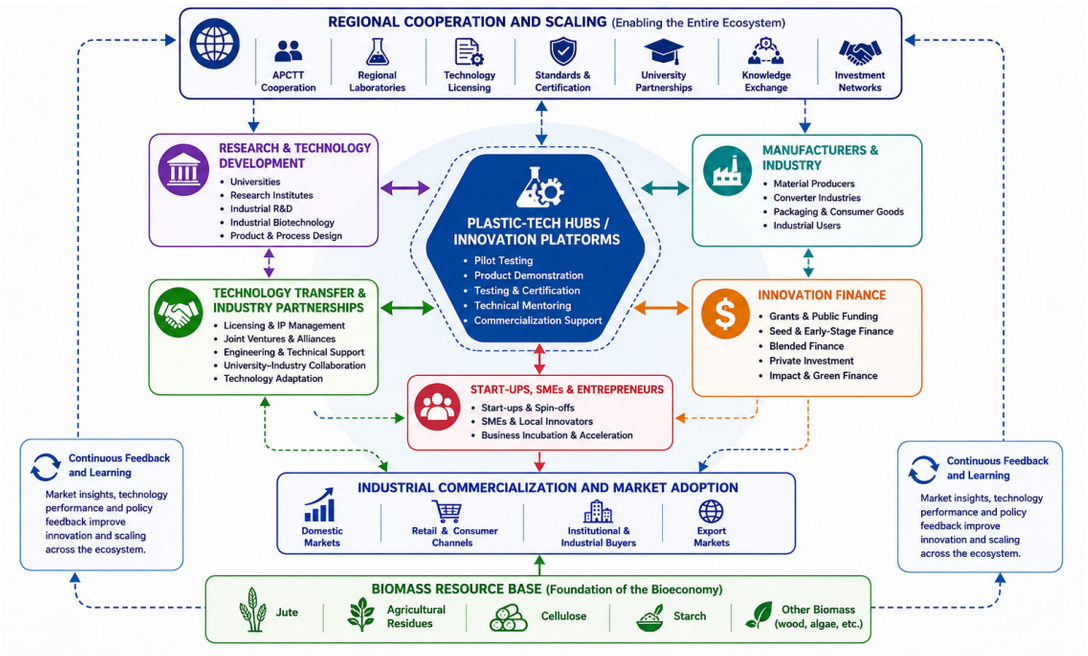


Figure 1: Innovation ecosystem for bioeconomy transition and commercialisation in Asia-Pacific

Innovation ecosystems connect renewable biomass with industrial commercialisation through research, technology transfer, finance and regional collaboration.

The transition to a sustainable bioeconomy will depend not only on renewable feedstocks but also on the capacity of countries to convert biological resources into competitive industrial materials. For plastics, this involves material science, industrial biotechnology, manufacturing capability and new business models. Reuse also belongs within this agenda because it changes how packaging is designed, circulated and retained in use.

In this article, an innovation ecosystem refers to the network of research institutions, technology providers, enterprises, investors and support platforms that enables new materials and production models to move from development to commercial application. Figure 1 sets out this ecosystem, showing how research, technology transfer, pilot testing, finance and market adoption connect around Plastic-Tech hubs and regional cooperation to reduce technical and commercial risk while supporting industrial adoption across Asia-Pacific economies.

This challenge is common across Asia-Pacific: India, Indonesia, Viet Nam and Malaysia each combine different strengths in biotechnology, natural fibres, manufacturing scale and research–industry links, yet all face similar constraints in linking scientific capability with production, testing, finance and market demand. Bangladesh reflects the same regional pattern. Its jute, starch resources, agricultural residues and manufacturing experience provide a credible base for selected bio-based products, but limited demonstration facilities, technical services and early-stage finance continue to restrict scale.

Public policy can support this process through standards, shared facilities, research partnerships and measures that reduce early technical risk. It cannot compensate for weak product performance or absent demand. The focus of this article is therefore on practical systems that improve technology uptake rather than on broad governance arrangements.

Four pathways follow: bio-based materials and industrial biotechnology; reuse and refill systems as business innovation; Plastic-Tech hubs for testing and commercialisation; and finance for start-ups and small enterprises. Digital tools and regional cooperation are treated as supporting mechanisms. Bangladesh is used as an illustrative industrial case, while the wider purpose is to identify lessons for Asia-Pacific economies seeking competitive bio-based industries.

2. Bangladesh's Opportunity for Bio-Based Material Innovation

Across Asia-Pacific, agricultural fibres, starch crops, forestry products and food-processing residues provide a substantial resource base for bio-based materials. These feedstocks can support packaging, composites, coatings, films and other industrial products. Their value, however, varies by application. Material quality, seasonal availability, transport costs and compatibility with existing production systems all influence whether a resource can support a viable industry.

Bangladesh offers a useful illustration of this wider opportunity. Jute is its most established advantage. The country has longstanding experience in cultivation, fibre processing and product manufacture, together with a workforce and industrial base familiar with the material. Higher-value uses may include reinforced composites, moulded products and selected packaging applications in which low weight, renewable content and mechanical strength are commercially relevant. These products are unlikely to replace conventional polymers across all uses, but they may compete in defined market segments when quality, design and cost are properly controlled (Pickering et al., 2016).

Rice residues, sugarcane by-products, starch-bearing crops and cellulose from agricultural processing broaden the range of possible applications. Films, coatings, fillers and selected biodegradable materials are among the more relevant options. Yet commercial planning must begin with a realistic assessment of feedstock quality and supply. Moisture, contamination, seasonal fluctuations and collection costs can affect processing efficiency and product consistency. Broad estimates of biomass availability are therefore less useful than detailed evaluation of the feedstock required for a specific product (FAO, 2024; Lokko et al., 2018).

Industrial demand is equally important. Bangladesh's packaging, textile, food-processing and consumer-goods sectors could provide early users of bio-based materials. Existing firms understand production costs, machinery constraints and buyer requirements, while smaller enterprises can respond quickly to specialised demand. Their contribution will depend on access to engineering support, testing services and appropriately scaled production equipment rather than on the creation of entirely new industrial structures (Asian Development Bank, 2022).

Comparable opportunities exist across the region. India combines agricultural resources with stronger biotechnology and polymer research, although many products continue to face cost and scale constraints. Indonesia has abundant natural fibres and residues, but conversion into industrial materials depends on more reliable links between suppliers, processors and manufacturers. Viet Nam's export-oriented industries create demand for materials that meet international technical and buyer requirements, giving testing and certification particular importance. Malaysia's investment in biotechnology and research–industry collaboration shows how sustained technical support can help firms move into higher-value markets (OECD, 2021; ESCAP, 2022).

These cases point to different national strengths rather than a single model. India offers deeper scientific capacity, Indonesia a broad agricultural resource base, Viet Nam strong manufacturing links and Malaysia more developed biotechnology support. Bangladesh's comparative advantage lies in jute, selected agricultural feedstocks and an established manufacturing sector. The practical task is to match those assets with product categories in which they can compete.

Market choice should also reflect end-of-life conditions. A material described as biodegradable may offer limited benefit where industrial composting or separate treatment is unavailable. Producers should therefore assess performance, cost and disposal conditions together before making environmental claims.

Focused value chains offer the most credible route forward. Bangladesh and other emerging Asia-Pacific economies are more likely to succeed by selecting a limited number of materials and applications, building dependable supply arrangements and proving their value in real industrial markets than by attempting to develop every available bio-based technology.

3. Bioplastics, Industrial Biotechnology and Technology Transfer

Bio-based plastics are frequently described as a single solution, although they represent a diverse group of materials with different feedstocks, production methods and performance characteristics. Some are manufactured partly or entirely from renewable biological resources, while others are designed to biodegrade under specific conditions. These distinctions matter because industrial adoption depends on product performance, manufacturing compatibility, production cost and end-of-life management rather than on feedstock origin alone (UNEP, 2023; European Bioplastics, 2024).

3.1 Local Material Pathways

Agricultural economies across Asia-Pacific already possess several feedstocks suitable for bio-based materials. Four pathways are particularly relevant. Jute can support reinforced composites and selected packaging products. Cellulose recovered from agricultural processing offers opportunities for films, coatings and fibre-based packaging. Starch can be used in bags, liners and other products where functional requirements remain modest. Agricultural residues can provide fillers or reinforcing materials in composite applications.

These pathways differ in commercial readiness. Jute composites already serve established industrial markets, whereas cellulose-based films and some starch-derived materials require further product development and testing. No single material is likely to replace conventional plastics across every application. Selection should therefore be guided by product performance, processing requirements, cost and market demand rather than by the expectation of a universal substitute (Pickering et al., 2016; Klemm et al., 2018).

3.2 Industrial Biotechnology Requirements

Industrial biotechnology provides the production systems that convert biological feedstocks into consistent industrial materials. Fermentation processes generate platform chemicals for polymer production, enzyme technologies improve feedstock conversion, and integrated biorefineries increase resource efficiency by producing several valuable products from the same biomass stream (Cherubini, 2010; Koutinas et al., 2014).

Scientific discovery alone is not sufficient for industrial success. Technologies must operate reliably beyond the laboratory, using variable agricultural feedstocks while maintaining consistent product quality. For many emerging economies, scaling production at competitive cost matters more than developing entirely new scientific breakthroughs (Lee et al., 2019; UNIDO, 2022).

Applied technical capacity therefore deserves priority. Firms need access to pilot-scale processing, material compounding and performance testing so that products can be evaluated under realistic manufacturing conditions. These facilities reduce technical uncertainty before substantial private investment is committed.

3.3 Technology Transfer Mechanisms

Many Asia-Pacific economies will continue to obtain bio-based technologies through international collaboration rather than domestic invention alone. Licensing agreements provide access to proven production methods. Joint ventures combine external technologies with local manufacturing capability. University–industry partnerships support product adaptation, technical testing and workforce development. Each pathway can shorten the time required to introduce new materials into commercial production.

Effective technology transfer extends beyond equipment purchase. Imported production systems deliver little value unless firms can adapt them to local feedstocks, manufacturing conditions and market requirements. Technical training, product testing and engineering support should therefore accompany any transfer arrangement so that technologies can be modified and operated successfully under local conditions (UNCTAD, 2023; ESCAP, 2022).

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Testing and certification play an equally important role. Manufacturers and buyers require confidence that new materials satisfy performance, quality and safety requirements before they are incorporated into production systems. Shared laboratories and regional testing facilities can provide these services more efficiently than duplicating specialised infrastructure in every country — a point developed further, alongside the role of the Asian and Pacific Centre for Transfer of Technology (APCTT), in Section 7.

Bangladesh illustrates this broader regional challenge. Technologies suited to jute, cellulose and starch-based materials are already available internationally, but successful adoption depends on combining technology partnerships with domestic engineering capability, pilot testing and product development. Industrial capability is created when imported knowledge is adapted to local production systems and accepted by manufacturers.

4. Reuse and Refill Systems as Business Innovation

Bio-based materials reduce dependence on fossil feedstocks by changing what products are made from. Reuse addresses the same objective by changing how products are delivered. Rather than producing a new package for every sale, reuse systems keep containers in circulation through repeated collection, cleaning and redistribution. Their success depends less on new materials than on efficient business operations.

Returnable beverage bottles and transport packaging have operated successfully for many years across Asia-Pacific. Bangladesh also retains formal and informal systems in which glass bottles, crates and other containers circulate between distributors, retailers and consumers. These established practices demonstrate that reuse is not a new concept. The commercial challenge is to adapt familiar models to modern retail formats, higher product safety standards and increasingly complex supply chains.

Packaging design is central to business performance. Containers must withstand repeated handling, transport and washing without losing quality. Standardised designs can lower costs because different producers or retailers can use the same collection and cleaning systems. Deposit-return arrangements can improve recovery rates when the financial incentive is sufficient to encourage returns while remaining convenient for customers.

Efficient reverse logistics determines whether reuse remains commercially viable. Delivery vehicles can collect empty containers during return journeys, while retailers or wholesalers can serve as collection points. Urban markets often provide the greatest opportunity because transport distances are shorter and container turnover is faster. Successful systems are therefore designed around existing distribution networks rather than copied directly from other countries (Ellen MacArthur Foundation, 2019; OECD, 2020).

Ownership of reusable packaging can also shift from product manufacturers to specialised service providers. Companies responsible for container supply, cleaning and redistribution recover their investment through repeated circulation rather than one-time sales. This approach reduces the capital burden on producers, particularly smaller firms that cannot justify dedicated return systems.

Regional experience illustrates the flexibility of this business model. Indonesia has expanded refill systems for household products through retail networks. India is testing reusable packaging across several consumer-product sectors. Thailand has promoted reuse as part of its broader Bio-Circular-Green (BCG) Economy Model (UNEP, 2021; Asian Development Bank, 2025; Royal Thai Government, 2023).

Bangladesh's most practical opportunities are likely to involve products with frequent purchasing cycles, stable distribution channels and limited packaging variation, including beverages, household products and business-to-business transport packaging. Decisions should be guided by operating costs, return rates, washing requirements and customer convenience. Where these conditions are favourable, reuse can complement bio-based materials by lowering demand for single-use packaging while creating commercially viable service models.

5. Plastic-Tech Hubs and Commercialisation Pathways

Many promising material technologies do not fail because of weak science. They fail because they cannot progress from laboratory results to reliable industrial production. Manufacturers need evidence that a new material can be produced consistently, comply with standards, operate on existing

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Table 1: From laboratory research to market adoption

Stage	Main actors	Principal challenge
Research	Universities and research institutions	Applied funding and user relevance
Prototype	Start-ups and technology developers	Technical validation
Pilot testing	Industry partners and pilot facilities	Production reliability and cost
Certification	Testing laboratories and standards bodies	Performance and safety verification
Commercialisation	Firms, buyers and investors	Market acceptance and investment risk
Scaling	Manufacturers and finance providers	Demand, working capital and production expansion

equipment and satisfy market requirements. Generating that evidence requires facilities, technical expertise and commercial support that many universities and small enterprises cannot provide on their own.

Plastic-Tech hubs are innovation platforms that combine laboratories, pilot facilities, testing services, entrepreneurship support and industry partnerships for sustainable material technologies. They are not regulatory institutions. Their purpose is to provide practical services that reduce technical uncertainty and help promising technologies progress towards commercial production.

Commercialisation follows a sequence in which each stage presents a different challenge. Research generates new ideas but must remain connected to industrial demand. Prototypes demonstrate technical feasibility. Pilot production confirms whether a process performs reliably under realistic operating conditions. Certification establishes compliance with recognised standards, while commercialisation and scaling depend on customer confidence, investment and production capability.

Early industrial involvement makes research more valuable. Material developers need to understand manufacturing requirements, processing conditions and market expectations before technologies reach the pilot stage. Regular interaction with manufacturers helps direct research towards applications with realistic commercial potential rather than technically successful products that lack industrial demand.

Pilot facilities provide the critical bridge between research and manufacturing. Small production runs allow engineers to refine formulations, optimise processing conditions and evaluate performance before large investments are made. For bio-based materials, pilot testing can identify practical issues such as feedstock variability, moisture sensitivity, colour consistency and equipment compatibility that are rarely evident under laboratory conditions. Reliable pilot data also reduces technical risk for manufacturers and investors (UNIDO, 2022; Lokko et al., 2018).

The next stage of commercialisation is testing and certification. Packaging, construction materials and consumer products must demonstrate compliance with recognised performance and safety standards before entering the market. Independent testing increases buyer confidence and supports access to domestic and export markets. Plastic-Tech hubs should therefore work through existing accredited laboratories and standards organisations rather than establishing parallel certification systems (UNEP, 2023).

Practical business support matters just as much. Start-ups and technology developers often require assistance with product costing, intellectual property management, licensing, customer trials and supplier relationships. Technical mentoring and industry partnerships are generally more valuable than generic business training because they address the operational barriers that determine whether a technology reaches commercial production.

These services do not require new institutions to work in Bangladesh's case. Existing universities, engineering centres, industrial clusters and sector-specific research organisations could provide complementary facilities linked through a coordinated service network. This distributed approach would make better use of existing expertise while limiting new infrastructure costs.

Not every innovation should receive the same level of support. Pilot facilities and commercialisation services should concentrate on technologies that demonstrate technical feasibility, reliable feedstock supply, clear market demand and a realistic pathway to standards compliance. Careful project selection allows limited resources to produce stronger commercial outcomes.

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Commercialisation also benefits from regional collaboration, since neighbouring economies hold complementary strengths in biotechnology, manufacturing and testing that Section 7 examines in more detail. Shared access to specialised facilities, technical expertise and industrial partnerships can reduce costs and accelerate market entry for emerging technologies. Progress should be measured by successful pilot trials, certified products, technology licensing, industrial adoption and investment mobilised rather than by the number of participating organisations.

Plastic-Tech hubs therefore perform a practical function within the innovation ecosystem. They help transform promising research into technologies that manufacturers, investors and customers are prepared to adopt with confidence.

6. Financing Innovation and Start-up Growth

Successful commercialisation depends as much on appropriate finance as on good technology. An unproven bio-based material, refill service or pilot production line rarely fits conventional bank lending because technical uncertainty remains high and commercial returns have yet to be demonstrated. At the same time, grant funding alone cannot support long-term industrial growth. As a result, financing needs to evolve with the maturity of the technology, combining public support during early development with increasing private investment as technical and commercial risks decline.

A staged financing approach reflects this progression. Research grants help establish proof of concept and applied experimentation. Seed finance enables start-ups to refine prototypes, recruit technical expertise and engage potential customers. Concessional finance and matching grants support pilot production where technical feasibility has been demonstrated but commercial risks remain significant. Blended finance can reduce investment risk during demonstration, while impact investors, corporate venture funds and private capital become more appropriate once products have entered the market (OECD, 2023; Asian Development Bank, 2024).

Selecting projects is as important as providing finance. Funding decisions should consider technical feasibility, market demand, feedstock availability, progress towards certification and the capability of the development team. Linking financial support to agreed milestones—such as prototype completion, successful pilot production or verified customer trials—helps direct resources towards technologies that continue to demonstrate commercial potential while maintaining accountability for public investment.

The largest financing gap in many emerging economies occurs between successful laboratory research and commercial production. Pilot equipment, testing, engineering services and customer validation require substantial investment, yet commercial lenders often regard these activities as too risky. The pilot facilities described in Section 5 lower these costs, but enterprises still need finance to complete demonstration, product testing and early market development. Combining concessional loans, matching grants and industry contributions offers a practical way to spread these costs (UNIDO, 2022).

Once technical performance has been demonstrated, many enterprises face a different challenge: financing production and market expansion. Working capital is often needed to purchase raw materials, fulfil orders and manage payment delays. Credit guarantees, purchase-order finance and supplier credit can be more valuable at this point than additional research grants. Public procurement can also support early demand where products meet recognised performance and value-for-money requirements.

Table 2: Financing pathways for bioeconomy innovation

Stage	Main financing source	Primary purpose
Research	Public grants and university funds	Proof of concept and applied research
Prototype	Seed funding and accelerator support	Product refinement and validation
Pilot	Concessional finance and matching grants	Testing under realistic conditions
Demonstration	Blended finance and strategic partnerships	Reducing risk before market entry
Commercialisation	Impact investment and corporate venture funds	Initial market expansion
Scaling	Private capital and working-capital facilities	Production and market growth

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These financing needs are not unique to Bangladesh. Small and medium enterprises across many Asia-Pacific economies require modest financial instruments linked with technical mentoring, market access and commercialisation support rather than large stand-alone funding programmes. Larger manufacturers, in contrast, are more likely to invest when pilot results, testing data and customer demand have already reduced commercial uncertainty.

Finance is most effective when it operates alongside commercialisation services. Investors gain confidence when technologies have passed credible testing, received technical mentoring and established links with industrial partners. Funding mechanisms should therefore work closely with Plastic-Tech hubs, accelerators and industry associations so that capital becomes available when technologies are ready to progress to the next stage of development.

7. Digital Technologies and Regional Cooperation

Digital technologies can strengthen bioeconomy innovation by making technologies, expertise and markets easier to access. Their greatest value lies in supporting technology transfer and commercialisation rather than becoming objectives in themselves. For most Asia-Pacific economies, practical digital tools that reduce information gaps are likely to deliver greater benefits than highly sophisticated systems that are costly to establish and maintain.

Technology databases can help enterprises identify available production processes, equipment suppliers, testing laboratories, certification services and licensing opportunities. This is particularly valuable for small and medium enterprises that lack dedicated research and development capacity. Regional platforms can also provide information on technology readiness, feedstock requirements and potential industrial partners, allowing firms to assess suitable options before committing significant investment.

Digital product passports and QR-based traceability systems can improve transparency across material value chains by recording feedstock origin, material composition, certification status and recommended applications. Similar technologies can support inventory management and container tracking in reuse and refill systems. Simple, interoperable data standards and low-cost digital identifiers are likely to be more practical for emerging economies than complex proprietary platforms requiring extensive maintenance (ESCAP, 2024; UNIDO, 2022).

Artificial intelligence and material informatics can assist with feedstock screening, material design and performance prediction, but they remain supporting technologies rather than primary drivers of industrial transformation. Their effectiveness depends on reliable datasets, technical capability and continued investment in research. For many emerging economies, immediate gains are more likely to come from improving digital access to technical knowledge, testing facilities and industrial networks than from advanced automation alone (Lee et al., 2019; OECD, 2023).

Few countries need to develop every capability independently, which is where regional cooperation can do the most good. Shared laboratories for polymer characterisation, biodegradation assessment and food-contact testing can reduce investment costs while improving access to specialised expertise. Mutual recognition of testing and certification can lower barriers to regional trade, and university partnerships, technology licensing and collaborative research can accelerate technology adaptation and workforce development.

The region already demonstrates complementary strengths. Thailand has advanced bio-based materials through its BCG Economy Model. Malaysia has strengthened biotechnology and research–industry collaboration. India combines scientific capability with a large domestic market, while Viet Nam provides strong manufacturing links to regional supply chains. Bangladesh contributes expertise in natural-fibre products together with an established manufacturing base that can support wider regional value chains (Royal Thai Government, 2023; ESCAP, 2024).

APCTT can strengthen these regional connections through technology databases, expert networks, technology matching and collaboration between research institutions and industry. The practical objective is straightforward: enable enterprises to identify appropriate technologies, connect with technical partners, obtain testing and certification services, and reach regional markets more efficiently. Regional cooperation is most valuable when it shortens the path from promising innovation to commercial adoption.

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8. Conclusion

The transition to a sustainable bioeconomy is, at bottom, an industrial transformation rather than solely an environmental objective. Bio-based polymers, natural-fibre composites and reuse systems can reduce dependence on fossil resources while creating new manufacturing and business opportunities. Their success, however, depends less on the availability of biomass than on the ability of firms to develop products that satisfy technical standards, compete in the marketplace and operate reliably at commercial scale.

Bangladesh illustrates a broader Asia-Pacific challenge. Many emerging economies possess renewable feedstocks, established manufacturing sectors and growing technical capability, yet they continue to face similar barriers. Technology development often remains disconnected from industrial demand. Pilot and testing facilities are limited, technology transfer is uneven, and financing is rarely aligned with the stages of commercialisation. These constraints slow the movement of promising innovations from research to competitive production.

The experience discussed in this article suggests that the priority is not to create entirely new technologies but to strengthen the systems that enable existing technologies to succeed. Focused material value chains, effective technology-transfer partnerships, pilot and testing facilities, trusted certification services, commercialisation support and stage-appropriate finance all contribute to stronger innovation ecosystems. Plastic-Tech hubs can bring these functions together through practical technical services, while reuse models provide an additional pathway by improving the efficiency of packaging systems rather than relying solely on new materials.

Regional cooperation can further accelerate progress through shared laboratories, technology licensing, university partnerships, common standards and APCTT-supported knowledge exchange. The principal challenge for many Asia-Pacific economies is therefore no longer the absence of promising bio-based technologies. It is building the technical capability, industrial partnerships and commercialisation pathways that allow those technologies to reach competitive markets. Progress is likely to come through a small number of well-tested, commercially successful innovations that demonstrate practical value and encourage wider industrial adoption across the region.

Acknowledgement

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Innovation and Technology for Bioeconomy Transition: Assessing BECCS and e-Fuel Potential from Oil Palm Residues in Southeast Asia

Joni Jupesta[1, *], Keigo Akimoto[2], Bandung Sahari[1,] Edi Iswanto Wiloso[3], Rizaldi Boer[4], Shabbir H. Gheewala[5,6], Alue Dohong[7]

[1] Centre for Transdisciplinary and Sustainability Sciences (CTSS), IPB University, Bogor, 16127, Indonesia

[2] Systems Analysis Group, Research Institute of Innovative Technology for the Earth (RITE), Kizugawa, 619-0292, Japan

[3] Research Centre for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency (BRIN), South Tangerang, 15314, Indonesia

[4] Centre for Climate Risk and Opportunity Management (CCROM), IPB University, Bogor, 16143, Indonesia

[5] The Joint Graduate School of Energy and Environment (JGSEE), King Mongkut's University of Technology Thonburi, Bangkok, 10140, Thailand

[6] Centre of Excellence on Energy Technology and Environment, Ministry of Higher Education, Science, Research and Innovation, Bangkok, 10400, Thailand

[7] Food and Agriculture Organization (FAO), Regional Asia Pacific, Bangkok, 10200, Thailand

[*] Corresponding author: jonijupesta@apps.ipb.ac.id

Abstract

Southeast Asia holds abundant oil palm resources, generating substantial agricultural residues such as palm oil mill effluent (POME). Valorising POME into biogas, biomethane, bioenergy with carbon capture and storage (BECCS), and synthetic fuels (e-fuels) offers a transformative pathway for the regional bioeconomy transition. Utilising remote sensing spatial analysis, Python-based mathematical optimisation modelling, and technoeconomic learning curve evaluations across Baseline, Decarbonisation, and Net Zero scenarios, this study projects resource availability and cost trajectories through 2060. Spatial assessments confirm 23.97 million hectares of oil palm plantations across ASEAN in 2023. By 2060, under the Net Zero scenario, palm oil utilisation supports 116.82 million kilolitres of biodiesel and yields 7,342 million m^3 of raw biogas. Biogas upgrading yields 4,588 million m^3 of biomethane, which holds a power generation potential of 16.13 TWh of electricity (assuming a lower heating value of 35.8 MJ/m^3 and a 35.35% electrical efficiency). Upgrading also isolates 2,754 million m^3 of biogenic CO_2 (~5.06 million tonnes of CO_2), enabling permanent negative emissions via BECCS. Integrated power-to-liquid (PtL) catalytic reforming and Fischer–Tropsch synthesis support a regional synthetic sustainable aviation fuel (SAF) potential of up to 36.69 billion US gallons (138.9 billion litres). Technoeconomic modelling demonstrates that learning rate effects will reduce e-SAF production costs from USD 1.20–2.30 per litre in 2025 to USD 0.25–0.77 per litre by 2060, emphasising the necessity of cross-border technology transfer and supportive regulatory frameworks.

Keywords: Oil palm residue, biogas upgrading, BECCS, sustainable aviation fuel (SAF), Fischer–Tropsch, Southeast Asia.

1. Introduction and Regional Context

The Sixth Assessment Report of the Intergovernmental Panel on Climate Change underscores that global warming will likely cross the 1.5°C threshold in the near term, increasing the frequency and intensity of climate catastrophes (IPCC, 2023). Reaching net-zero emissions requires systemic transformations across energy and industrial sectors. Net-zero energy systems mandate a drastic reduction in unabated fossil fuel combustion, widespread electrification, deployment of zero-carbon power grids, adoption of alternative energy carriers for hard-to-abate applications, and the implementation of carbon dioxide removal (CDR) mechanisms such as bioenergy with carbon capture and storage (BECCS) (IPCC, 2023; Feng & Rosa, 2024).

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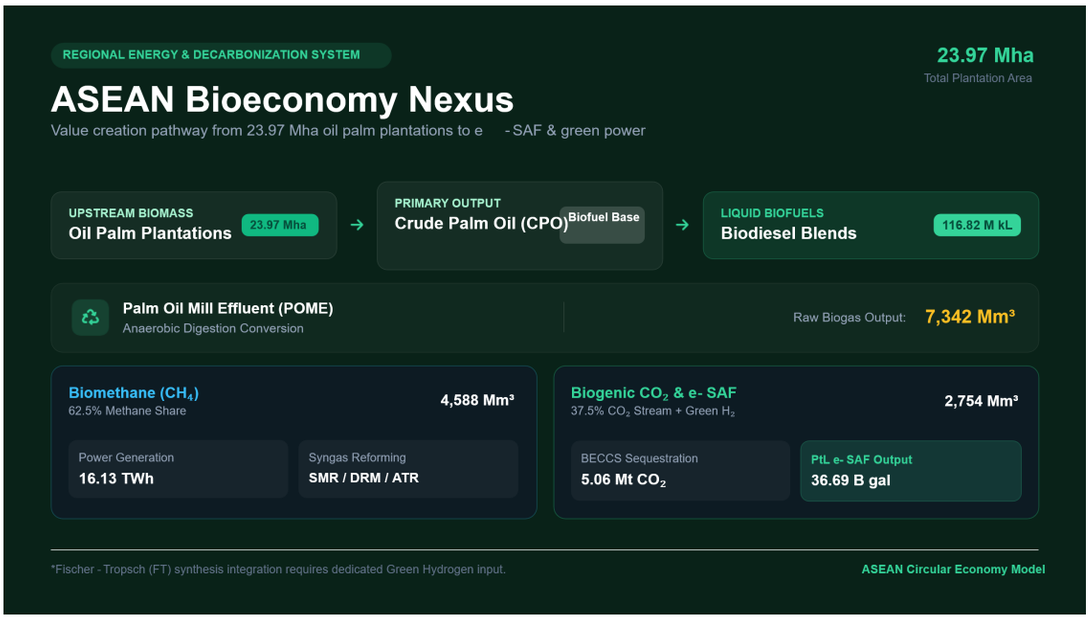


Figure 1: ASEAN bioeconomy nexus.

Integrated cascade utilisation of palm oil mill effluent (POME) into biomethane power generation, BECCS carbon removal, and Fischer–Tropsch SAF production pathways.

Southeast Asia is a major hub of global energy growth. According to the International Energy Agency, the region accounted for 11% of global energy demand growth since 2010 and is projected to drive more than 25% of global growth through 2035 (IEA, 2024). Heavy reliance on imported fossil fuels poses severe risks to regional energy security, balance of payments, and environmental sustainability, with energy-related emissions projected to rise by one-third by 2050 without intervention (IEA, 2024).

Renewable energy deployment in Southeast Asia has expanded, with modern bioenergy, geothermal, and hydropower currently constituting 96% of the region's renewable energy supply (IEA, 2024). Liquid biofuels derived from crude palm oil (CPO)—primarily biodiesel blends in Indonesia, Malaysia, and Thailand—have played a key role in decarbonising transport. However, converting primary agricultural products for energy raises land-use competition between food security and bioenergy. Valorising agro-industrial residues, specifically palm oil mill effluent (POME), presents a highly sustainable alternative. POME processing via anaerobic digestion produces biogas, which can be purified into biomethane (CH_4) for power generation or gas grid injection. Globally, biomethane can offset natural gas demand substantially, including up to 83% in Indonesia and 45% in Thailand (Feng & Rosa, 2024).

Biogas upgrading yields concentrated biomethane and pure biogenic carbon dioxide (CO_2). The biogenic CO_2 stream can be permanently sequestered via BECCS, serving as a negative emissions pathway. Alternatively, biogenic CO_2 or reformed biomethane synthesis gas ($CO+H_2$) can be combined with green hydrogen derived from water electrolysis to yield drop-in sustainable aviation fuel (e-SAF) via Fischer–Tropsch (FT) Power-to-Liquid (PtL) synthesis or Hydroprocessed Esters and Fatty Acids (HEFA) from lipid residues (IRENA, 2024; Swinbourn et al., 2024). Because waste residues carry zero allocated upstream land-use emissions, e-SAF produced from POME biogas achieves a near-zero lifecycle greenhouse gas footprint (IRENA, 2024).

This study evaluates the long-term regional potential of oil palm residues across Southeast Asia to generate biomethane, negative emissions via BECCS, and synthetic e-SAF. By integrating high-resolution remote sensing, multi-objective optimisation, and technoeconomic learning curves, this paper provides actionable insights for bioeconomy management and regional decarbonisation.

2. Methodology and Modelling Framework

A three-stage analytical framework was established: spatial analysis via remote sensing, mathematical optimisation modelling, and technoeconomic assessment (TEA) employing experience curves.

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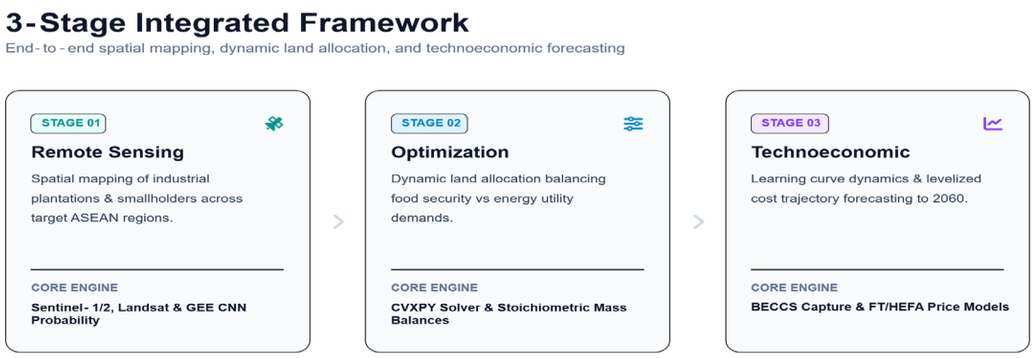


Figure 2: Integrated methodology framework.

Coupling spatial remote sensing, convex optimisation modelling, and technoeconomic experience curves.

2.1 Spatial Mapping of Oil Palm Distribution

To map oil palm plantations, spatial datasets from Descals et al. (2021, 2024) and Clinton et al. (2024) were integrated. Descals et al. applied Convolutional Neural Networks (CNNs) to Sentinel-1, Sentinel-2, Landsat-5, Landsat-7, and Landsat-8 imagery at a 10-metre resolution, classifying industrial and smallholder plantations globally from 1990 to 2021. Clinton et al. (2024) established a community machine-learning model trained on multi-stakeholder pooled satellite data via the Google Earth Engine platform. A probability threshold of 0.5 was applied to extract palm coverage. Spatial boundary processing and area extractions were executed using ArcGIS Desktop (ArcMap 10.8.2).

2.2 Optimisation Model Formulation

A multi-period numerical optimisation model was constructed in Python 3.12 using the cvxpy convex optimisation package (Agrawal et al., 2018; Van Rossum & Drake, 2002). The objective function maximises the cumulative land allocation utility for food ($A_{\text{food},t}$) and energy ($A_{\text{energy},t}$) production over time horizon T (2025–2060):

$$\text{Maximise } U = \sum_{t=0}^{T} \left(A_{\text{food},t} + A_{\text{energy},t} \right)$$

subject to technical and physical constraints:

Land Availability Constraint:

$$A_{\text{food},t} + A_{\text{energy},t} \leq A_{\text{total},t}, \ \forall\, t$$

where $A_{\text{total},t} = A_{\text{total},0} \times (1+g_{\text{land}})^t$, with g_{land} representing the annual land growth rate.

Food Demand Constraint:

$$Y_{\text{CPO},t} \cdot A_{\text{food},t} \leq D_{\text{food},t}, \quad \forall t$$

where $Y_{\text{CPO},t}$ is the dynamic crude palm oil yield per hectare.

Biodiesel Volume Constraint:

$$V_{\text{biodiesel},t} = \eta_{\text{biodiesel},t} \cdot Y_{\text{CPO},t} \cdot A_{\text{energy},t} \leq D_{\text{biodiesel},t}, \quad \forall t$$

Biogas Generation and Stoichiometric Separation:

$$V_{\text{biogas},t} = \eta_{\text{biogas},t} \cdot Y_{\text{POME}} \cdot Y_{\text{CPO},t} \cdot A_{\text{total},t} \geq D_{\text{biogas},t}, \quad \forall t$$

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Table 1: **Input parameters for optimisation modelling.**

Input Parameter	Variable	Indonesia	Malaysia	Thailand	Unit	Source
Initial Land Area	L_{max}	16,725,125	6,337,733	909,932	ha	Clinton et al. (2024)
Land Efficiency	E_0	2.90	2.90	2.90	tonne CPO/ha/yr	Silalertruksa & Gheewala (2012)
Biodiesel Yield	η_b	1.20	1.20	1.20	L/tonne CPO	Silalertruksa & Gheewala (2012)
POME Yield Ratio	β	3.81	3.81	3.81	tonne POME/ tonne CPO	Silalertruksa & Gheewala (2012)
Biogas Efficiency	η_g	28.00	28.00	28.00	m³/tonne POME	Aziz et al. (2020)
Food CPO Demand	F_{demand}	44.3×10^9	17.0×10^9	16.7×10^9	L/yr	MEMR (2024); DEDE (2024)
Biodiesel CPO Demand	B_{demand}	13.15×10^9	0.998×10^9	1.602×10^9	L/yr	MEMR (2024); Energy Commission (2024)
Biogas Allocation	G_{demand}	100×10^6	549×10^6	0.464×10^6	m³/yr	MEMR (2024); DEDE (2024)
Biogas Revenue	R_g	0.66	0.66	0.66	USD/m³	Energy Market Estimates (2024)
Biodiesel Revenue	R_b	0.88	0.88	0.88	USD/L	Energy Market Estimates (2024)
Biogas Cost	C_g	0.60	0.60	0.60	USD/m³	Energy Market Estimates (2024)
Biodiesel Cost	C_b	0.80	0.80	0.80	USD/L	Energy Market Estimates (2024)

Note: Baseline input data compiled from national administrative datasets and technical literature.

Table 2: **Dynamic growth rates across policy scenarios.**

Model Growth Variable	Baseline (IDN / MYS / THA)	Decarbonisation (IDN / MYS / THA)	Net Zero (IDN / MYS / THA)
Land Growth (γ)	3% / 1% / 1%	3% / 3% / 3%	5% / 5% / 5%
Land Efficiency (δ_e)	1% / 1% / 1%	3% / 3% / 3%	5% / 5% / 5%
Biodiesel Efficiency (δ_b)	1% / 1% / 1%	3% / 3% / 3%	5% / 5% / 5%
Biogas Efficiency (δ_g)	1% / 1% / 1%	3% / 3% / 3%	5% / 5% / 5%
Food CPO Demand Growth	5% / 5% / 5%	6% / 6% / 6%	7% / 7% / 7%
Biodiesel Demand Growth	5% / 5% / 5%	7% / 7% / 7%	9% / 9% / 9%
Biogas Demand Growth	5% / 5% / 5%	7% / 7% / 7%	9% / 9% / 9%

Note: Parameters represent annualised growth percentages applied across Indonesia, Malaysia, and Thailand (IDN / MYS / THA).

Biogas component separation follows a standardised volumetric model (*v*/*v*) derived from Rahayu et al. (2015) and Swinbourn et al. (2024), where raw scrubbed biogas consists of 62.5% methane (CH_4) and 37.5% biogenic carbon dioxide (CO_2):

$$V_{CH_4,t} = 0.625 \cdot V_{biogas,t}$$
$$V_{CO_2,t} = 0.375 \cdot V_{biogas,t}$$

Non-negativity Constraints:

$$A_{food,t} \geq 0, \quad A_{energy,t} \geq 0, \quad V_{biodiesel,t} \geq 0, \quad V_{biogas,t} \geq 0, \quad \forall t$$

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Technological improvements in yields and efficiencies follow compounding growth functions:

$$\eta_{\text{biodiesel},t} = \eta_{\text{biodiesel},0} \times (1 + r_{\text{biodiesel}})^t, \quad \eta_{\text{biogas},t} = \eta_{\text{biogas},0} \times (1 + r_{\text{biogas}})^t$$

Three policy pathways were evaluated:

- **Baseline Scenario:** Historical trends (1% annual growth rates).
- **Decarbonisation Scenario:** Moderate growth (3% annual growth rates).
- **Net Zero Scenario:** Accelerated policy deployment (5% land/yield growth; 7–9% annual biofuel demand growth).

2.3 Technoeconomic Analysis (TEA) and Learning Curves

Technoeconomic cost trajectories for BECCS capture technologies (Amine Scrubbing [AS], High-Pressure Water Scrubbing [HPWS], Pressure Swing Adsorption [PSA], Membrane Permeation [MP]) and e-SAF conversion technologies (FT and HEFA) were evaluated using single-factor experience curves. Technological unit cost reduction ($P_{t,s}$) is modelled as a function of cumulative deployment (Q_t):

$$P_{\text{CC},t,s} = P_{\text{CC},0} \times \left(\frac{Q_{\text{CO}_2,t}}{Q_{\text{CO}_2,0}} \right)^{\beta_{\text{CC},s}}$$

$$P_{\text{e-SAF},t,s} = P_{\text{e-SAF},0} \times \left(\frac{Q_{\text{e-SAF},t}}{Q_{\text{e-SAF},0}} \right)^{\beta_{\text{e-SAF},s}}$$

The learning elasticity β_s relates to the learning rate LR_s by:

$$\beta_s = \frac{\log(1 - \text{LR}_s)}{\log(2)}$$

Three sensitivity scenarios were evaluated based on energy technology benchmarks:

- **Scenario 1 (**0.5 × **Solar PV):** LR = 11.95%.
- **Scenario 2 (**1.0 × **Solar PV):** LR = 23.90%.
- **Scenario 3 (**1.5 × **Solar PV):** LR = 35.85%.

3. Results and Discussion

3.1 Spatial Extent of Oil Palm Coverage

Spatial analysis confirms the high concentration of oil palm cultivation in Southeast Asia. Industrial estates represent approximately 60% of total regional acreage, while smallholders manage the remaining 40% (Qaim et al., 2020).

Using Clinton et al. (2024) as the baseline spatial layer, total oil palm plantation area across ASEAN reached 23.97 million hectares in 2023.

3.2 Optimisation Dynamics: Land Allocation

Under the Net Zero scenario by 2060, land allocated for food palm oil in Indonesia stabilises at 3.42 million hectares as agricultural yields improve. Conversely, land dedicated to bioenergy expands:

- **Indonesia:** Expands from 3.74 million hectares in 2025 to 20.12 million hectares in 2060.
- **Malaysia:** Expands from 0.34 million hectares in 2025 to 2.74 million hectares in 2060.
- **Thailand:** Grows from 0.35 million hectares in 2025 to 1.00 million hectares in 2060.

3.3 Biodiesel, Biogas, and Power Potential

Under the Net Zero scenario by 2060, regional biodiesel output reaches 116.82 million kilolitres (98.50 M kL in Indonesia, 13.42 M kL in Malaysia, and 4.90 M kL in Thailand). Concurrently, total raw biogas generation from POME scales up to 7,342 million m^3 (5,122 million m^3 in Indonesia, 1,941 million m^3 in Malaysia, and 279 million m^3 in Thailand).

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Table 3: **Comparative remote sensing mapping of oil palm area across ASEAN.**

Country	Clinton et al. (2024) [2023 Area, ha]	Descals et al. (2021) [2019 Area, ha]	Descals et al. (2024) [2021 Area, ha]
Indonesia	16,725,125.40	11,522,755.80	13,774,828.80
Malaysia	6,337,733.00	5,072,036.30	6,235,328.70
Thailand	909,932.00	746,075.00	858,439.20
Philippines	—	76,462.40	64,562.30
Myanmar	628.95	37,756.90	50,384.70
Cambodia	99.18	20,988.30	16,967.19
Brunei Darussalam	225.88	187.00	500.00
Lao PDR	—	—	116.40
Viet Nam	—	29,230.00	—
Total ASEAN	**23,973,744.41**	**17,505,491.70**	**21,001,127.29**

Note: Area figures compiled from satellite observational datasets.

Table 4: **Projected bioenergy, gas yield, and e-SAF potential in 2060 under Net Zero.**

Product / Gas Output (2060 Net Zero)	Indonesia	Malaysia	Thailand	ASEAN Total
Biodiesel (million kilolitres)	98.50	13.42	4.90	**116.82**
Total Biogas (million m^3)	5,122.00	1,941.00	279.00	**7,342.00**
Biomethane (CH_4) (million m^3)	3,201.00	1,213.00	174.00	**4,588.00**
Biogenic CO_2 for BECCS (million m^3)	1,921.00	728.00	105.00	**2,754.00**
Power Generation Potential (TWh electricity)	11.25	4.26	0.62	**16.13**
Sequestered Biogenic CO_2 (million tonnes)	3.53	1.34	0.19	**5.06**
Integrated e-SAF Potential (million US gallons)	25,600.00	9,700.00	1,390.00	**36,690.00**

Note: Reconciled national and regional potential estimates for 2060.

Upgrading this raw biogas yields 4,588 million m^3 of pure biomethane (CH_4). Assuming a lower heating value (LHV) of 35.8 MJ/m^3 (9.944 kWh/m^3), the total thermal energy content is 45.63 TWh. Utilising standard internal combustion or gas turbine combined heat and power systems operating at an electrical conversion efficiency of 35.35%, this biomethane potential yields **16.13 TWh of electricity**.

3.4 Biogas Upgrading, Synthesis Gas, and e-SAF Conversion Pathways

To evaluate e-SAF output rigorously, the manuscript distinguishes between four explicit chemical engineering pathways:

1) **Biogas Upgrading and Separation:** Raw POME biogas (62.5% CH_4, 37.5% CO_2) is scrubbed of trace impurities (H_2S, moisture) and separated into pure biomethane and biogenic CO_2.
2) **Syngas Generation:** Biomethane (CH_4) undergoes catalytic reforming—via Steam Methane Reforming (SMR: $CH_4 + H_2O \rightarrow CO + 3H_2$), Dry Reforming of Methane (DRM: $CH_4 + CO_2 \rightarrow 2CO + 2H_2$), or Autothermal Reforming (ATR)—to yield synthesis gas ($CO + H_2$). Alternatively, biogenic CO_2 is converted to CO via Reverse Water-Gas Shift (RWGS: $CO_2 + H_2 \rightarrow CO + H_2O$).
3) **Power-to-Liquid (PtL) Fischer–Tropsch e-SAF:** The syngas is catalytically combined ($nCO + (2n+1)H_2 \rightarrow C_nH_{2n+2} + nH_2O$) and hydroprocessed into e-SAF. Achieving the full regional e-SAF potential of 36.69 billion US gallons (138.9 billion litres) requires external green hydrogen produced via water electrolysis, demanding approximately 12.8×10^6 tonnes of green H_2 and renewable power.
4) **HEFA Pathway:** HEFA processes residual lipid feedstocks (recovered POME oil/sludge and crude palm oil) through hydrotreating, deoxygenation, and hydrocracking to produce bio-SAF.

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For the biogenic H_2 present in trace process streams (73.2 million m^3), mass calculations at Normal Temperature and Pressure (NTP: 20□, 1 atm, gas density ρ = 0.08375 kg/m^3) yield **6,131 tonnes** of H_2 (or **6,579 tonnes** at STP: 0□, 1 atm, ρ = 0.08988 kg/m^3).

3.5 Technoeconomic Cost Trajectories

e-SAF Production Costs

Benchmark 2025 production costs for e-SAF via FT range from **USD 1.20 to 2.30 per litre** (Indonesia: USD 1.20/L; Malaysia: USD 2.30/L; Thailand: USD 1.50/L), while HEFA pathway costs range from **USD 1.60 to 2.10 per litre**, fully consistent with IRENA (2024) regional benchmarks. Technological learning drives substantial cost declines by 2060:

- **Indonesia (FT Pathway):** Costs fall from USD 1.20/L (2025) to USD 0.77/L (Scenario 1, LR = 11.95%), USD 0.46/L (Scenario 2, LR = 23.90%), and USD 0.25/L (Scenario 3, LR = 35.85%).
- **Malaysia (FT Pathway):** Costs fall from USD 2.30/L (2025) to USD 1.47/L (Scenario 1), USD 0.88/L (Scenario 2), and USD 0.48/L (Scenario 3).
- **Thailand (FT Pathway):** Costs fall from USD 1.50/L (2025) to USD 0.96/L (Scenario 1), USD 0.57/L (Scenario 2), and USD 0.31/L (Scenario 3).

BECCS Carbon Capture Unit Costs

Initial capture costs for biogenic CO_2 from biogas streams start at USD 0.061–0.072 per m^3 in 2025. Cumulative deployment reduces capture costs significantly by 2060 across all separation technologies.

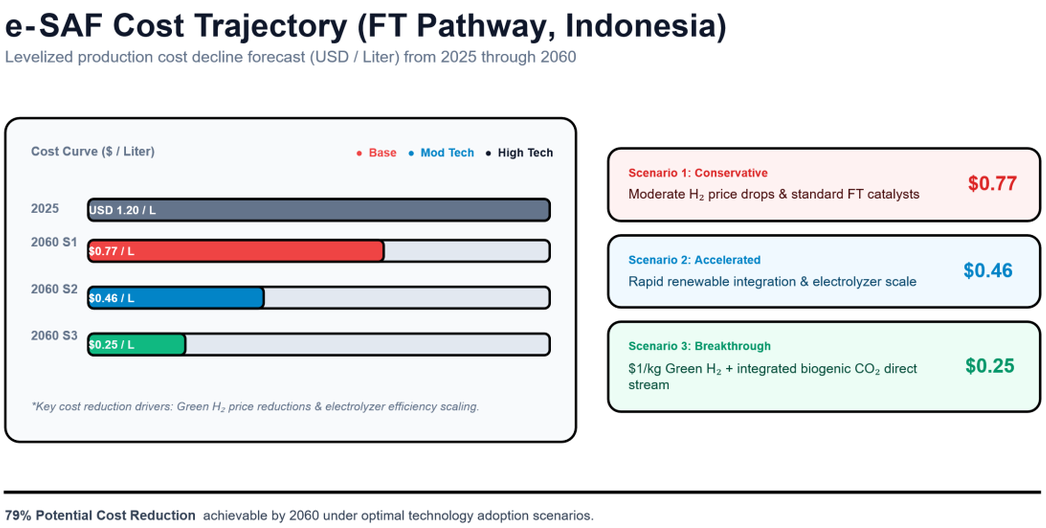


Figure 3: e-SAF Cost Trajectories for Indonesia (Fischer–Tropsch Pathway, 2025–2060).

Cost trajectories under Scenario 1 (LR = 11.95%), Scenario 2 (LR = 23.90%), and Scenario 3 (LR = 35.85%).

Table 5: BECCS carbon capture technology unit cost projections through 2060 (USD/m^3).

Technology Pathway	2025 Base Cost (USD/m^3)	2060 Cost (Scenario 1, LR = 11.95%)	2060 Cost (Scenario 2, LR = 23.90%)	2060 Cost (Scenario 3, LR = 35.85%)
Amine Scrubbing (AS)	0.072	0.046	0.028	0.015
High-Pressure Water Scrubbing (HPWS)	0.062	0.039	0.024	0.014
Pressure Swing Adsorption (PSA)	0.070	0.045	0.027	0.015
Membrane Permeation (MP)	0.061	0.039	0.023	0.013

Note: Evaluated across four separation technologies and three learning scenarios.

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4. Policy Frameworks, Technology Transfer, and Bioeconomy Management

Realising the potential of POME valorisation in Southeast Asia requires addressing structural, regulatory, and market barriers.

4.1 Cross-Border Technology Transfer and Capacity Building

Biogas upgrading, biogenic gas fractionation, and catalytic e-SAF synthesis require specialised industrial infrastructure. Regional technology transfer mechanisms under ASEAN governance should focus on:

- **Decentralised Modular Processing:** Developing standardised POME upgrading units capable of operating at individual oil palm mills (processing 30–60 tonnes of fresh fruit bunches [FFB] per hour).
- **Joint R&D Frameworks:** Establishing collaborative research initiatives between ASEAN centres of excellence (e.g., BRIN Indonesia, JGSEE Thailand, IPB University) to commercialise advanced membrane separation and Fischer–Tropsch catalysis.

4.2 Regulatory Standards and Blended Finance Mechanisms

Capital investment in bioenergy requires long-term regulatory certainty and de-risking financial structures:

- **Standardised Carbon Accounting:** Aligning national carbon accounting rules with Article 6 of the Paris Agreement to facilitate cross-border trading of BECCS negative emissions credits.
- **Blending Mandates:** Establishing progressive regional blend targets for SAF (e.g., 2% by 2030, scaling to 30% by 2050) to guarantee offtake demand.
- **Blended Finance:** Utilising green bond taxonomies, multilateral development financing, and concessional loans to de-risk commercial debt for POME-to-biogas infrastructure.

4.3 Smallholder Integration and Community Governance

Smallholder farmers manage approximately 40% of ASEAN palm oil land (Qaim et al., 2020). Including smallholders in POME supply chains is critical for equitable bioeconomy development:

- **Yield Intensification:** Enhancing smallholder agronomic productivity reduces expansion pressure on forest frontiers while increasing FFB availability for centralised mills.
- **Cooperative Biogas Hubs:** Establishing shared community-owned POME processing hubs allows smallholders to participate in biogas value chains, generating supplementary revenues.

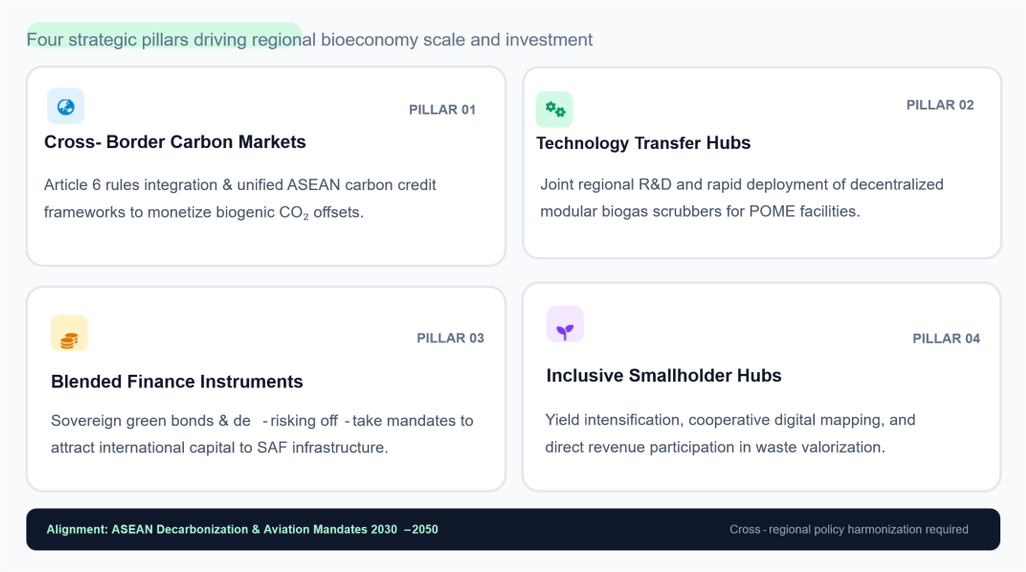


Figure 4: Bioeconomy strategic execution framework.

Key policy, financial, and technological enablers for ASEAN regional implementation.

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5. Conclusion

Valorising POME across Southeast Asia offers a dual benefit: producing renewable low-carbon fuels and generating permanent biogenic carbon removals. Spatial analysis confirms 23.97 million hectares of oil palm coverage across ASEAN. Under an aggressive Net Zero scenario through 2060, POME-derived biogas reaches 7,342 million m^3, providing 4,588 million m^3 of biomethane (16.13 TWh power potential), sequestering 5.06 million tonnes of biogenic CO_2 via BECCS, and supporting up to 36.69 billion US gallons of e-SAF.

Technoeconomic assessments demonstrate that deployment scale and learning curves can reduce BECCS capture costs down to USD 0.013–0.015 per m^3 and lower e-SAF production costs to USD 0.25–0.77 per litre by 2060. Capitalising on these opportunities requires coordinated regional policies, cross-border technology transfer, blended finance instruments, and inclusive smallholder integration to advance the bioeconomy transition across Southeast Asia.

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From Biological Carbon Capture to Circular Bioeconomy: Smart Microalgal Technologies for Sustainable Industrial Transformation in the Asia-Pacific

Arya[a,b], Muthu Arumugam[a,b,1]

[a] Biosciences and Bioengineering Division, CSIR-National Institute for Interdisciplinary Science and Technology, Thiruvananthapuram 695019, India

[b] Academy of Scientific and Innovative Research (AcSIR), Ghaziabad 201002, India

[1] https://orcid.org/0000-0003-4697-6925

Abstract

The Asia-Pacific region hosts one of the world's largest concentrations of coal-fired power plants, cement kilns, and steel plants, which together drive the majority of global industrial CO emissions. Under the Paris Agreement's 1.5°C goal, India has committed to Net Zero by 2070, with NITI Aayog's 2026 Scenarios Towards Viksit Bharat and Net Zero roadmap identifying carbon capture, utilisation, and sequestration (CCUS) as a critical enabler. The region's position as a leading commercial microalgae hub makes it well-placed to advance this transition. This article examines how microalgal cultivation—strengthened by sensor-based monitoring, artificial intelligence, and strain improvement—offers a scalable platform for biological CO valorisation and bioproduct generation. It reviews smart photobioreactor systems, adaptive strain engineering, and integrated biorefinery design, drawing on pilot projects from India, China, Japan, and Malaysia. The article outlines policy, financing, and cooperation measures needed to move algae-based carbon utilisation from pilot scale to industrial deployment, positioning Asia-Pacific to lead this circular bioeconomy frontier.

1. Introduction

The development narrative of Asia-Pacific and its climate responsibilities are coming together at the same set of smokestacks. The majority of the world's approximately 9,000 coal-fired power plants are located in this region, and in contrast to the ageing fleets of North America and Europe, the coal and heavy-industry assets in developing economies are typically under 15 years old, compared to more than 40 years in other regions (IEA, 2022). That youth is a double-edged fact: it means these plants and kilns have decades of operating life ahead of them, but it also means the region has a correspondingly long window in which to retrofit them with carbon-utilisation pathways rather than waiting for natural retirement.

India's own long-term planning exercise illustrates the scale of the challenge. The eleven volumes of research by NITI Aayog, Scenarios Towards Viksit Bharat and Net Zero, published till 2026, project that India can achieve a more than eight-fold growth of its economy, from USD 4.18 trillion to USD 30 trillion, and simultaneously reach net-zero GHG emissions by 2070 (NITI Aayog, 2026a). One volume of the research is devoted to industry sectors, and it admits that under the trajectory of current policy, fossil fuels would still provide 52% of energy used in industry by 2070, compared to 83% in 2025, and CCUS is listed among long-duration energy storage and small modular reactors as "nascent and unproven at scale" (NITI Aayog, 2026a). B. V. R. Subrahmanyam, the CEO of NITI Aayog, was reported to have noted at the report's launch that fossil fuels would still account for about 25% of industrial energy use even in 2070, a residual load that would need to be managed through carbon capture and related technologies (News On AIR, 2026). Two concrete initiatives are already underway, according to the same industry volume: the introduction of five industrial CCUS test beds in the cement industry in 2025 and the use of low-clinker cement blends like Limestone Calcined Clay Cement, which can reduce CO emissions from the cement process by up to 40% (NITI Aayog, 2026a).

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Most of the CCUS conversation in India and across the region still centres on geological storage and chemical absorption. Microalgae-based biological carbon capture is a complementary and, in some ways, more instantly deployable method. Microalgae may be fed directly with flue gas without first being purified, and fix CO□ photosynthetically at rates claimed to be 10–50 times higher per unit area than terrestrial plants, and transform nitrogen and sulphur oxides that would normally need to be scrubbed into usable nutrients (Zhang, 2015). Importantly, Asia-Pacific does not need to build this capability from scratch. The region already hosts the world's largest commercial microalgae market, accounting for an estimated 42.3% of global revenue in 2025, underpinned by decades of commercial *Spirulina* and *Chlorella* cultivation in China, Japan, Taiwan, and India (Dataintelo, 2026). This article explores how the current cultivation base can be expanded from nutraceutical production to industrial-scale carbon utilisation using smart photobioreactor monitoring, artificial intelligence, and adaptive strain engineering. It also discusses what financial and policy changes would be required to make that transition bankable.

2. The Case for Biological Carbon Capture

The appeal of microalgae for use in CO□ utilisation is based on four key advantages. To start with, flue gas requires no complex pre-treatment prior to being fed to the culture of microalgae. Research has shown that the species of *Chlorella* can survive up to 100% CO□ content; however, optimal growth is attained at 10% CO□ content, which corresponds to industrial flue gases (Zhang, 2015). Secondly, nitrogen and sulphur oxides contained in the flue gas, which would normally necessitate the installation of separate scrubbing units, can act as nutrients to promote microalgal cultivation, thus making the whole process of flue gas handling simpler (Zhang, 2015). Thirdly, in contrast with the geological sequestration, where the captured carbon does not generate any additional profit but is simply stored, microalgal cultivation creates a product in the form of biomass from which lipids, proteins, pigments, and other valuable substances are produced to provide an economic incentive to balance part of the cost of the process **(**Dutta et al., 2025**)**.

Fourthly, the technology promotes a circular bioeconomy, whereby after the extraction of high-value materials, the leftover biomass is anaerobically digested to create biogas. Moreover, there are numerous microalgae species capable of growing in municipal, industrial, and agricultural wastewater to allow for the combined CO□ capture, nutrient recovery, and wastewater treatment processes.

These benefits explain why, over the past 15 years, utilities, oil and gas firms, and speciality chemical producers around the region have shown consistent, if still sub-commercial, interest in microalgal CO□ biofixation, as the case studies below show.

3. From Pilot to Practice: Asia-Pacific Case Studies

3.1 India

One of India's earliest and most widely cited demonstrations of biological carbon capture was the pilot reactor established at ONGC's Hazira facility in Surat, Gujarat, to capture CO□ from vent gas using *Chlorella* sp. and a mixed consortium of *Scenedesmus quadricauda, Chlorella vulgaris*, and *Chlorococcum humicola*. Anaerobic digestion of the harvested biomass at Hazira produced methane yields of 386 L CH□ kg□¹ VS_{fed} when *Chlorella* was cultivated alone, against 228 L CH□ kg□¹ VS_{fed} for the mixed consortium — a gap the researchers attributed partly to the carbonation column's performance upstream, which had brought vent-gas CO□ down from an average of 34% to 15% by volume while sustaining *Chlorella* growth of 18 g m□² day□¹ (Yadav et al., 2016). Separately, Baral et al. (2015) reported pilot microalgal carbon capture initiatives at the Angul thermal power plant in Odisha and the Kolaghat Thermal Power Station in West Bengal. The review noted that the 1,260 MW Kolaghat plant had an estimated CO□ footprint of approximately 15,000 t day□¹, with plans to redirect about 50% of these emissions to microalgal cultivation. The residual oil cake remaining after lipid extraction was also proposed as a supplementary fuel for the power plant (Baral et al., 2015). An integrated study involving GAIL India utilised 90–99% CO□ from natural gas processing together with 13–15% CO□ from thermal power plant flue gas (Chandrapura and Santaldih Thermal Power Stations) for microalgal cultivation. The study screened freshwater algal

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strains for rapid growth, photosynthetic efficiency, tolerance to NO_x and SO_x, temperature resilience, and the production of value-added products (Anguselvi et al., 2019).

3.2 China

China's CCUS programme is considerably larger in scale, with roughly 40 demonstration and pilot projects in operation or under construction as of the early 2020s, collectively capturing on the order of three million tonnes of CO annually, though the bulk of this activity remains concentrated in enhanced oil recovery in the petroleum, coal-chemical, and thermal-power sectors rather than in full-chain, large-scale industrialisation (Liu et al., 2022). Bibliometric analysis of the field confirms that China leads global CCUS research output, with the Chinese Academy of Sciences among the most prolific institutional contributors (Liu et al., 2022), and the same review estimates that CCUS-driven emission reductions of 0.6–1.4 billion tonnes by 2050 and 1–1.8 billion tonnes by 2060 will be needed to meet the country's carbon-neutrality pathway. Within this landscape, microalgae-based biofixation appears specifically as one of the utilisation routes tracked alongside enhanced oil recovery, saline-aquifer storage, and mineral carbonation (Liu et al., 2022). At the project level, journalistic reporting from the early 2010s documented the energy company ENN Group operating a greenhouse-style facility in which CO piped from a nearby coal-fired power plant was fed through banks of tubes to cultivate oil-rich microalgae destined for biodiesel production, while China Huaneng Group had equipped coal plants in Beijing and Shanghai with capture systems selling the recovered CO to beverage manufacturers. Shenhua's coal-to-liquids complex at Erdos in Inner Mongolia was operating a geological storage pilot, with reports indicating that only around 5% of the plant's annual CO emissions were being sequestered because of cost constraints (Liu, 2012). As these reports date back to the early 2010s, the current operational status of these facilities could not be independently verified for this review. Nevertheless, they illustrate China's early exploration of both geological and biological CO utilisation pathways and highlight the economic considerations that continue to drive interest in lower-capex biological approaches. More recently, Chinese state media reported that Shanxi Agricultural University had developed a microalgae-based flue-gas treatment system reported as being approximately 10 times more effective at removing carbon than equivalent terrestrial vegetation, absorbing more than 65% of the CO from treated waste gas (International Centre for Sustainable Carbon, 2019, citing Xinhua).

3.3 Japan

Japan has been an early and consistent adopter of microalgal CO utilisation technologies, particularly those based on *Euglena*, a photosynthetic microalga capable of tolerating elevated CO concentrations representative of industrial flue gases (Xin et al., 2023; Erfianti et al., 2025). According to Japan for Sustainability (2009), a 2009 field trial conducted jointly by Euglena Co. and Okinawa Electric Power Company injected exhaust gas from the utility's Kin Thermal Power Station into cultivation tanks and found it increased *Euglena* growth by up to 20 times relative to air-fed controls; the resulting acidification also helped suppress contaminating organisms**.** According to Euglena Co. (2016), the company subsequently partnered with Chubu Plant Service and local authorities in Mie Prefecture, with support from a Ministry of Economy, Trade and Industry subsidy, to construct what it described as Japan's largest fuel-microalgae culture pond, co-located with a woody-biomass power plant and using its exhaust gas, wastewater, and waste heat as combined inputs for cultivation. On the industrial-fuels side, IHI Corporation, working under a programme funded by the New Energy and Industrial Technology Development Organization (NEDO) since 2017, has developed integrated cultivation-to-fuel technology around a fast-growing, oil-rich microalga (*Botryococcus braunii*), operating pilot outdoor cultivation facilities in both Kagoshima, Japan, and Saraburi Province, Thailand. The resulting bio-jet fuel met the ASTM D7566 Annex 7 international standard for sustainable aviation fuel in May 2020, and on 17 June 2021 was blended into the fuel used for a pair of one-off demonstration flights departing Tokyo's Haneda Airport — a Japan Airlines service to Sapporo and an All Nippon Airways service to Osaka — rather than into an ongoing commercial supply chain (NEDO, 2021). The Japan–Thailand collaboration provides a useful model for the cross-border technology-transfer partnerships needed to accelerate the regional bioeconomy transition.

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3.4 Malaysia

Malaysia's pilot-scale work is shaped by its position as the world's second-largest palm oil producer (Malaysian Palm Oil Board, 2024) and the correspondingly large volumes of palm oil mill effluent (POME) generated by its palm oil industry. Because POME is nutrient-rich but also a major water pollutant if discharged untreated, it has been studied extensively as a low-cost growth medium for *Chlorella* sp.; one peer-reviewed study identified an optimal combination of roughly 10.9% CO□ concentration and approximately 9,964 lux of light intensity for maximising simultaneous CO□ sequestration and biodiesel-relevant lipid accumulation (Bhuyar et al., 2021). An integrated system combining CO□-rich flue gas from palm oil mill boilers with POME could, in principle, utilise two industrial waste streams simultaneously. However, this review did not identify published studies directly evaluating such an integrated approach and therefore presents it as a potential design concept rather than a demonstrated process. This agro-industrial pairing represents a distinctively Southeast Asian variant of the biological CCU model that does not depend on power-sector infrastructure.

3.5 Synthesis

Read together, these four national experiences show a consistent pattern: the underlying biology is well understood and has been demonstrated at pilot scale for more than a decade, but almost none of these projects has crossed from pilot into a commercially self-sustaining, industrial-scale operation. The recurring bottlenecks are less about whether microalgae can tolerate flue gas — they have consistently been shown to do so in pilot-scale studies — and more about the economics and operational reliability of scaling cultivation, harvesting, and downstream processing to match the gigatonne-scale carbon streams that power plants, cement kilns, and steel mills actually produce. Addressing that gap is where smart cultivation technologies and improved strains become decisive.

4. Smart Photobioreactor Systems: Sensors, IoT and Artificial Intelligence

Historically, one of the major obstacles to scaling microalgal cultivation has been the cost and limited speed of process monitoring: photobioreactors (PBRs) require continuous tracking of temperature, pH, light intensity, dissolved gases, and biomass density, and manual sampling methods are both labour-intensive and too slow to support real-time process control (Imamoglu, 2024). Artificial intelligence and machine learning are increasingly closing this gap. A recent review catalogues applications of support vector machines, genetic algorithms, decision trees, random forests, artificial neural networks, and deep learning across the full microalgae production chain — from real-time growth monitoring and species identification through to optimisation of cultivation conditions, harvest timing, and downstream purification of bioproducts (Imamoglu, 2024). The same review highlights the potential of machine-learning approaches to optimise harvest timing and improve process efficiency in microalgal cultivation systems (Imamoglu, 2024).

Concrete implementations illustrate what this looks like in practice. One tubular photobioreactor system for *Chlorella* sp. cultivation integrates seven types of sensors—temperature, pH, light intensity, electrical conductivity, flow rate, dissolved oxygen, and light-exposure duration—managed through an ESP8266 microcontroller, with an attached camera capturing images every 30 minutes to track growth non-invasively, all combined with computational fluid dynamics modelling of the reactor's internal flow (Tummawai et al., 2024). At the commercial scale, a machine-learning decision-support framework developed for tubular photobioreactors cultivating *Nannochloropsis* sp. integrated three years of farm operational logs, meteorological data, and digital-imaging cell-concentration measurements to predict next-day post-harvest cell density, allowing operators to make harvest-fraction decisions on a data-driven rather than heuristic basis; in a twelve-reactor commercial field trial, this approach matched conventional yields with lower variability (Kadosh et al., 2026). A related real-time imaging system for *Scenedesmus dimorphus* monitoring combined RGB colour-histogram image analysis with decision-tree and random-forest models; the authors discuss how such an approach could be extended through multi-sensor data fusion, automated feedback control, and Internet-of-Things connectivity for continuous, industrial-scale decision-making (Uguz et al., 2025).

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For the Asia-Pacific pilot projects described above, these technologies could provide one of the key enablers for scaling microalgal CO utilisation beyond demonstration projects. Sensor- and AI-enabled process control can improve operational stability while reducing the expertise and labour required to manage large photobioreactor arrays. Such advances are likely to help bridge the gap between pilot-scale demonstrations and commercial deployment, allowing biological carbon utilisation systems to operate more reliably at scales relevant to industrial CO emissions.

5. Adaptive Strain Engineering: Building CO_2-Tolerant, High-Value Algae

Sensors and control systems can only optimise what a given strain is biologically capable of. Many wild-type microalgae experience growth inhibition at CO concentrations above about 5%, while some strains can grow at the higher concentrations typically found in flue gas (10–15%), although carbon fixation and biomass production may decline (Zhang, 2015). In contrast to genetic engineering, Adaptive Laboratory Evolution (ALE) selects for beneficial spontaneous mutations by subjecting cultures to gradual, step-wise increases in an environmental stressor—typically CO concentration, but also temperature, salinity, or co-pollutant load—without introducing foreign genetic material. This has made ALE a particularly appealing approach for this purpose (He et al., 2025). Recent work on adaptively evolved *Nannochloropsis oceanica* demonstrates how strain improvement can alter stress-related and biochemical characteristics, including selenium-associated functional properties (Reshma and Arumugam, 2022; Pawar and Arumugam, 2026). This matters practically as well as scientifically: because ALE does not require the deliberate introduction of foreign genetic material, it may offer regulatory and public-acceptance advantages over genetically modified microalgae, particularly for open-pond or environmental applications.

A recent review of microalgae-driven CCUS strain engineering documents the results such programmes have achieved: sequential exposure of *Chlorella* sp. to 10% and then 20% CO across dozens of adaptation cycles produced evolved lines capable of sustained growth at CO concentrations up to 30%, alongside significantly elevated chlorophyll content relative to the unadapted parent strain (Li et al., 2015; He et al., 2025). The same review reports that ALE protocols incorporating the toxic co-pollutants found in real flue gas — including nitrogen and sulphur oxides — have been used successfully to adapt *Chlorella* sp. to gas mixtures approximating actual industrial exhaust, through gradual stepwise increases in pollutant concentration sustained over several months (Cheng et al., 2019; He et al., 2025). Temperature tolerance is a parallel and, for Asia-Pacific's outdoor open-pond systems, equally important target: ALE work on the diatom *Nitzschia inconspicua* has specifically targeted improved thermal tolerance at temperatures above 37°C, a condition highly relevant to raceway-pond cultivation under South and Southeast Asian ambient conditions (LaPanse et al., 2022).

Strain-improvement efforts need not target CO or temperature tolerance alone. The same stress-based ALE logic has been used to co-select for high-value product traits — for instance, combining elevated CO exposure with adaptation cycles that simultaneously increase carotenoid or pigment content — which is directly relevant to the biorefinery framing this article advocates, since it means a single strain-improvement programme can target flue-gas tolerance and commercial product value at once, rather than treating them as separate research tracks (Udayan et al., 2017). Genetic-engineering approaches using CRISPR-Cas systems, most developed in the model species *Chlamydomonas reinhardtii*, offer a complementary route with potentially larger single-step gains, though the technology still faces meaningful optimisation and regulatory hurdles before it is field-deployable at the scale ALE-derived strains already permit.

6. Circular Bioeconomy and Market Context

A defining feature of the Asia-Pacific opportunity is that it does not require building a new industry from the ground up. China's dominance of the sector is stark: of the roughly 56,000 tonnes of microalgae biomass the FAO recorded worldwide in 2019, China alone supplied more than 97%—a concentration built on decades of established *Spirulina* and *Chlorella* farming across East and South Asia (Ashour and Omran, 2022). The same FAO-sourced figures caution that reported totals likely undercount production in countries where the industry is less centrally tracked, so the true regional base is probably larger than the figures suggest (Ashour and Omran, 2022). This existing cultivation base could provide a useful foundation for carbon-utilisation deployment: new CO-fed facilities would not necessarily

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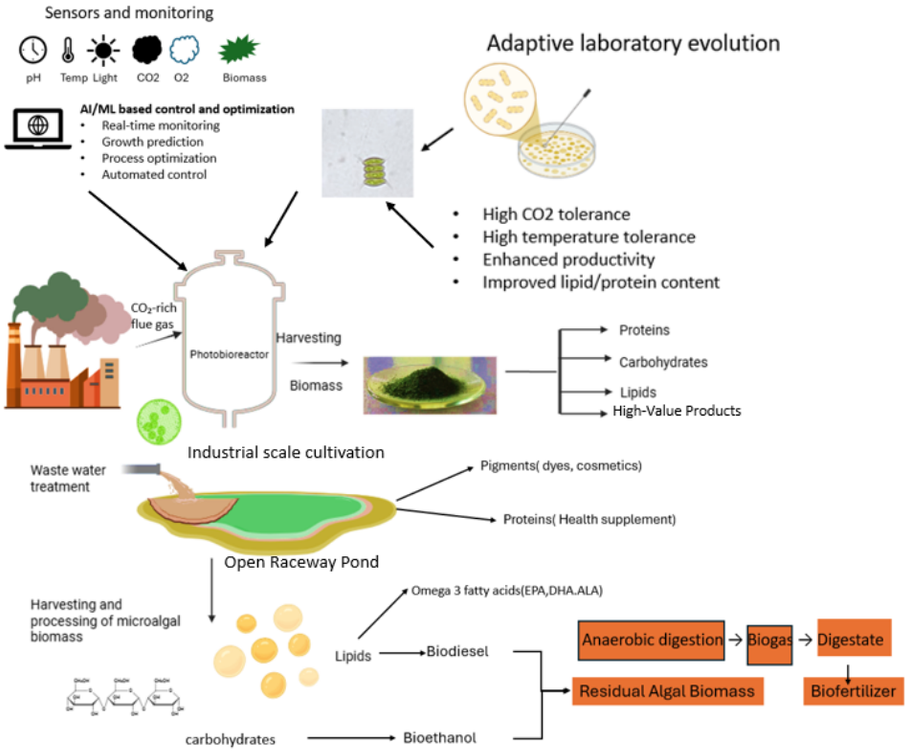


Figure 1: Microalgal CO_2 utilisation pathway from cultivation to biomass valorisation and resource recovery.

need to develop basic cultivation and harvesting capabilities from scratch, but would instead need to adapt existing systems to flue-gas feedstocks and, where relevant, incorporate the sensor and strain-improvement approaches discussed above.

The economic framing of these projects matters as much as the underlying biology. Global patent activity in microalgal biofuels rose sharply through the early 2010s and subsequently declined, highlighting the vulnerability of business models centred on a single commodity product whose economics are sensitive to energy-market conditions (Li et al., 2020). Techno-economic analysis across multiple algal biorefinery pathways bears this out: to reach economic viability, algal biofuel production must either incorporate higher-value non-fuel co-products or achieve drastic capital-cost reductions that have not yet materialised at scale (Cruce and Quinn, 2019). The more resilient model — one that several of the cases reviewed above point toward, from Hazira's biogas co-product to Malaysia's proposed integration of POME with CO□-rich flue gas — pairs carbon capture with higher-value products: lipid and carotenoid products have been reported to command approximately eightfold and 135-fold higher prices, respectively, in food-additive markets than as biofuel feedstocks (Sun et al., 2018). A laboratory whose existing technical strength lies in nutraceutical extraction and characterisation is, in this sense, well positioned to contribute to CO□-sequestration research: the same biomass-characterisation and product-recovery expertise that supports high-value extract development is directly transferable to evaluating the co-product economics of a carbon-capture strain, rather than being a separate line of work bolted onto it.

Closing the loop further, harvested biomass can be routed to anaerobic digestion for biogas, as demonstrated at Hazira, potentially recovering energy and reducing residual-waste disposal costs that would otherwise erode the economics of the facility (Yadav et al., 2016).

7. Policy, Financing and Cooperation Measures

Translating these technical building blocks into industrial deployment will require deliberate policy design across at least four areas.

First, demonstration-stage risk capital needs to be explicitly available for biological, and not only geological, CCU pathways. The NITI Aayog *Scenarios Towards Viksit Bharat and Net Zero* study identifies

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CCUS among technologies that remain at an early stage of deployment and require further development and demonstration in India (NITI Aayog, 2026a). The industry volume similarly indicates that a substantial share of India's future industrial emissions reductions will depend on technologies that are not yet available at commercial scale and remain at the pilot or demonstration stage (NITI Aayog, 2026a). Given the scale of investment required across the wider net-zero transition, dedicated support for emerging biological CCU pathways could help diversify India's portfolio of industrial decarbonisation technologies. Explicitly including microalgae-based utilisation in demonstration and support programmes alongside chemical and geological CCUS pathways could provide a route for biological CCU technologies to progress beyond the pilot stage. Biological CCU approaches also remain at varying stages of technological maturity; for example, the bio-integrated carbon capture and utilisation (BICCU) concept described by Sieborg et al. (2024) had reached only laboratory proof-of-concept development (TRL 2), highlighting the need for further demonstration before industrial deployment. Because microalgal biofixation can provide an alternative or complementary pathway to geological sequestration, it should be considered within demonstration-stage CCUS funding programmes alongside conventional capture and storage routes. Economic modelling has shown that integrating microalgal biofixation with geological sequestration can create synergies in CO□ abatement and supply-chain design (Yue et al., 2015). This is not a marginal financing question: the same study projects India's private-consumption share of GDP to decline from 58% in 2025 to 52% by 2070, while public spending and investment gain importance (NITI Aayog, 2026b).

Second, carbon-market design needs to catch up with biological utilisation specifically. China's national emissions trading scheme has expanded beyond the power sector to cover steel, cement and aluminium smelting, with the expanded coverage applying from the 2024 compliance year, while the country is also developing policies aimed at controlling both total carbon emissions and carbon intensity (International Carbon Action Partnership, 2025). In principle, such market mechanisms could create a future revenue stream for verified microalgal CO□ utilisation. However, monitoring, reporting and verification (MRV) frameworks for emerging carbon-removal pathways are still developing, with approaches being developed in a fragmented manner across stakeholders (Hoffmann et al., 2026). Establishing credible MRV methods for biological CO□ utilisation will therefore be important for its meaningful participation in carbon markets and offset mechanisms.

Third, intellectual property and access-and-benefit-sharing frameworks need deliberate attention as the field commercialises. Patent activity in algae-related biotechnology has historically concentrated in the United States, Japan, and China (Li et al., 2020), and the Budapest Treaty provides an internationally recognised mechanism for depositing microorganisms for patent-procedure purposes (WIPO, 2026), but developing-country research institutions across the wider Asia-Pacific region need better practical access to these mechanisms if they are to protect strains they develop rather than depending entirely on licensed foreign technology. Because biodiverse marine and coastal environments represent important sources of microbial and algal resources for bioprospecting (Chen et al., 2024; Pattapulavar et al., 2026), research programmes should build Nagoya Protocol-consistent access-and-benefit-sharing procedures into strain-collection work from the outset (Convention on Biological Diversity, 2011), both as a legal safeguard and as a matter of equitable practice with the communities and ecosystems from which strains are sourced.

Fourth, cross-border technology transfer within the region should be actively cultivated rather than left incidental. The Japan–Thailand collaboration between IHI Corporation and NEDO, which established integrated cultivation and SAF-production technology using fast-growing microalgae and operated a pilot outdoor cultivation facility in Saraburi, Thailand, provides a working example of bilateral technology demonstration; microalgae-derived SAF was subsequently supplied to regular commercial flights in Japan (NEDO, 2021; IHI, 2021). Similar partnerships could link India's cement-sector CCUS test beds with Southeast Asian palm-oil-sector POME–CO□ integration work, where the underlying biological and engineering challenges overlap substantially despite differing feedstocks. Regional bodies with an explicit technology-transfer mandate are well placed to broker exactly this kind of matchmaking between complementary pilot experiences.

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Gender considerations are also relevant to how this transition is designed, not only how it is measured. Biorefinery pathways oriented toward nutraceutical, food, and feed applications could create downstream opportunities in quality control, formulation, and extension services. Deliberately designing skill-development programmes and small-scale enterprise models — for example, POME-fed or wastewater-fed algae units suited to cooperative or smallholder operation — could help broaden participation in the emerging circular bioeconomy and ensure that employment opportunities are distributed across the value chain rather than concentrated solely in capital-intensive industrial roles.

8. Conclusion

Asia-Pacific occupies a distinctive position in the global carbon-utilisation landscape: it hosts a major concentration of the industrial CO□ sources that need to be addressed and a large existing base of commercial microalgae cultivation capacity that could help address them. The pilot projects reviewed here — from Hazira's carbonation column to Euglena Co.'s exhaust-gas trials, from ENN Group's coal-fed cultivation tubes to Malaysia's POME-integrated systems — have demonstrated the technical feasibility of microalgal carbon utilisation across different industrial contexts. What has been missing is the combination of process technologies that make cultivation reliable and cost-effective at industrial scale: sensor- and AI-enabled photobioreactor control to close the monitoring gap; non-GM adaptive strain engineering to improve CO□ and temperature tolerance and maintain productivity under industrial conditions; biorefinery economics anchored in diversified, high-value product portfolios rather than biofuel alone; and financing, carbon-market, and intellectual-property frameworks specifically calibrated to the bio-resource-dependent character of biological CCU. Bringing these elements together within the region's existing cultivation infrastructure, rather than building parallel capacity from scratch, offers a practical pathway for Asia-Pacific to move from being a site of pilot demonstrations to a genuine architect of the circular bioeconomy transition its industrial emissions profile now demands.

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The Missing Provenance Layer: Patent Disclosure, Genetic Resources and Commercialisation Readiness for Australia's Bioeconomy

Pratap Devarapalli*[1,2,3,4] and Seema Soni[1,2]

[1] Faculty of Business, Economics and Law, University of Queensland, St Lucia, Queensland, Australia

[2] ARC Centre of Excellence for Plant Success in Nature and Agriculture, Australia

[3] ARC Centre of Excellence in Synthetic Biology, Australia

[4] Centre for Law and Genetics, Faculty of Law, University of Tasmania, Australia

* Corresponding author: Dr Pratap Devarapalli, p.devarapalli@uq.edu.au

Abstract

Australia's bioeconomy opportunity is often framed through scientific capability, patenting, investment and scale-up infrastructure. Yet for bio-based innovation involving native plants, microbial resources, biological materials, digital sequence information or associated Indigenous Knowledge, a further layer is becoming commercially decisive: provenance readiness. This article argues that provenance readiness should be treated as technology-transfer infrastructure for the Asia-Pacific bioeconomy. Using Australia as a country case study, it examines how patent disclosure, access and benefit-sharing, Indigenous Knowledge policy and digital sequence information governance are reshaping commercialisation practice. It also uses selected patent examples to show what patent documents disclose, and what they often leave invisible, about biological source, material access and benefit-sharing. The article proposes a practical checklist for universities, start-ups, MSMEs, public research organisations and policymakers seeking to move bio-based innovation into responsible regional markets.

Keywords: bioeconomy; patent disclosure; genetic resources; traditional knowledge; technology transfer; access and benefit-sharing; digital sequence information; Australia; Asia-Pacific

1. Introduction: Why does provenance now matter?

The Asia-Pacific bioeconomy is increasingly moving from policy aspiration to practical implementation. Across the region, biological resources, biological processes and bio-based innovations are being positioned as pathways to produce food, energy, materials and services more sustainably. This transition is unfolding against a broader backdrop of climate change, biodiversity loss, resource depletion, food-system pressure and uneven development. In response, governments and regional institutions are placing greater emphasis on innovation systems, technology transfer, financing mechanisms, capacity-building and regional cooperation to support the responsible deployment of bio-based technologies. ESCAP Resolution 82/2 reflects this shift by supporting the transition towards a sustainable bioeconomy in Asia and the Pacific and calling for stronger innovation, finance and regional capabilities (Economic and Social Commission for Asia and the Pacific [ESCAP], 2026). The central policy question is therefore no longer whether biotechnology can contribute to sustainable development, but how bio-based innovation can be translated into commercially viable, socially responsible and regionally useful outcomes across countries with different institutional, technological and market capacities.

This article argues that one layer of that deployment pathway remains underdeveloped: provenance readiness. In conventional technology-transfer practice, commercialisation readiness is usually assessed through patentability, ownership, freedom to operate, market opportunity, regulatory pathway, investment case and technical validation. While these questions remain essential, bioeconomy innovation often depends on biological resources, native plants, microbial strains, biological samples, sequence information, data sets, plant varieties, Indigenous Knowledge or community-held knowledge. For those

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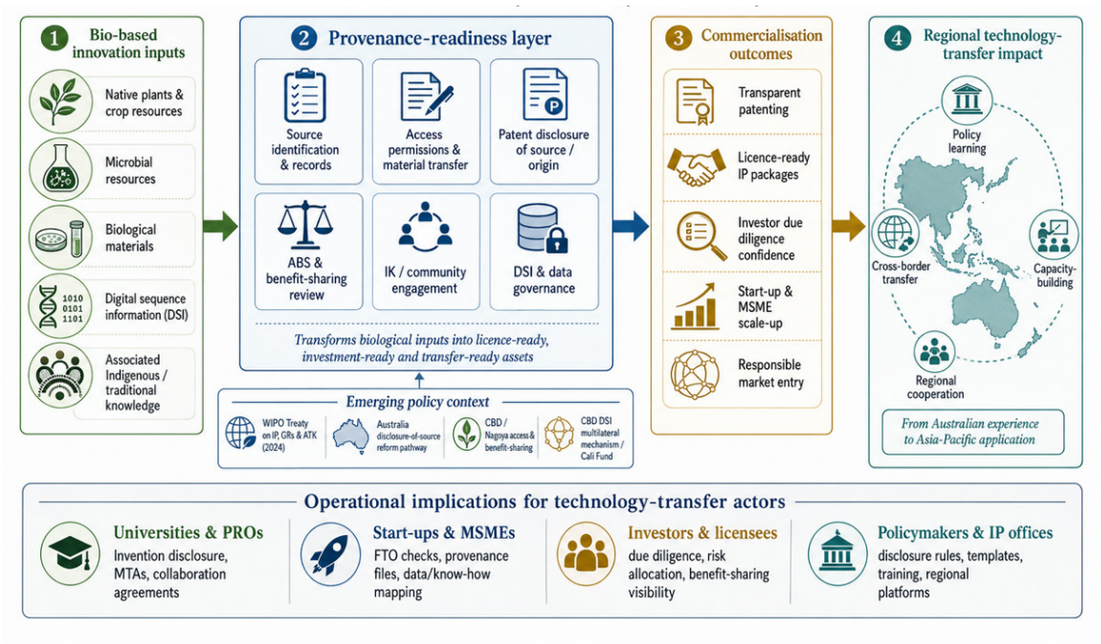


Figure 1: The missing provenance layer in bioeconomy commercialisation.

Bio-based innovation inputs become commercially transferable only after a provenance-readiness layer translates source, access, disclosure, ABS, Indigenous Knowledge and DSI/data governance into licence-ready, investment-ready and transfer-ready assets.

assets, the question is not only whether the invention is new or inventive. The question is whether the innovator can explain where the biological input came from, how it was accessed, what permissions apply, whether benefit-sharing expectations have been considered, how any associated Indigenous or traditional knowledge has been handled, and whether the resulting IP package is credible for licensing, investment and cross-border transfer.

Provenance readiness is therefore proposed here as a practical technology-transfer concept. It means the ability to identify, document, verify and disclose the biological and knowledge inputs that underpin a bio-based innovation, and to translate that information into patent strategy, contractual governance, investor due diligence and responsible market entry. It is a missing layer because it often sits between research compliance and commercial deal-making. Research teams may have ethics approvals, permits or collection records. Patent attorneys may draft claims around extracts, compounds, formulations, processes or engineered biological systems. Investors may review IP title and freedom to operate. Yet the chain connecting biological source, lawful access, knowledge contribution, patent disclosure and benefit-sharing is frequently not built as a coherent commercialisation asset.

Australia provides a useful case study for this argument. It is a biodiversity-rich economy with strong research capability, an active university technology-transfer system, growing interest in synthetic biology and plant science, and live policy developments on genetic resources and Indigenous Knowledge. It also sits in the Asia-Pacific region, where many economies face similar tensions between biodiversity-based opportunity, uneven research capacity, digital sequence information, Indigenous and local-community rights, and the need to support start-ups and MSMEs. The article therefore uses Australia as a practical policy laboratory from which broader lessons can be drawn.

2. From patentability to provenance readiness

Patentability has long been central to biotechnology commercialisation. A patent may help a public research organisation or start-up attract investment, define a protectable market position and negotiate a licence. But in the bioeconomy, patentability is only one part of the asset. A biologically derived product may also depend on a material transfer agreement, a plant collection permit, a microbial strain deposit, cultivation know-how, sequence data, extraction protocols, analytical data, Indigenous or traditional knowledge, or confidential scale-up information. Each of these components may affect whether the

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technology can be transferred. A patent can describe an invention sufficiently for patent-law purposes while saying little about the provenance records needed for access and benefit-sharing due diligence.

The distinction matters because technology transfer is a process of risk translation. A university or public research organisation converts research outputs into assets that another party can adopt, develop, finance, manufacture or sell. The transferee, whether a start-up, established company, community enterprise or overseas licensee, will ask practical questions. Who owns the invention? Are the claims supported? Are there third-party rights? Was the material collected lawfully? Can the material be transferred to another jurisdiction? Did the research use genetic resources or associated traditional knowledge? Does the patent application trigger a disclosure obligation? Are there ongoing obligations to access providers or communities? Can the product be developed for commercial use if the original collection was for non-commercial research only? These questions may not defeat the science, but they can delay or derail a deal.

Provenance readiness should not be seen as a substitute for patents but as a complement to them. In an ideal commercialisation workflow, the provenance file would sit alongside the invention disclosure, patentability assessment, freedom-to-operate review, data package, regulatory plan and financial model. It would record the biological material, source location where appropriate, access provider, collection authority, permit status, transfer chain, contractual restrictions, Indigenous Knowledge or community engagement issues, digital sequence information use and patent disclosure implications. Where information is unavailable, it would record the reasonable efforts made to identify it and the risk allocation proposed.

This is especially important for Asia-Pacific start-ups and MSMEs. Larger companies often have specialist regulatory, IP and compliance teams. Smaller firms may inherit university materials, published sequences, culture collection strains, plant extracts, research collaboration outputs or historical samples without a complete documentary chain. If provenance questions arise only during investment due diligence or licence negotiation, the practical options may be limited. Provenance readiness should therefore be treated as upstream infrastructure, not downstream repair.

3. Australia as a country case study

Australia's case is analytically valuable for three reasons. First, it combines biodiversity-based opportunity with strong commercial research capability. The Australian Government states that genetic resources from plants, animals and microorganisms are valuable in developing speciality enzymes, enhanced genes and small molecules, with uses across crop protection, drug development, specialised chemicals and industrial processing (Department of Climate Change, Energy, the Environment and Water [DCCEEW], 2026a). These are precisely the kinds of applications that the regional bioeconomy seeks to expand. Australia is also one of the world's megadiverse countries and has high levels of endemism, making biological-resource governance commercially and culturally significant (DCCEEW, 2026c).

Secondly, Australia has a fragmented but functioning access and benefit-sharing landscape. The Commonwealth, states and territories have different laws and processes for access to biological resources, depending on where biological samples are collected. Commonwealth areas are regulated under federal legislation and permits may be required, while states and territories operate their own systems (DCCEEW, 2026a). Australia is a party to the Convention on Biological Diversity (CBD) but is not currently a party to the Nagoya Protocol, which implements the CBD's access and benefit-sharing objectives for genetic resources (CBD, 2010; DCCEEW, 2026a). The Australian Government nevertheless states that its domestic measures are consistent with the Protocol (DCCEEW, 2026a). For commercial or potentially commercial access to biological resources in Commonwealth areas, a benefit-sharing agreement must be used, and the Minister must be satisfied that it was made with prior informed consent of access providers (DCCEEW, 2026b).

Thirdly, Australia is actively considering reforms concerning patent disclosure of genetic resources and Traditional Knowledge. IP Australia's Enhance and Enable Indigenous Knowledge consultations identified declaring the source of Indigenous Knowledge in new inventions and plant varieties as one possible reform to encourage transparency and recognition of Indigenous Knowledge owners (IP Australia, 2022). IP Australia now states that there is currently no requirement in the patent or plant breeder's rights

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system for applicants to disclose that they have used genetic resources or Traditional Knowledge in their inventions, or to disclose how and where they obtained those resources or knowledge (IP Australia, 2026). Australia signed the World Intellectual Property Organization (WIPO) Treaty in December 2024, and IP Australia is considering options to require patent applications to include disclosure of the source of genetic resources and Traditional Knowledge, with similar requirements potentially considered for plant breeder's rights (IP Australia, 2025; IP Australia, 2026).

These policy settings make Australia a useful microcosm of the broader Asia-Pacific challenge. Many countries in the region are rich in biological resources and associated knowledge, but differ in patent-office capacity, ABS implementation, technology-transfer maturity, bioinformatics capability and research funding. A practical Australian case study can show how provenance readiness might be built into technology-transfer practice before disputes arise. It can also show why disclosure rules, although important, are not enough. Disclosure is a patent-system trigger; provenance readiness is a broader commercialisation capability.

4. The emerging international disclosure and benefit-sharing environment

The international environment has changed rapidly since 2024. The WIPO Treaty on Intellectual Property, Genetic Resources and Associated Traditional Knowledge was adopted on 24 May 2024 after more than two decades of negotiations (World Intellectual Property Organization [WIPO], 2024b). WIPO explains that the Treaty aims to enhance the efficacy, transparency and quality of the patent system in relation to genetic resources and associated traditional knowledge, and to prevent patents being granted erroneously for inventions that are not novel or inventive in light of such resources or knowledge (WIPO, 2024a). The Treaty establishes a mandatory disclosure requirement where claimed inventions are based on genetic resources or associated traditional knowledge. Applicants must disclose the country of origin of the genetic resources and/or the Indigenous Peoples or local community providing the associated traditional knowledge, where that information is known. If not known, the source must be disclosed, or the applicant must declare that the information is not known (WIPO, 2024a).

The Treaty is procedurally cautious but symbolically important. It does not create new substantive rights in genetic resources or traditional knowledge. It does not by itself require benefit-sharing. It also provides that, fraud aside, failure to disclose should not be the sole basis for revoking or rendering unenforceable a patent (WIPO, 2024a). Yet the Treaty matters because it inserts source and knowledge disclosure into the global patent architecture. As Perron-Welch (2026) argues, the Treaty is a doctrinally significant development within the global ABS regime complex, strengthening procedural transparency while leaving implementation to national legal systems. Okediji (2025), Oguamanam (2025), and Yu (2024) similarly emphasise that the Treaty represents a major step in international IP governance, even if its practical impact will depend on implementation, patent-office guidance, databases and national policy choices.

Digital sequence information adds a further layer. The CBD Conference of the Parties first addressed DSI on genetic resources in 2016. In 2022, COP15 decided to establish a multilateral mechanism for benefit-sharing from the use of DSI, and in 2024 COP16 adopted modalities for operationalising that mechanism, including the Cali Fund (CBD, 2025a). The Cali Fund was launched in February 2025 and is intended to receive contributions from private-sector entities making commercial use of DSI. The CBD states that 50 per cent of Cali Fund resources will be allocated to the self-identified needs of Indigenous Peoples and local communities, including women and youth (CBD, 2025b). The CBD also identifies sectors expected to contribute where they commercially benefit from DSI, including pharmaceuticals, cosmetics, plant and animal breeding, agricultural biotechnology, industrial biotechnology, sequencing-related laboratory equipment and information, and scientific and technical services related to DSI, including artificial intelligence (CBD, 2025b).

Recent scholarship underscores the practical implications. The DSI Scientific Network (2025) explains that DSI is widely available through open databases and that synthetic biology, gene editing and AI can enable commercial product development without access to physical genetic resources. Blom et al. (2025) describe COP16's multilateral mechanism as a transition from frameworks to finance, with remaining challenges in how benefit-sharing contributions are triggered and implemented. Lawson et al. (2025) extend the

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debate to AI, machine learning and deep learning, arguing that information and knowledge about biological materials create new challenges for ABS governance. Together, these developments support the article's central claim: commercial bioeconomy actors increasingly need a provenance system that links patents, materials, data and knowledge, not a siloed approach to IP.

5. Patent documents as evidence: what they reveal and what they leave invisible

Patent documents are useful sources of technology information. They can identify applicants, priority dates, jurisdictions, claim categories, technical fields, cited literature and sometimes species, extracts, accession numbers, sequences, deposits, culture collections or geographical source. For technology-transfer professionals, patent documents can therefore help map opportunity spaces, detect commercialisation trajectories and identify possible freedom-to-operate risks. In bioeconomy contexts, however, patent documents are imperfect provenance records. Their legal function is to disclose the invention sufficiently and define the claimed monopoly. They are not designed to provide a complete chain-of-custody record for genetic resources, biological materials, Indigenous Knowledge, benefit-sharing agreements or material-transfer restrictions.

A targeted patent-document scan can demonstrate this gap without claiming to be a comprehensive patent landscape. For the present article, selected public patent examples involving Australian or Australia-associated biological resources were reviewed to ask a narrow question: what kinds of provenance information are visible in patent documents, and what kinds of information remain outside the patent record? The examples include patents concerning Terminalia ferdinandiana, commonly known as Kakadu plum, Melaleuca alternifolia, commonly known as tea tree, and Eucalyptus-related extracts and processes. These examples were selected because they involve identifiable plant-derived resources with commercial applications in cosmetics, antimicrobial products, textiles or extraction processes.

The pilot scan suggests a recurring pattern. Patent documents often identify the biological species and sometimes provide a broad geographical or ethnobotanical background. For example, patent documents relating to Terminalia ferdinandiana leaf or fruit extracts may state that the plant grows wild in northern Australia or that the fruit has a history of Indigenous use as food or medicine. Melaleuca and Eucalyptus patent documents may identify the species, the oil or extract, the relevant composition, or the extraction process. This information can assist technical understanding and patent classification. But it usually does not answer the commercialisation questions that provenance readiness requires: who supplied the material, whether collection was authorised, whether an access provider or Indigenous community was engaged, whether the material was transferred through an intermediary, whether commercial use was within the original permission, whether benefit-sharing was agreed, and whether any associated knowledge shaped the research direction.

This does not mean that the patent applicants acted improperly. The point is structural. A patent document may be adequate for patentability and still inadequate for downstream licence due diligence. Conversely, a patent document that includes broad statements about plant origin or traditional use may create reputational or regulatory questions if it does not also show how source, access and benefit-sharing were handled. For technology-transfer actors, the practical lesson is that patent information must be supplemented by a provenance file held by the research institution or company.

Table 1 summarises the kinds of information commonly visible in selected bio-based patent documents and the provenance questions that typically remain invisible. The table is illustrative rather than exhaustive. It is intended to show why patent analytics should be used as an entry point for commercialisation due diligence, not as a substitute for it.

6. Commercialisation implications for technology-transfer actors

The immediate implication is that technology-transfer offices should treat provenance information as part of the invention intake process. Many invention disclosure forms ask whether third-party IP,

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Table 1: **Illustrative patent-document scan: visible disclosure and invisible provenance questions**

Patent example and resource	Information visible in patent document	Provenance information usually not visible	Commercialisation implication
Terminalia ferdinandiana leaf/fruit extract examples, including AU2017379412A1 and US20200016062A1	Species name, extract type, cosmetic or product use, and broad statements about northern Australian distribution or known properties.	Specific collection site, access provider, material-transfer history, Indigenous Knowledge engagement, benefit-sharing terms and permission for commercial use.	Patent document may support technical assessment, but a separate provenance file is needed for licence, investor and reputational due diligence.
Kakadu plum cosmetic composition examples, including US10918591B2	Species and extract used in a topical composition, sometimes alongside another botanical extract.	Supply chain, community benefit-sharing, traditional-use connection, and source documentation.	Commercial use of high-profile native ingredients may require strong provenance records even where the patent claims are formulation-specific.
Melaleuca alternifolia oil composition examples, including WO1999048511A1 and WO2022003731A1	Species, essential oil fractions, antimicrobial use, fabric finish use, or composition ranges.	Whether the oil was sourced from cultivated material, wild material, intermediaries or particular jurisdictions, and whether any benefit-sharing arrangements apply.	Established commercial botanicals can still raise provenance questions when used in new bio-based products or cross-border licensing.
Eucalyptus extract/process examples, including EP2286678A1	Species/genus reference, extraction process and technical effect.	Exact biological source, access pathway, material provenance and local/community knowledge contribution.	Process claims can create commercial value without revealing enough about biological-resource governance for technology-transfer purposes.

research tools, grants, students, collaborators or publications are involved. For bioeconomy inventions, comparable questions should be asked about biological materials, collection permits, access providers, intermediaries, Indigenous Knowledge, traditional-use information, sequence data and intended commercial fields. This should not be reduced to a compliance checkbox. It should be used to build an evidence pack that can travel with the technology from laboratory to patent filing, option agreement, licence, start-up formation or investor review.

Material transfer agreements are particularly important. A biological material may move several times before it becomes part of an invention. It may pass from a landholder to a researcher, from a herbarium or culture collection to a laboratory, from one university to another, or from a public research organisation to a start-up. Each transfer may carry restrictions on use, publication, onward transfer, commercialisation or benefit-sharing. The Nagoya Protocol Best Practice Guidelines of the ARC Centre of Excellence in Synthetic Biology (CoESB) recognise this problem in practical terms. They state that when researchers receive genetic resources from intermediaries such as herbaria, traders, nurseries or culture collections, they should inquire whether the resources are ABS compliant, and if the intended use goes beyond an existing agreement, a new benefit-sharing agreement covering commercial uses should be negotiated (ARC Centre of Excellence in Synthetic Biology, 2026).

Investors and licensees also need a clearer provenance position. In many technology deals, patent title and freedom to operate receive detailed attention, but access and benefit-sharing obligations are treated late or not at all. This can create hidden liabilities. A licensee may discover that the licensor cannot provide evidence of lawful access, that commercial use was not covered by the original collection permission, or that the patent filing will trigger disclosure questions that the research team cannot answer confidently. Even where legal risk is manageable, reputational risk may be material, especially for consumer-facing products involving native plants, cosmetics, foods, nutraceuticals or wellness claims. Provenance readiness therefore strengthens bargaining credibility. It gives investors and licensees a basis to allocate risk rather than abandon the transaction.

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Start-ups and MSMEs face the most acute burden. They are often encouraged to use biodiversity, waste streams, microbial platforms and local biological resources to create sustainable products, but they may lack access to patent analytics, ABS advice and template agreements. For them, provenance readiness should be simplified into practical tools: a source record, a material-transfer record, a permissions map, a data-use map, a patent disclosure assessment and a benefit-sharing risk note. These tools do not remove the need for legal advice. They reduce the likelihood that commercialisation stalls because foundational information was never collected.

For Indigenous Peoples and local communities, provenance readiness can support recognition, consent, benefit-sharing and control over the use of knowledge and resources. However, it must be implemented carefully. Documentation systems should not extract or expose sensitive knowledge without community authority. The WIPO Treaty itself contemplates information systems for genetic resources and associated traditional knowledge in consultation with Indigenous Peoples, local communities and other stakeholders (WIPO, 2024a). The practical lesson is that better information can support patent examination and commercialisation, but only if information governance respects cultural authority, confidentiality, data sovereignty and local benefit.

7. A provenance-readiness framework for the Asia-Pacific bioeconomy

The framework proposed here has five stages. The first is input identification. The research team should identify each biological input, including plant material, microbial resource, tissue, germplasm, extract, compound, environmental sample, database sequence, AI-generated biological design or associated knowledge claim. Vague descriptions such as ‘plant extract’ or ‘microbial sample’ may be insufficient for later patent disclosure, material transfer or benefit-sharing questions. Where scientific uncertainty exists, the uncertainty should be recorded.

The second stage is access and source verification. The relevant question is not merely who supplied the material to the laboratory, but who had authority to permit access and use. This is particularly important where materials arrive through intermediaries. The CoESB guidelines define intermediaries to include nurseries, museums, arboretums, seed traders, herbaria or microbiome culture collections (ARC Centre of Excellence in Synthetic Biology, 2026). In commercialisation terms, an intermediary can be a weak link in the chain if the original collection circumstances are unclear.

The third stage is knowledge and data mapping. Bioeconomy innovations increasingly combine physical material with information. DSI may allow product development without repeated physical access to genetic resources. AI and machine learning can also identify patterns, predict functions, design biological pathways or screen biological candidates. The provenance file should therefore map not only tangible material, but sequence data, databases, metadata, associated publications, traditional-use references and community-held knowledge inputs. Where knowledge is culturally sensitive or confidential, the record should indicate governance conditions rather than disclose restricted content.

The fourth stage is IP and patent disclosure assessment. Before filing, the institution should ask whether the claimed invention is based on genetic resources or associated traditional knowledge in a way that may trigger disclosure obligations under current or emerging law. In Australia, this issue is live because IP Australia is considering disclosure-of-source options for patents and potentially plant breeder’s rights (IP Australia, 2026). For cross-border patent strategies, the assessment should also consider disclosure requirements in other jurisdictions. Even before formal rules apply, voluntary clarity may support commercial credibility where the provenance information is available and appropriate to disclose.

The fifth stage is deal integration. Provenance information should be reflected in licences, collaboration agreements, MTAs, start-up assignments, investment due diligence and benefit-sharing arrangements. A licence that grants commercial rights without addressing material-transfer restrictions or benefit-sharing obligations may create uncertainty. A start-up licence should specify whether the company receives patents only, or also biological materials, strains, samples, know-how, data, regulatory materials and the right to continue negotiations with access providers. Investor due diligence should include a provenance schedule in the data room, not only a patent schedule.

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8. Policy lessons for Asia-Pacific regional cooperation

The policy implications extend beyond Australia. Asia-Pacific economies differ widely in biodiversity, industrial capability, patent-office resources, ABS implementation, Indigenous and local-community governance, and bioeconomy finance. A single regional model would be unrealistic. However, ESCAP and member States can support common infrastructure that helps innovators move from research to responsible markets.

First, the region should develop provenance-ready technology-transfer templates. These could include model invention disclosure questions for bioeconomy inventions, standard material-transfer clauses, benefit-sharing issue checklists, patent disclosure prompt sheets and licence schedules for genetic resources and associated knowledge. Templates should be adaptable to national law and community protocols. Their value would not lie in legal uniformity, but in making the right questions routine.

Secondly, regional capacity-building should include patent and provenance analytics. Patent databases are valuable technology-information sources, but users need to understand their limits. Training should teach TTOs, start-ups and MSMEs how to read patent documents for species, source, accession numbers, deposits, assignee patterns, claim scope and missing provenance information. The goal is to build enough capability to identify risks early and seek specialist support where needed.

Thirdly, patent offices and innovation agencies should coordinate with biodiversity and Indigenous Knowledge authorities. Disclosure-of-source rules will be implemented through patent systems, but the information they depend on often sits in environmental law, community governance, research ethics, databases, permits and material-transfer documents. Without coordination, disclosure may become a formal statement disconnected from benefit-sharing practice. With coordination, disclosure can become a gateway to better technology-transfer documentation.

Fourthly, ESCAP could support regional peer learning between biodiversity-rich and technology-intensive economies. Australia, India, ASEAN economies, Pacific Island States, Japan, Singapore and the Republic of Korea bring different strengths. Some have advanced biotech manufacturing capability, some have rich biodiversity and community knowledge systems, some have strong patent-office infrastructure, and some have high MSME relevance in agricultural and natural-product sectors. A regional provenance-readiness agenda would help these systems interact more fairly.

Fifthly, blended finance and innovation programmes should require appropriate provenance documentation early. Funding programmes that support bio-based start-ups, circular bioeconomy pilots, biodiversity-based products or synthetic biology applications should not wait until market entry to ask provenance questions. A staged approach would be more practical: light-touch screening at grant application, detailed provenance planning at proof-of-concept, contractual review before pilot transfer, and full due diligence before commercial licensing or investment. This is consistent with wider climate technology transfer literature, which cautions that IP debates can obscure the importance of finance, local adaptation, co-development and institutional capacity (Jee et al., 2024).

9. Inclusion and community dimensions

Provenance readiness has an inclusion dimension because benefit-sharing may include employment, training, scholarships, co-authorship, attribution, research participation, community-controlled data governance and support for local enterprises. The CBD has stated that 50 per cent of Cali Fund resources will be allocated to the self-identified needs of Indigenous Peoples and local communities, including women and youth (CBD, 2025b). This provides a useful signal for bioeconomy commercialisation: inclusive benefit-sharing should be considered at the design stage, not treated as a reputational add-on.

For Australia and the wider region, the relevant policy question is how to avoid reproducing extractive models of innovation. A provenance-ready system should ask who contributes knowledge, who controls access, who bears environmental and cultural risk, and who participates in value creation. For community-based enterprises and MSMEs, the framework should be enabling rather than burdensome. The objective is to make responsible commercialisation easier by clarifying expectations, not to make bioeconomy innovation administratively impossible.

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Table 2: Provenance-readiness checklist for bioeconomy technology transfer

Readiness question	Evidence to collect	Who should own the task?	Commercialisation use
What biological inputs underpin the invention?	Species/strain names, sample identifiers, collection notes, accession or deposit records, sequence identifiers.	Research team with TTO support.	Defines patent disclosure, material transfer and technical due diligence scope.
How were resources accessed?	Permits, prior informed consent records, access-provider details, intermediary declarations, collection location where appropriate.	Research team, compliance office and TTO.	Reduces licence risk and supports evidence-based warranties.
Are Indigenous Knowledge or community knowledge inputs relevant?	Engagement record, consent pathway, confidentiality restrictions, benefit-sharing expectations, attribution preferences.	Research team with Indigenous governance expertise.	Supports ethical commercialisation and avoids reputational harm.
Was DSI or public database information used?	Database records, sequence identifiers, data-use terms, AI/ML training or screening records.	Research team, data steward and TTO.	Supports data governance, DSI benefit-sharing review and product-traceability claims.
Is patent disclosure of source/origin required or advisable?	Patent disclosure assessment, jurisdictional matrix, statements for patent attorney, uncertainty record.	Patent attorney and TTO.	Enables transparent filing and reduces future correction risk.
How will benefits be shared?	Benefit-sharing agreement, public benefit-sharing declaration, non-monetary benefit plan, royalty or milestone terms where appropriate.	TTO, legal team and access provider/community representatives.	Converts compliance obligations into deal terms.
Can the asset be transferred?	MTA review, licence restrictions, onward transfer rights, export or import restrictions, permitted commercial fields.	TTO and legal team.	Determines whether the technology can be licensed, assigned or spun out.

10. Conclusion

The Asia-Pacific bioeconomy will not be built by patents alone. Nor will it be built by biodiversity access rules alone. It will require practical systems that convert biological resources, data, knowledge and research outputs into assets that can be trusted, licensed, financed and transferred. Provenance readiness is the missing layer in that process.

Australia's current policy setting illustrates the opportunity. The country has biodiversity resources, public research capability, commercialisation institutions and live reform discussions on disclosure of source for genetic resources and Traditional Knowledge. It also faces the practical complexity of fragmented access laws, Indigenous Knowledge governance, DSI developments and cross-border technology transfer. These features make Australia a useful case study for the Asian and Pacific Centre for Transfer of Technology (APCTT) and its regional audience.

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The key recommendation reflecting this discussion is that provenance should be built into technology-transfer workflows before patent filing, licensing or investment due diligence. Specifically, invention disclosures should ask provenance questions and patent strategies should consider source/origin disclosure. At the commercialisation level, MTAs should preserve access and benefit-sharing terms, start-up licences should transfer the provenance documentation needed to use biological materials responsibly, and investors should ask for provenance files alongside the appropriate patent schedules and IP strategy. From the policy support perspective, it would be helpful if policymakers provide templates, training and regional cooperation mechanisms.

If Asia-Pacific economies are to use bio-based innovation to address climate change, biodiversity loss, resource depletion and inequality, they need commercialisation systems that are technically credible and socially legitimate. Provenance readiness can help provide that bridge. It turns biological origin, access, Indigenous Knowledge, data governance and benefit-sharing from late-stage risks into early-stage technology-transfer infrastructure. That is the practical step needed to move from native bio-resources to responsible bioeconomy markets.

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Tech Events

4–6 November 2026
World Hydrogen Expo 2026 (H2 MEET)
Goyang, Republic of Korea
Contact:
World Hydrogen Expo Organizing Committee
Tel: +82 2 3660 1858
Email: h2meet@h2meet.com
https://www.h2meet.com/

11–12 November 2026
Solar & Storage Live Indonesia 2026
Tangerang, Indonesia
Contact:
Mr. Steven Tang
Sponsorship and Exhibition
Email: steven.tang@terrapinn.com
https://www.terrapinn.com/exhibition/solar-storage-live-indonesia/

17–19 November 2026
Bengaluru Tech Summit 2026
Bengaluru, India
Contact:
Event Secretariat
MM Activ Sci-Tech Communications
Tel: +91 80 6932 8400
https://www.bengalurutechsummit.com/

18–20 November 2026
Smart Energy Week Osaka 2026
Osaka, Japan
Contact:
RX Japan GK (Organiser)
Tel: +81 3 6739 4119
https://www.wsew.jp/osaka/en-gb.html

18–20 November 2026
Singapore FinTech Festival 2026
Singapore
https://www.fintechfestival.sg/

26–28 November 2026
28th China Hi-Tech Fair (CHTF)
Shenzhen, China
Contact:
Ms. Sarah Wang
Visitor Enquiries
Tel: +86 151 3061 3049
Email: sarah@zhenweiexpo.com
https://www.chtf.com/english/

January 2027
International Conference on Biotechnology and Bioengineering (ICBB)
Bali, Indonesia; Tokyo, Japan; Singapore (multiple locations)
https://conferenceindex.org/conferences/bioeconomy

12–14 January 2027
World Future Energy Summit 2027
Abu Dhabi, United Arab Emirates
https://www.worldfutureenergysummit.com/

28–31 January 2027
India Energy Week 2027
Kolkata, India
Contact:
Ms. Nidhi Kumar
Delegate Enquiries
Tel: +91 83770 57122
Email: delegates@indiaenergyweek.com
https://www.indiaenergyweek.com/

24–25 February 2027
5th ANZ Biologics Festival 2027
Melbourne, Australia
https://www.imapac.com/events/anz-biologics-festival-2027

3–4 March 2027
Bio Innovations APAC 2027 — Industrial Biomanufacturing
Gardens by the Bay, Singapore
https://www.bioinnovationsapac.com/

4–5 March 2027
Solar & Storage Live Thailand 2027
Bangkok, Thailand
Contact:
Ms. Korawan Pinyovanichkul
Sponsorship and Exhibition
Email: korawan.pin@terrapinn.com
https://www.terrapinn.com/exhibition/solar-storage-live-thailand/

9–11 March 2027
The smarter E India 2027 (Intersolar India, ees India, Power2Drive India)
Gandhinagar, India
Contact:
Mr. Brijesh Nair
Group Exhibition Director
Tel: +91 22 4255 4707
Email: brijesh.nair@mm-india.in
https://www.thesmartere.in/

17–18 March 2027
11th Biologics Festival India 2027
Hyderabad, India
https://www.imapac.com/events/biologics-festival-india-2027

24–26 March 2027
Smart Energy Week [Spring] 2027
Tokyo, Japan
Contact:
RX Japan GK (Organiser)
Tel: +81 3 6739 4119
https://www.wsew.jp/spring/en-gb.html

14–15 April 2027
Solar & Storage Live Malaysia 2027
Kuala Lumpur, Malaysia
Contact:
Mr. Steven Tang
Sponsorship and Exhibition
Email: steven.tang@terrapinn.com
https://www.terrapinn.com/exhibition/solar-storage-live-malaysia

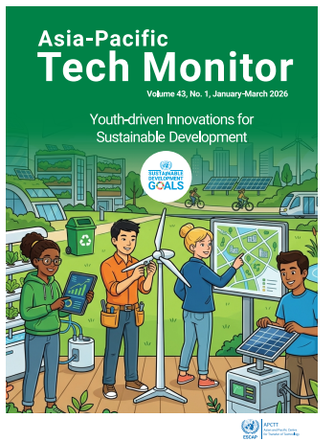
29–30 April 2027
GITEX AI Asia 2027
Singapore
https://gitexasia.com/

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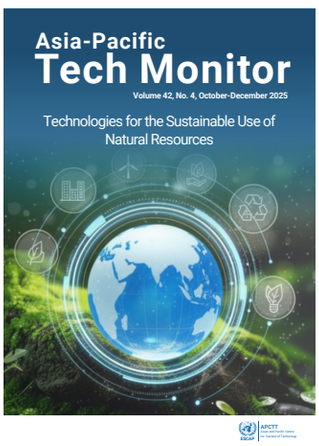
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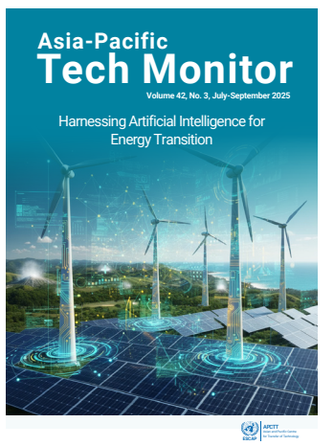
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C2, Instituitional Area, New Delhi 110016, India

www.apctt.org apctt.techmonitor@un.org +91 11 69013710

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