PLACE 2024

Nourishing the final frontier

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THE ANNUAL REPORT OF

PLANTS FOR SPACE
ARC CENTRE OF EXCELLENCE

Australian Government
Australian Research Council

PLACE

For those that know us it will not be a surprise that we wanted to do something a little out of the ordinary for our Annual Report.

Just like for our logo design, we ran a competition to seek the ideas of our community to give our annual report an identity that was fit for purpose – that captured our essence and was consistent with our culture.

We instantly connected with the name, not just because it is a contraction of 'Plants for Space', but also for the word PLACE itself.

'Sense of place', wherever we are as humans, is part of the DNA of the Centre. We are developing technologies for all places, whether in space or anywhere on Earth, to make these places a better home while connecting us back to nature. For this reason, the word and its meaning really resonated as a reflection of our philosophy.

We hope you enjoy engaging with us over the following pages.

The Plants for Space (P4S) team

We are a global collaborative network funded by the Australian Research Council and our partners.

Our five Australian University nodes are:

Our partner organisations:

Acknowledgement of Country

In the spirit of reconciliation, Plants for Space acknowledge the Traditional Custodians of Country throughout Australia and their deep connections to land, sea, and sky. We pay our respect to their Elders past and present and extend that respect to all Aboriginal and Torres Strait Islander peoples today.

Contents

Driving change

"This is so exciting and a huge step forward for the plant space community worldwide."

Gioia Massa
Project Scientist at NASA Kennedy Space Centre

"This research will be a pivotal step toward understanding how we might use agriculture in space to support human crews, paving the way for sustained lunar exploration and even missions to Mars."

Christine Escobar
LEAF Project Lead and Space Lab Vice President

"As humankind looks to return to the Moon, this time we do it with the view to establishing a sustainable presence that will allow us to explore further than ever before."

Enrico Palermo
Head of the Australian Space Agency

"The goal, to provide fresh food for astronauts without the workload."

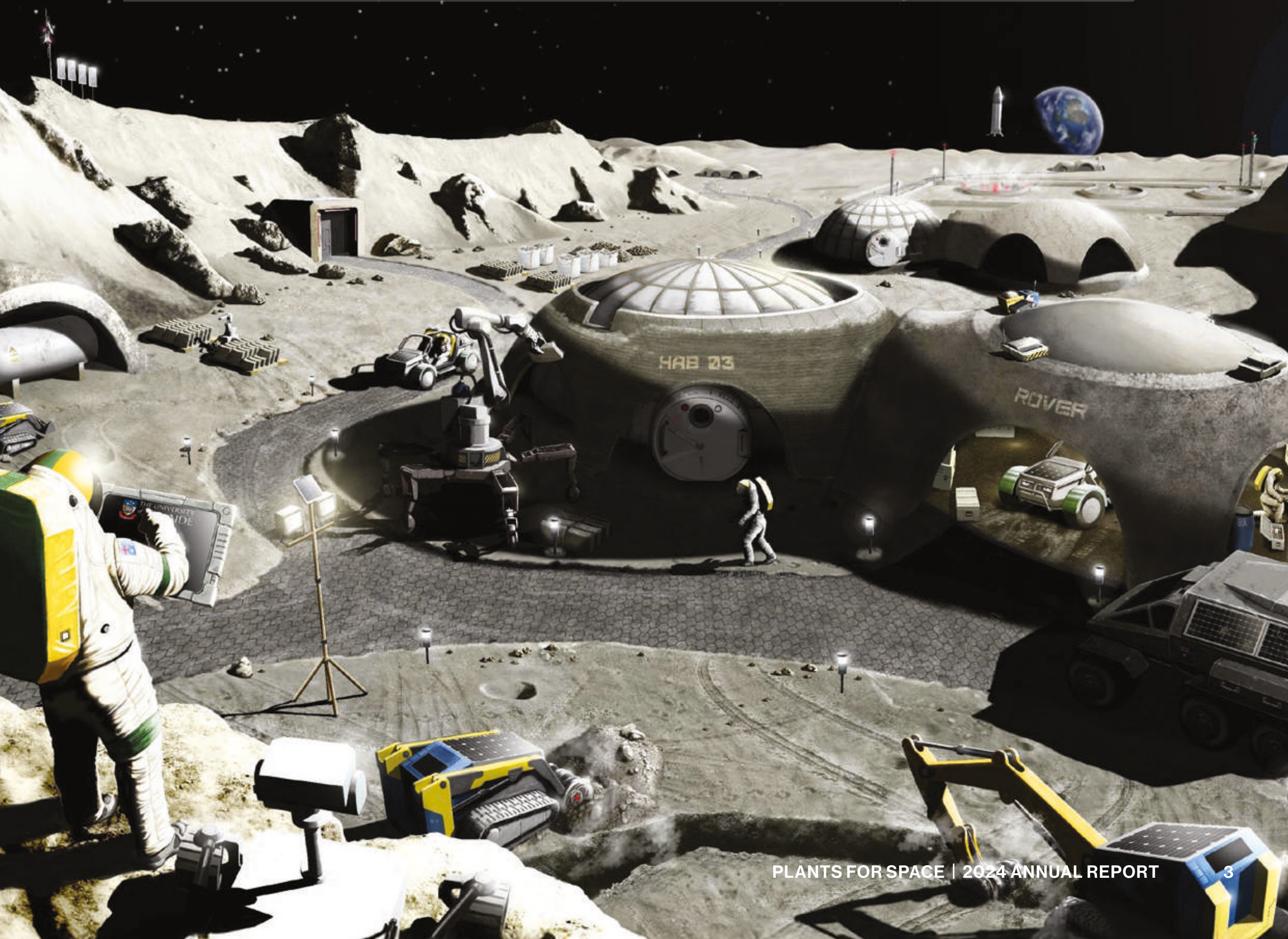
Steven Thomas
Ten News First

"Australia is a producer of great ideas and innovations, and if this project is successful, it could position Australia as a key partner in future long-range space travel and [settlement]. But, it could also have applications on Earth, by creating cheap and sustainable food production wherever we need it."

Ryan Winn
CEO at Science and Technology Australia

> "We clearly have seen the extraordinary university system that Australia offers, and that is really important to us. The research that we do is the foundation of the future, so the technical activities, such as we saw with Plants for Space at the University of Adelaide, those are the foundational investments that will support us on Moon to Mars, and Artemis, and going out into the solar system."

Col. (USAF, ret) Pam Melroy
NASA Deputy Administrator (2021-2025)



Bill Nelson
@SenBillNelson

I had a fantastic time hearing from ARC Plants for Space researchers at the University of Adelaide! Fascinating to see how cutting-edge plant technology can facilitate long-term space travel and support Artemis missions.

4:00 AM · Mar 21, 2023 · **12K** Views

49 30 144

Senator Bill Nelson, NASA Administrator (2021-2025)

From the Chair of the Advisory Committee

It is my pleasure, as Chair of the Advisory Committee of the ARC Centre of Excellence in Plants for Space, to extend my congratulations for the official launch of the Centre, following its establishment in early 2024, and for its achievements and strategic planning to date.

The exploration and use of space for peaceful purposes is a crucial endeavour for the future of humanity, enabling us all to learn more about the wonders of space, whilst at the same time providing incredible benefits across the globe.

> Yet, we are still at a relatively early stage in our extraterritorial adventures – untold possibilities await us with the rapid development of technology and space-science.

In this regard, the work of the Centre is crucial. Our future in space will, increasingly, engage a greater human presence in orbit and, more significantly, on celestial bodies. The Centre is exploring and developing the technological capability and capacity to enable humans to survive and thrive in space. The work of the Centre in researching, designing, developing and validating new science that will facilitate in-space growth of plants will be an important aspect of these initiatives. World-leading researchers are collaborating to facilitate this important research.

Of course, the research undertaken by the Centre, though space-focused, will also be highly relevant for plant science on Earth, adding further to its significance. Together with a range of excellent partner institutions and agencies, the Centre sits at the forefront of plant science research and technology and will further the interests of humanity both extra-terrestrially and terrestrially.

I look forward with great interest to following the work and achievements of the Centre over the coming years and, together with my wonderful colleagues on the Advisory Committee, stand ready to offer whatever advice and guidance we can to help further promote its activities.

Steven Freeland

Emeritus Prof Steven Freeland

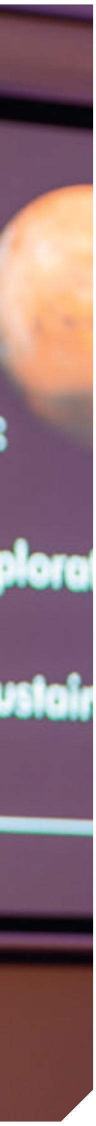
Chair of the Advisory Committee
ARC Centre of Excellence in Plants for Space

From the Director

As I sit down to write the Director's message for our first annual report, it's hard to reconcile with the reality that we have been operating effectively as a Centre for much longer. Though funding was awarded in November 2022, after eighteen months of formal applications and three years of planning, it took another 13 months before we officially opened our doors. Our establishment phase during 2023 was challenging and enjoyable implementing our systems and finalising agreements between our partners. That is of course now all in the distant past, because what a whirlwind blur 2024 has been.

We are grateful to the ARC and all Centre participants for their support, this multi-disciplinary partnership has allowed us to establish a focal point for aligned research around the world, and to realise the synergies within the global network of expertise to tackle some of the most challenging projects of this age.

As you will read over the following pages, 2024 was the year we established our four key missions and began new projects, aligned to each of those missions. Collectively these initiatives will help us deliver our overarching aim



of establishing the core technologies to implement sustainable and resilient food and biomanufacturing for Earth and space exploration.

Notably, as well as starting to deploy our baseline funding of AUD$90M, in 2024, we have been awarded new money for aligned projects, such as:

- The Australian Wine Research Institute on valorisation of horticultural waste funded through the South Australian Genomics Centre and BioPlatforms Australia
- NASA and Space Lab Technologies deploying and returning a plant growth system on the Moon when humans return to the Moon for the first time in 50 years with Artemis III
- UK and Australian Space Agencies developing an Autonomous Agriculture system
- iLaunch Trailblazer, the University of Southern Queensland, Axiom and Yuri, developing monitoring systems for plant health
- Bioplatforms forming a new National Collaborative Research Infrastructure Strategy Facility, Plant SynBio Australia, involving initially La Trobe and ANU to enhance interaction and growth stimulation capability for the plant-based biomanufacturing industry
- BBSRC Fellowship in the UK to create a single cell resolution map of duckweed nutrient transport (Alex Ware, at the University of Nottingham)

We have many reasons to celebrate this year including recruitment of a stellar set of researchers and administrators, we are already over 100 strong and we have further capacity to almost double this over the next year. We installed three vertical farm facilities in La Trobe and Adelaide built by our industry partners GAIA and Vertical Future. We held our successful official launch event in October, that was followed by a well-attended engagement week with industry, the media and public. We connected with over 120,000 school students through our engagement programs. The quality of our people is reflected in their promotions and awards for our staff and partners listed throughout this report.

Lastly, I would like to extend my deepest gratitude to all our members for their unwavering commitment and dedication in 2024. The efforts and successes of the Centre's research teams have been showcased at various conferences and events, such as the Australian Society of Plant Scientists Conference, Life in Space Symposium and the International Astronautical Congress where we celebrated our latest research outputs and the continued growth of our Centre. It was a privilege to engage with fellow researchers and stakeholders, strengthening our collaborative networks and sharing the exciting developments happening within the Centre.

The ARC Centre of Excellence in Plants for Space remains focused on its goal to explore new frontiers in future foods and bioproduction. We look forward to further advancements in the coming year, and I encourage anyone interested in exploring new opportunities to connect with us.

MGilliham

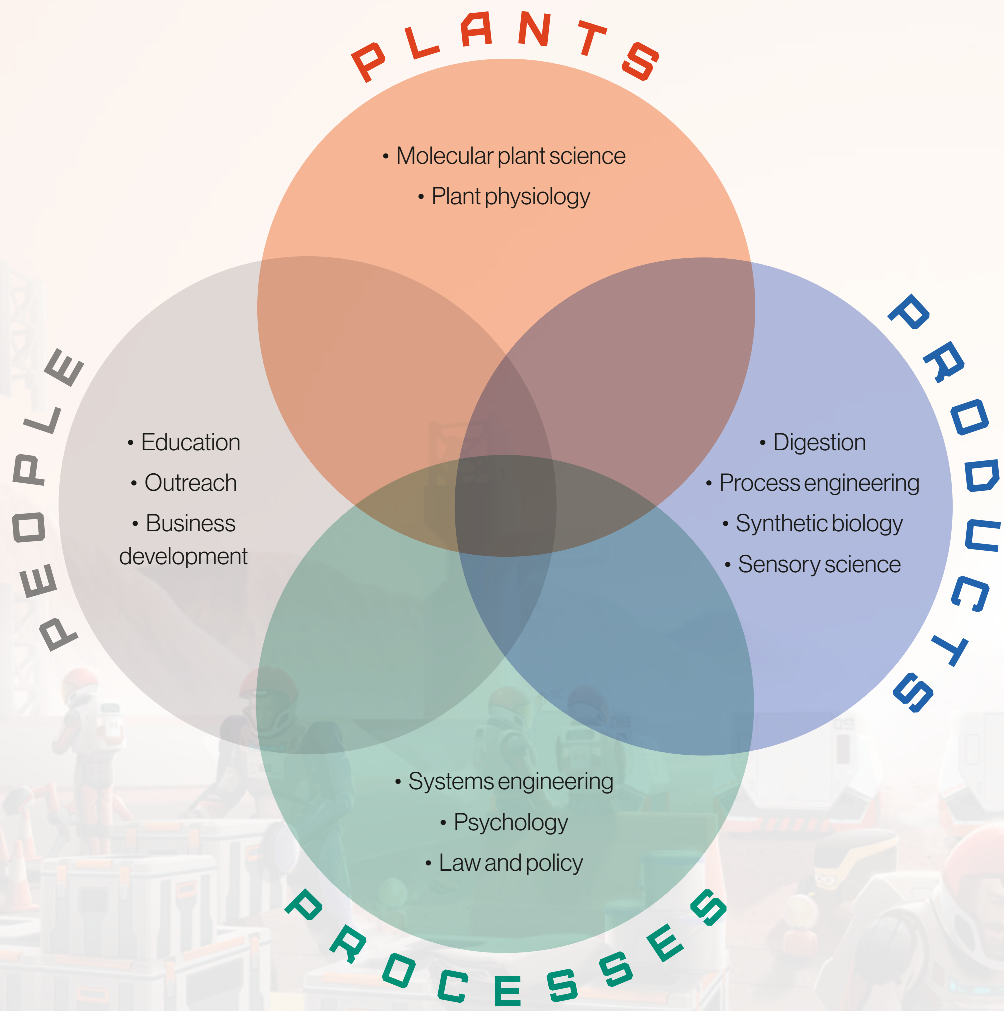
Prof Matthew Gilliham

Director
ARC Centre of Excellence in Plants for Space

Our Vision

To enable long duration human space exploration and improve on-Earth sustainability through plant and food re-design. Inspire and equip the next generation with the skills and ambition to solve the world's great challenges.

P4S' research capability is led by domain experts that provide robust discipline-specific expert review, support professional development of future research leaders, and a framework that facilitates integrated multidisciplinary projects.



Our Missions

P4S' 7-year goal is to enable humans to survive and thrive in space, through developing new plant forms, products, and uses; and leadership in a global community that transforms plant performance and sustainability, on and off Earth. We plan to achieve this goal through four missions that guide our research endeavours:

Zero-waste plants optimised for controlled environments

Zero-waste plants focuses on fast-growing, zero-waste, 'pick and eat' plant varieties that exceed current on-Earth performance. Plants will be 're-engineered' to be able to remove redundant energy-intensive processes to accelerate growth; enhance nutrient and water use-efficiency; optimise salt tolerance; and create a use for all plant parts.

The use of digital and physical twins of our plant and food production systems will assist in fully integrating environmental constraints with resource requirements. Simulation of space conditions on Earth will allow iterative calibration of plant and product design, and the development of new experimental platforms in space.

On-demand bioresource production

On-demand bioresource production uses smart plants that operate as programmable biological factories for robust and rapid biomolecule synthesis. Innovations in this mission encompass development of new technology platforms for on-demand or large-scale production of novel, recyclable biomolecules, including plant-based construction materials and pharmaceuticals, that can be processed with minimal energy, resources, and waste.

Furthermore, this mission includes the sustainable processing of these biomolecules into usable products, employing integrated tools for prediction and assessment of food taste and digestibility. Our depth of processing, sensory, psychological, and nutritional expertise enables key technological innovations to deliver nutritious plant-based foods and sustainable processing of plant-generated flavours, pharmaceuticals, and plastics.

Complete nutrition plant-based foods

Complete nutrition plant-based foods aims for the development of 'complete nutrition' plants that humans could survive on for a year without sacrificing health. Our focus will be on optimising concentrations of all essential macro- and micro-nutrients in a minimal suite of plants that can be processed into appealing food forms to fulfil nutritional needs.

Future-ready workforce and society

Future-ready workforce and society focuses on the impact of our research on society and includes the anticipatory and responsive legal, regulatory, ethical, and psychological frameworks to determine and refine process design to facilitate successful outcomes. A key element will be to dissect the complexity of human responses to extreme and constrained environments, to ensure that the novel process design is both compliant with legal standards and capable of situational evolution.

Furthermore, P4S aims to support its teams by including evidence-based training, leadership, and mentoring framework to inspire and equip staff, students, and stakeholders at scale. Finally, we aim to provide an industry-ready translation pipeline integrating and informing outputs across P4S research, including co-design between academia, government, industry, and start-ups to provide major sector uplift. Our advocacy will strengthen research and linkages, create synergies, and maximise efficiency of global effort, leading to creation and leadership of a single global space plant research community, as well as informing the public through outreach and engagement for students and the broader community.

P4S Team

Centre Launch

After commencing in January 2024, Plants for Space officially launched on the 30th of October 2024 coinciding with the Centre's inaugural annual conference. This deliberate timing allowed all members to come together for this momentous and celebratory occasion. The event fostered collaboration, knowledge sharing, and camaraderie among members, while highlighting the remarkable achievements of our inaugural year.

Conference Opening

On Tuesday 29th October all Centre members and Advisory Committee members convened in Adelaide and enjoyed the conference opening event at the Australian Space Discovery Centre.

After a welcome by Centre Director Matthew Gilliham attendees enjoyed drinks, nibbles, and the opportunity to explore the Australian Space Discovery Centre to learn about space exploration and Australia's growing role in the space industry.

The evening concluded with a dinner at the Stamford Plaza, setting the stage for meaningful connections and a shared vision for the future.

Australian Space Discovery Centre

Conference Day 1

The following day the Centre members gathered at Waite Campus for the first official conference day, starting with a stimulating plenary address by Partner Investigator Dr Gioia Massa from NASA Kennedy Space Centre, who shared insights on Plants in Space and Space Crop Production.

The remainder of the day was dedicated to a series of research presentations focusing on Plants and Processes.

Our zero-waste and complete nutrition plants projects were introduced by Chief Investigators Prof Mathew Lewsey and Prof Harvey Millar. Chief Investigators Prof Volker Hessel and Prof Melissa de Zwart introduced Processes projects including the 'Sustainability of farming systems and supply chains in space' and 'Developing legal and ethical frameworks for space activity'.

These presentations highlighted the interconnectivity of the Centre's work, providing a foundation for postdocs, and PhD students to showcase their work.

The afternoon finished off with a panel discussion session with our Advisory Committee members and mediated by Centre COO Dr Richard Harvey. Discussion ranged from the international legal implications of human habitation in space to the technical challenges of long duration space travel, fundamental plant sciences discoveries expected from Plants for Space, entrepreneurship and the training and professional development of the Centre's postdocs and students.

Prof Mathew Lewsey from La Trobe University presenting at the inaugural P4S Conference

Centre Launch

In the evening of the 30th of October the official launch of the Centre took place, kindly MC'd by Deputy Vice-Chancellor (Research), the University of Adelaide, Prof Anton Middelberg.

The event featured an engaging Welcome to Country by Mr Rob Taylor, as well as speeches from esteemed guests, including University of Adelaide Vice Chancellor and President Prof Peter Høj AC, Australian Research Council Acting Chief Executive Officer Dr Richard Johnson and State Member for Waite Catherine Hutchesson MP. The Centre was officially launched by Federal Member for Boothby, Louise Miller-Frost MP.

Plants for Space Director Prof Matthew Gilliham and Deputy Directors Prof Sally Gras and Prof Melissa de Zwart shared an inspiring vision for the Centre, accompanied by an engaging video overview of Plants for Space research.

Guests then celebrated with drinks, duckweed canapés, and an immersive Mars experience, marking an unforgettable evening.

Above: L-R Centre Director Prof Matthew Gilliham, Acting Australian Research Council CEO Dr Richard Johnson, Member for Boothby Louise Miller-Frost MP, Vice-Chancellor and President Prof Peter Høj AC and Deputy Vice-Chancellor (Research) Prof Anton Middelberg

Opposite: Cadell Canute from the University of Adelaide

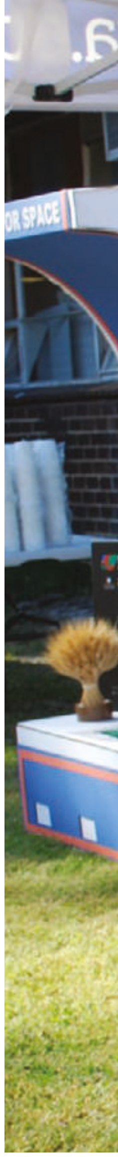
Conference Day 2

On Thursday the 31st October Centre members gathered at the University of Adelaide North Terrace campus for our Future workforce and Society and Products presentations. Chief Investigator A/Prof Kim Johnson shared the education and engagement team's successes in 2024, as well as the vision and missions for the years to come. The engagement team has already been reaching and surpassing many of the goals that were set for the first year of the Centre. The Products session was led by Prof Ryan Lister and Prof Sally Gras. Prof Lister described research activity understanding and applying breakthroughs in gene circuits creating on and off switches for the production of products on demand. Prof Gras described the smart food structuring and downstream sensory and digestion research effort tasked with developing new and appealing plant-based foods.

The afternoon was spent at an amazing Centre-wide workshop, led by Ms Amy Griessl and Dr Richard Harvey. The workshop on Equity Diversity and Inclusion provided a guided, informal but thoughtful afternoon of interaction for all Centre members, to discuss what Centre inclusivity should look like and how to best achieve this. Supported by input from Centre members themselves, this session provided a supportive environment to discuss inclusion through empathy, understand exclusion from different perspectives, and shape an equitable future for the Centre. The workshop was a great way to finish off a shared time at this conference.

Our members expressed great enthusiasm for the conference, praising its seamless organisation and the valuable opportunity it offered for face-to-face interactions.

Building on the success of this inaugural event and constructive feedback received, future conferences will aim to deepen the connections established, fostering even stronger networks within our community.



Overview of the Centre

The ARC Centre of Excellence in Plants for Space is on a mission to transform the future of food, sustainability, and space exploration.

Our goal is to enable humans to not only survive but thrive in space, and to develop innovations that deliver important advancements to our agricultural, food and biomanufacturing sectors on Earth. By developing innovative plant-based solutions, we're working to create a future where food production is more efficient, resilient, and sustainable—whether on Mars, or remote and extreme environments on Earth.

P4S is a unique transdisciplinary collaboration, bringing together experts in plant biology, food chemistry, engineering, psychology, and space law, among others. Our international and national consortium spans industries including space, controlled environment agriculture, plant-based foods and biomanufacturing. P4S is building a community of 200 researchers, with plans to have trained 400 students by 2031, while fostering a culture of innovation, entrepreneurship, and public inspiration.

Guided by four key missions—complete nutrition plant-based foods, zero-waste plants for controlled environments, on-demand bioresource production, and a future-ready workforce and society—we aim to revolutionise how we grow, consume, and think about plants. In doing so, we hope to pave the way for a more sustainable and resilient future plant and food systems on Earth and lay the groundwork for long-term space exploration.

Top right: University of Western Australia showcasing the ARC Centre of Excellence in Plants for Space at the UWA Institute of Agriculture's Open Day in Shenton Park.

Bottom right: Her Excellency the Hon. Ms Sam Mostyn AC, Governor-General of the Commonwealth of Australia and the Hon Catherine Branson AC KC visiting P4S hosted by CI Prof Matthew Tucker.

Right: Filming for our P4S Launch video at the University of Adelaide's North Terrace Campus, with CI Prof Melissa de Zwart in the Extraterrestrial Environmental Simulation (EXTERRES) Laboratory.


PLANTS FOR SPACE
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PLANTS FOR SPACE
MISSION:
RESEARCH:
PLANTS FOR SPACE
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Our Impact

Establishment of single-cell transcriptional states during seed germination

This research has discovered that as a seed begins to grow, its cells wake up at different paces in response to the germination call, activating various functions based on their specific roles. This finding will aid in creating practical solutions to ensure that germination occurs uniformly and at the optimal time.
Liew *et al.*, (2024) Nature Plants

Conceptualising sustainability in outer space resource utilisation

Space exploration is supported by the development of laws and regulations, to ensure research will suit a sustainable framework. This study examines the meaning of the concept of sustainability with respect to space activities and concludes that the current international space law regime must evolve to ensure that all space activities, including space resource activities, are undertaken in a sustainable manner.
de Zwart *et al.* (2024) Griffith Law Review

CRISPRi-based circuits to control gene expression in plants

This study shares the work on developing synthetic genetic circuits to control and customise where, when, and under what environmental conditions, genes are turned on or off in a plant. The research developed a new genetic 'programming language' that can be written into a plant's genome to enable the construction of customised patterns of gene activity and could potentially help to adapt crops for distinct environments such as altered Earth climates or in vertical farming and space exploration.
Khan *et al.* (2024) Nature Biotechnology

Plant synthetic biology as a tool to help eliminate hidden hunger

Agricultural systems are under increasing pressure from declining environmental conditions, a growing population, and changes in consumer preferences, resulting in widespread malnutrition-related illnesses. The review covers recent biotechnological approaches to biofortifying plants with vitamins, minerals, and other metabolites, such as vitamin D and omega-3 fatty acids. Improving plant nutritional content through biotechnology techniques such as synthetic biology is a promising strategy to help combat hidden hunger caused by the lack of affordable and healthy foods in human diets.
Edwards *et al.* (2024) Current Opinion in Biotechnology

Green horizons: how plant synthetic biology can enable space exploration and drive on Earth sustainability

Exploring the cosmos has always been a driving force for innovation. As humanity sets its sights on space habitation, innovation becomes paramount and the lessons learned from space exploration are increasingly applicable to challenges here on Earth. This review covers the many ways plant synthetic biology can deliver on-demand production for off-Earth human habitation and support the growing closed-environment agriculture and bioeconomy sectors on Earth.
Morgan *et al.*, (2024) Current Opinion in Biotechnology

Exploring consumer acceptability of leafy greens in Earth and space immersive environments using biometrics

Our senses play an important role in food likes and dislikes, as well as guiding eating behaviour. To produce nutritious and desirable food from plants in space, it's therefore important to consider how the sensory properties (e.g., flavour and mouthfeel) of food and beverages are perceived.

Previous research has shown that our senses perceive food and beverages differently in space conditions. As a result, on-Earth research into the sensory properties of food and beverages for off-Earth consumption requires researchers to try and replicate the changes in sensory perception experienced in space conditions. This paper covers the use of biometrics to better study how we perceive our food, in natural and off-Earth environments.
Gonzalez Viejo *et al.* (2024) NPJ Science of Food

Submissions to Government inquiries

- Australian Space Agency: Australian sustainability of space activities policy
- Australian Space Agency: "Moon to Mars spin-in capabilities: expressions of interest"
- FSANZ: "Definitions for gene technology and new breeding techniques"
- South Australia's space sector strategy update - workshop presentation

Submissions to Parliamentary inquiries

- Joint Standing Committee on Treaties (Parliament of Australia) "Agreement between the Government of Australia and the Government of the United States of America on Technology Safeguards Associated with United States Participation in Space Launches from Australia"

Industry engagement

- Hosted P4S introductory event for representatives from Federal, State and Local Government, controlled environment agriculture, space and food sectors
- Participation in the Australian SynBio Slipstream at SynBioBeta (led by MainSeq Ventures)
- Contributions to the TRISH/EBRC technical roadmapping workshop and subsequent report publication
- Participation in the SABRE Biosecurity Workshop

8

Journal publications in the top 5% of field by CiteScore

19

Journal articles in 2024

79

Presentations to government and industry in 2024

974

Teachers trained in P4S-hosted workshops

5

Submissions to government and participation in parliamentary inquiries

120,000

Students engaged by P4S education and engagement activities (including as a result of teacher professional development)

From seed to galaxy...

Australian duckweed takes flight

P4S launched its first payload of duckweed into space aboard the German Aerospace Centre's MAPHEUS 15 rocket. The experiment aims to study how altered gravity affects duckweed, a promising plant for astronaut food. The successful launch took place on 11 November 2024, as part of a global mission featuring 21 scientific experiments.

Left: A/Prof Jenny Mortimer with Dr Sebastian Feles preparing samples for the sounding rocket launched by the German Aerospace Centre (DLR)

NASA's deep space food challenge

La Trobe University and Australian start-up Gaia Project Australia, an ARC Centre of Excellence in Plants for Space partner, were international runners-up in NASA's Deep Space Food Challenge at The Ohio State University. The challenge tasked teams with creating food-growing prototypes for long space missions. The team developed an innovative vertical farm that grows leafy greens and microgreens in just 28 days, offering a potential space-ready solution for astronaut nutrition.

Below: P4S COO Dr Richard Harvey (L) with runner-up team members (L-R) Dr Alex Stumpf (La Trobe University), Nadun Hennayaka (GAIA Project Australia), and Adam Console (La Trobe University).

Creating a sustainable future for food

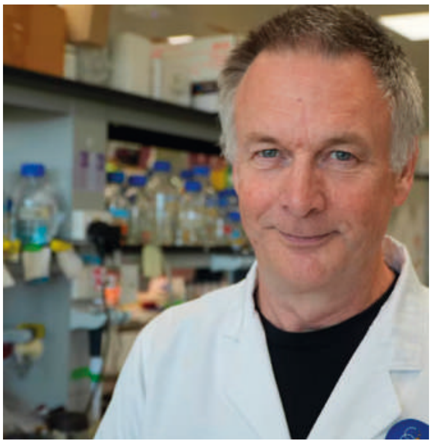
As we enter 2025, global food and water security remain pressing challenges. To ensure long-term sustainability, we must combine traditional farming with innovations like vertical farming and controlled environment agriculture (CEA). Vertical Future, a leader in this field, is helping drive these advancements. These technologies offer climate-resilient, high-yield solutions that use less water, reduce food miles, and minimise import dependence. Vertical farming promises year-round production, healthier food, and better resource efficiency—key to overcoming the instability caused by climate change and extreme weather.

Above: Image supplied by P4S Partner Vertical Future

Axiom Space expedites Axiom Station development

Axiom Space announced it will accelerate its plans for Axiom Station, aiming to make it an independent orbital platform as early as 2028. By revising the module attachment sequence, the station will operate as a free-flyer two years earlier than planned, meeting both customer needs and national objectives. This new strategy, developed in collaboration with NASA, ensures the station will transition smoothly from government to commercial operations, maintaining a continuous human presence in space for global customers and partners.

Below: Thales Alenia Space in Turin, Italy. Courtesy of Thales Alenia Space / Axiom Space.



A new era in astronaut nutrition

Astronauts often crave fresh food like a crunchy salad while in space, but growing vegetables aboard shuttles has been a challenge. Now, P4S researchers Prof Ian Small and Leni Campbell-Clause from Perth's UWA are designing nutrient-rich plants that can thrive in space. The team are re-imagining plant design to support human health and wellbeing in deep space.

Above: CI Prof Ian Small, University of Western Australia

Groundbreaking lunar plant study

NASA has selected a team led by P4S partner Space Lab Technologies, including P4S researchers from The Universities of Adelaide and La Trobe, for one of three investigations under the Artemis III Deployed Instruments (A3DI) program. Their experiment, "LEAF ß - Lunar Effects on Agricultural Flora Beta," will be the first to examine plant photosynthesis, growth, and stress in response to space radiation and partial gravity on the Moon. This groundbreaking research will help advance space agriculture for future lunar missions.

Find out more about the LEAF project on page 24.

Right: The LEAF experiment will aim to see whether plants can be grown on the Moon. Credit: NASA

Australian strawberries in space

Prof Michelle Watt, University of Melbourne +
Prof Harvey Millar, University of Western Australia

It is 2044, a mere 20 years away, and a group of astronauts living on Mars take a break.

They reach into the space garden, pick strawberries, and eat them fresh. The taste is sensational – intensely sweet with some tart undertones – engineered to overcome limitations of tastebuds in space.

These space strawberries are not only delicious but also provide essential nutrients like vitamin C, sugar, and fibre. They also present an essential contrast to dried packaged food that can lead to 'menu fatigue' or non-eating because of lack of food palatability. Importantly, they also stimulate astronaut dopamine and endorphin production that can elevate mood and enhance pleasure, beauty and companionship when strawberries are picked collaboratively.

In 2024 the Australian Research Council Centre of Excellence Plants for Space (P4S), in conjunction with NASA and Australian Space Agency partners, have brought this vision one step closer to reality. The primary aim of P4S is to develop plants, like strawberries, to sustain humans in space while also improving agricultural practices on Earth.

Target traits for strawberries created for space and on Earth. Photo credit: Prof Michelle Watt.

Strawberries were chosen as one of four key plants for this mission, alongside duckweed, lettuce, and tomatoes. Strawberries not only offer unique psychological benefits to astronauts, providing both nutritious food and mental wellbeing, the entire strawberry plant, including its leaves, can be used for food, making it an efficient and sustainable option. Moreover, strawberries have a diverse genetic base, which can be explored through modern biotechnology to create space-optimised varieties and they are readily reproduced (through seeds, runners and propagating tissues).

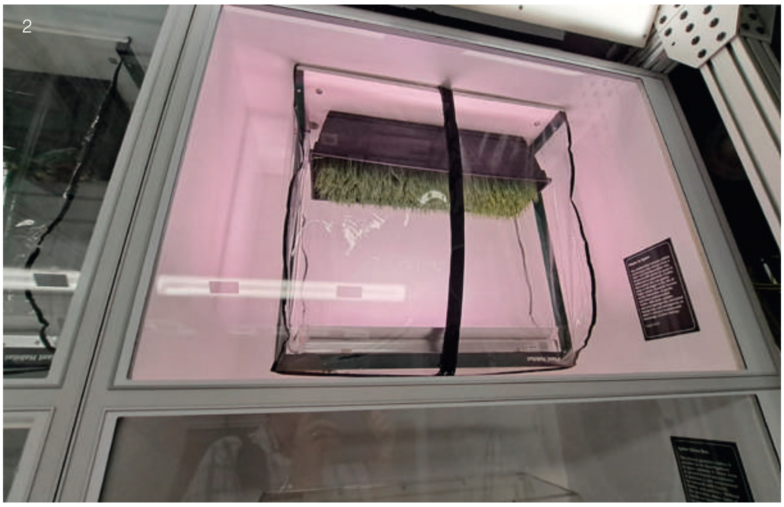
Space-grown strawberries will be developed to thrive in soilless high salt hydroponic systems, using minimal water and nutrients. These innovations are also aimed at improving Earth-based agriculture, addressing issues like climate variability, environmental regulations and the need for developing alternative farming methods. For example, space strawberries will be bred for greater fruit yield, improved flavour, and better adaptability to daylength variations, making them ideal for different growing conditions on Earth.

In space, the goal is to create zero-waste plants where every part of the strawberry plant can be consumed or repurposed. This approach reduces waste and maximises plant efficiency, a concept that can also benefit Earth's agriculture. Today, much of the strawberry plant goes unused (largely the roots), but researchers are looking to increase strawberry fruit, enhance the flavour and nutritional value of strawberry leaves for potential consumption and select for more water and nutrient efficient reduced root systems.

In Australia, the strawberry industry faces environmental challenges related to the use of plastics and fumigants, as well as the impacts of climate change, including water salination. However, innovations from space research could offer new solutions to these problems. The genetic potential of strawberries makes them an ideal candidate for space exploration, and the innovations developed in this field could have far-reaching benefits for food production both in space and on Earth.

Features that make strawberry an ideal plant for space development

- Meets human needs: Strawberry supplies nutritional and psychological needs of humans.
- High potential edible index as leaves and berries can be eaten safely.
- Low risk of extinction since strawberry regenerates by seed, runner or tissue propagation.
- Wide, untapped genetic variation. Strawberry functions are controlled to turn on or off in specific parts of the plant (e.g. the roots) or at specific times (e.g. flowering window). All these approaches can aid the strawberry space program.
- High on-Earth demand for innovation in growth and harvesting systems. Strawberries for space will be bred for soilless systems, without soil fumigation, and with ultra-efficient use of recycled water and nutrients by salt-tolerant, minimal root systems. Fruit and leaves will be picked by hand and machines. These space innovations are required to increase on-Earth sustainability and productivity.



Models of space habitats for plants and research on the best varieties of plants for space. 1: Plants in a model of the Sierra Space Life Habitat. 2: Life-sized model of the Lockheed Martin Deep Space Habitat with chambers for inverted plant growth. 3: Test crop species being evaluated for space missions at NASA Kennedy Space Centre. Photo credit: Harvey Millar during visit to NASA Kennedy Space Centre August 2023.

Exploring duckweed: A promising future for food Innovation

Multiple authors, University of Adelaide

P4S researchers have identified duckweed (*Wolffia* and *Lemna* species) as an ideal candidate to help support human nutrition and on-demand bioresource production in remote and extreme environments in space and on Earth.

Duckweeds possess several desirable features including fast growing, nutritional value, genetic tractability and space heritage. P4S researchers are studying duckweeds as a source of complete nutrition as a fresh food ingredient and a base for new plant-based foods, and a plant system that can be manipulated to produce essential products and materials.

Duckweed as a complete food

Duckweed can grow extremely rapidly (2-day doubling time), is entirely edible with a high protein (~20–45%) and fibre (~25%) content, and excellent amino acid and micronutrient profile. On a per area basis, they produce ~60× the protein yield of soybean. In Thailand, duckweed is known as khai-nam (water eggs) and is eaten in soups and salads.

Duckweeds are suited for vertical farming, as they are simple to harvest and don't require continuous water circulation. The plant's flat profile allows dense stacking of shelving racks, and rapid growth allows continuous production.

P4S researchers are manipulating the macro- and micro-nutrient profiles in duckweed to further improve the nutritional value of duckweed as both a fresh food, and a protein source for new plant-based foods. P4S researchers are increasing the protein content of the plant by increasing lysine and phenylalanine amounts, improving fat (triacylglycerol and oleic acid) content and stability, enhancing carbohydrate profiles to boost caloric content and digestibility, and reducing anti-nutrients such as oxalates. As a protein source for new plant-derived foods, P4S researchers are developing a detailed understanding of the molecular properties of duckweed materials and how they respond to processing to generate appealing product microstructure.

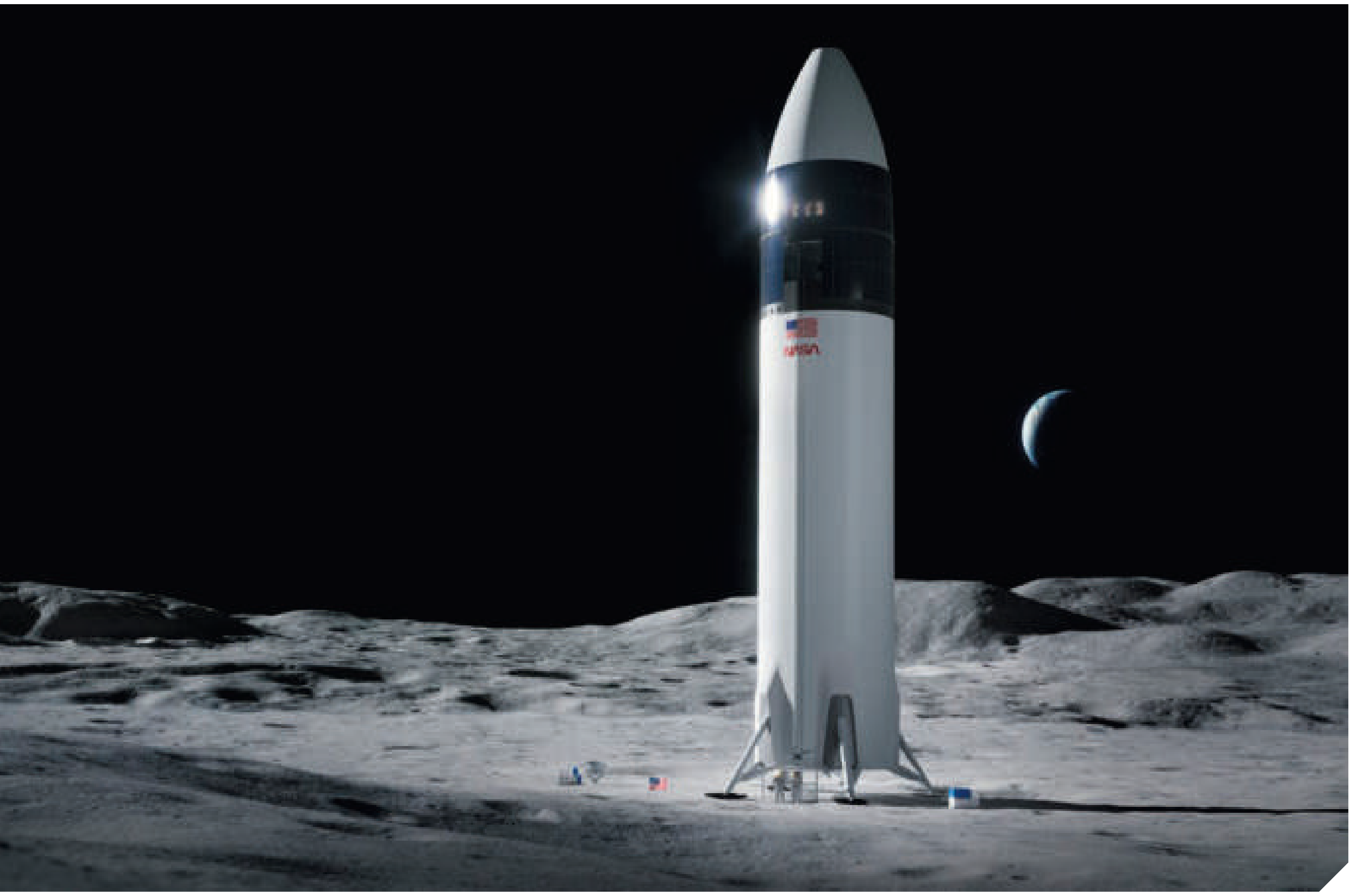
Duckweed as a biosynthetic factory

Duckweed is being studied as a candidate for high value bioproduction of compounds such as partholenide (PTL) and polyhydroxybutyrate (PHB).

PTL exhibits anti-cancer properties and enhances the impact of radiation therapy. It is currently sourced from feverfew plants, whose generally low yield can be further compromised by weather and postharvest procedures; further, PTL conjugates to inactive forms within weeks of storage. With partners from several Adelaide institutes, P4S researchers aim to develop a synthetic biology approach for rapid, on-demand, local production of PTL that facilitates year-round, consistent production not susceptible to climate, and offers massive space savings compared to field-grown plants.

PHB is one of the simplest and most commonly occurring polymers with a practical market size of USD$121 million by 2028. Traditional petrochemical plastics are based on a dwindling resource and are difficult to recycle in practice, resulting in non-recoverable waste streams and widespread contamination. PHB is a biodegradable bioplastic which may serve as a sustainable drop-in alternative. It can be used in a variety of applications, from food containers to absorbable sutures. However, the costs to produce this material using existing technology are a major hurdle. P4S is overcoming this by harnessing duckweed as a high-performance biomanufacturing platform, facilitating efficiency in human resource use here on Earth and beyond.

Left: Close-up view of duckweed, showcasing its intricate structure and potential as a sustainable, nutrient-rich food source for future space missions.
Above: A University of Adelaide student researching duckweed, exploring its potential as a nutritious food source for future applications.



LEAF: Plants head to the Moon... and return!

A/Prof Jenny Mortimer, University of Adelaide + **Prof Mathew G Lewsey,** La Trobe University, with additional content from **Space Lab Technologies**

Humanity is heading back to the Moon.

NASA's Artemis III mission is poised to land the first woman and the first person of colour on the lunar surface, blazing a trail for a more inclusive era of space exploration (Figure 1).

Scheduled for a late 2026 launch, Artemis III will bring astronauts to the Moon's south pole—a region that remains largely uncharted. This area is thought to hold vast reserves of water ice, a precious resource that could support future lunar bases and fuel deep-space missions to Mars and beyond.

But Artemis III is not just about humanity's return for the first time since the Apollo missions. Artemis III will also carry experiments aimed at uncovering the Moon's secrets, delivering knowledge that could benefit life on Earth and propel us further into the cosmos.

The LEAF (Lunar Effects on Agricultural Flora) has been selected as one of only three experiments to be developed for the Artemis III Deployed Instruments (A3DI) program, which identified high-priority science investigations that can be uniquely accomplished by human deployment of payloads on the surface of the Moon. The project is led by P4S partner Space Lab Technologies (PI Chris Escobar), with several P4S CIs and PIs making key contributions.

LEAF will study how the Lunar environment affects the germination and growth of plants that may be used to feed astronauts of the future. Human nutrition and life support (carbon dioxide removal, oxygen production, and water purification) provided by space agriculture will enable long-duration human exploration of the Moon and beyond. Plant biology research on the Lunar surface is needed to understand the effects of partial gravity and space radiation on crop physiology and to demonstrate the potential for sustained, off-planet propagation.

The LEAF payload (Figure 2) will protect plants within from excessive Lunar sunlight, radiation, and the vacuum of space, while observing their photosynthesis, growth, and responses to stress. The experiment includes a plant growth chamber with an isolated atmosphere, housing red and green varieties of *Brassica rapa* (Wisconsin Fast Plants®), *Wolffia australiana* (duckweed), and *Arabidopsis thaliana*. By bringing seedling samples back to Earth, as part of Artemis III, the research team will apply advanced system biology tools to study physiological responses at a molecular level.

Only one other payload has studied plants on the Moon; the 2019 Chinese Chang'e 4 mission provided a picture of a 4-day old cotton sprout then suffered thermal control failure.

The Lunar Effects on Agricultural Flora (LEAF) research will provide the first, comprehensive assessment of organism-wide effects of the Lunar environment, reducing risks for sustainable off-planet crop production and bioregenerative life support.

The LEAF management team includes Principal Investigator Christine Escobar, Space Lab Principal Engineer Adam Escobar, and space biologists from NASA Kennedy Space Center (4S PIs Dr Aubrie O'Rourke, Dr Gioia Massa, and Dr Raymond Wheeler), University of Colorado, Boulder (Prof Barbara Demmig-Adams), Purdue University (Prof Marshall Porterfield), USDA (Dr Gayle Volk), La Trobe University (Prof Mathew G Lewsey), and University of Adelaide (Prof Jenny Mortimer). Funding is from NASA, with support from P4S partner BPA.

Opposite: Figure 1, illustration of Starship Human Landing System on the lunar surface (credit: SpaceX).

Above: Figure 2, left: Design for the LEAF payload showing the unfurled solar panels. Right: Showing the plants that will be grown on the lunar surface, with samples returned to Earth for analysis (credit: Space Lab Technologies).

CASE STUDY

Autonomous plant growth system for Axiom Station

Dr Richard Harvey, University of Adelaide

ARC Centre of Excellence in Plants for Space researchers are participating in a project led by UK-based vertical farming company Vertical Future, to build a fully autonomous plant growth system for one of the world's first commercial Space Stations, Axiom Station.

Funded by by the UK Space Agency with support from the Australian Space Agency, this project is a collaboration between Vertical Future, Axiom Space, Saber Astronautics, The Universities of Adelaide, Western Australia and Cambridge, Southern Queensland and the South Australian Space Industry Centre.

The project aims to develop a system to autonomously, non-invasively and remotely monitor the health of plants in a controlled environment.

Multiple trials are underway in Adelaide, Perth and Cambridge, where lettuce plants are grown in different stresses reflecting those likely to be encountered during space travel. Plant health data are collected using a range of cameras and sensors and used to train a machine learning algorithm to detect changes in plant health. Saber Astronautics is supporting real time data communications between the different plant growth sites. Vertical Future has constructed an engineering design unit of a space-compatible plant growth system including lighting and irrigation components. Parabolic flight was used to subject the unit to microgravity.

At the interface of controlled environment agriculture (CEA), plant science and space this project provides a unique opportunity for student engagement in some of the key principles of this project aligned to the school curriculum in Australia and the United Kingdom. Four animated educational videos targeted at school-age children are being developed highlighting project activities through topics such as the need for growing plants in space, autonomous agriculture and how gravity affects plant development.

The ability to monitor plant health autonomously and remotely will in future be taken further to enable autonomous intervention to maintain and respond to changes in plant health. Autonomous agriculture will support long-duration space travel and NASA's Moon to Mars goals, by saving valuable astronaut time and facilitating efficient production of fresh food remote from Earth where resupply from Earth is not possible. Autonomous agriculture also delivers significant benefits for our communities on Earth. The horticulture sector in Australia suffers from significant labour shortages, and currently the unit economics of CEA systems, such as vertical farming, are unfavourable for most crops. Autonomous agriculture has the potential to improve the cost competitiveness of CEA and provide a more sustainable and climate resilient supply of fresh food to supplement conventional farming practices.

Above: Axiom Space hosting the UKSA-ASA funded IBF team, led by Vertical Future PI Dr Jen Bromley, at Houston.

Left: A screen shot from one of the four animated educational videos targeted at school-age children.

Opposite: Red romaine lettuce being grown in a VF Vertical Farm at the University of Adelaide's Waite Campus.

Precision plant programming with synthetic gene circuits

Prof Ryan Lister, University of Western Australia

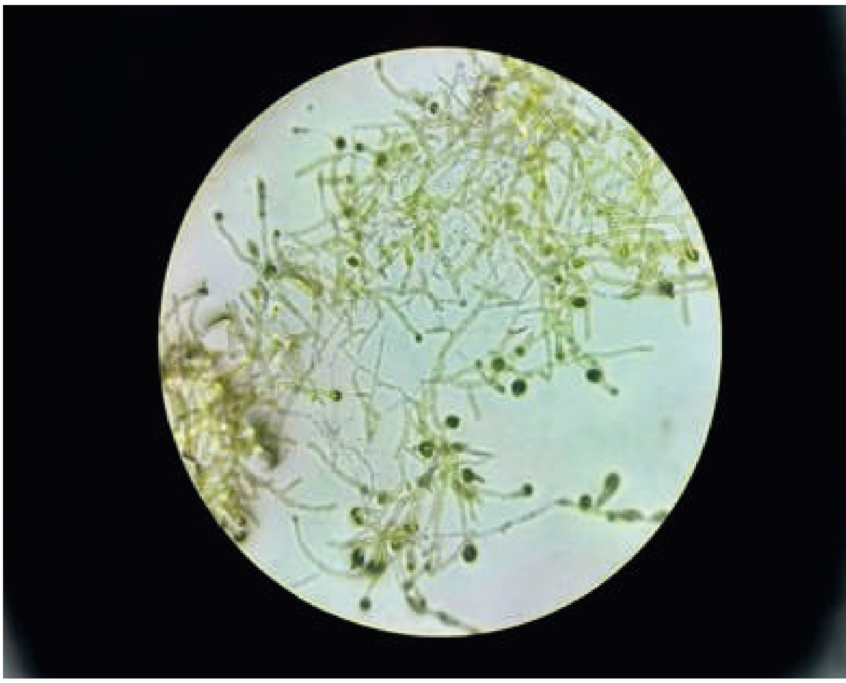
As humanity sets its sights on deep space exploration, one crucial question looms large: how will we sustain life during long-duration missions?

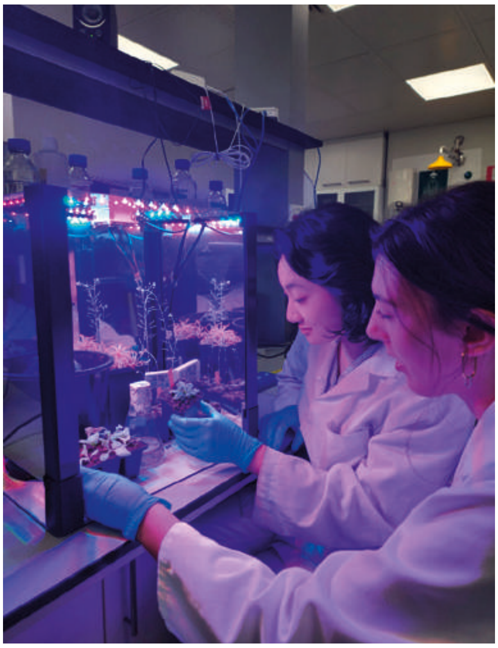
While it's easy to take the comforts of life on Earth for granted - popping down to the supermarket for groceries or grabbing some over-the-counter medicines to soothe a headache - astronauts embarking on long-duration deep space missions face a very different reality. The extreme limitations of space and the impracticality of cargo resupply missions require us to make the concept of self-sustaining, multi-purpose, zero waste ecosystems that produce food, medicines, materials, and energy, a reality. Synthetic gene circuits are a key emerging technology that can be used to rewrite plant form and function to help achieve this vision.

"Artificially-designed gene circuits represent a significant step towards the development of a more sustainable and productive, climate-smart agricultural industry that is needed to more readily meet the plant-based products, food demands and nutritional needs of an ever-growing world population"

Gabrielle Herring
PhD candidate, P4S (Lister lab)

Synthetic gene circuits are analogous to electrical circuits, but composed of biological parts, such as DNA, RNA, and proteins, and are capable of sensing multiple predefined signals to produce a programmed change in plant form or function. New gene circuit technologies, such as those developed in the Lister Laboratory within the Plants for Space program at the University of Western Australia, can enable precise control over when and where particular genes are expressed in a plant.





Above: Tomato plants grown on artificial media in a controlled environment (photo showing plants in a bottle)

Left: A microscopic view of Physcomitrium patens (moss)

Right: Gabrielle Herring and Jia Yuan Zhu (PhD candidates, Lister Lab) observing plants engineered for space in a controlled environment

"Synthetic genetic circuits are anticipated to play an increasingly important role in the production of next-generation "smart crops" that are able to more efficiently sense and adapt to altered or challenging growing conditions on Earth and in space"

Jia Yuan Zhu,
PhD candidate, P4S (Lister lab)

These circuits will allow researchers to not only control gene networks, but also re-engineer plant cells to introduce new capabilities. For example, imagine a tomato plant growing in the controlled-environment of an off-world ship. A temperature-triggered gene circuit could be designed so that after the plant has been exposed to a short cold treatment, the production of an anti-inflammatory medicine is turned 'on' in the edible fruit tissue. Alternatively, after a short heat treatment, the production of an essential nutrient could be enriched in the fruit. Finally, when the tomato plant is near the end of its life cycle, the synthetic gene circuit could trigger the production of a valuable bioproduct, such as a bio-plastic precursor in the stem and leaves - parts of the plant that would typically be discarded. Instead of being wasted, these tissues can be harvested for use in other applications, making the entire plant part of a closed-loop system with minimal waste.

"This technology could greatly enhance our ability to modify complex plant traits, such as stress tolerance and disease resistance, and has the potential to yield entirely new capabilities that could not be achieved through conventional plant breeding alone, such as the on-demand bioproduction of medicines and raw materials"

Dr Adil Khan,
Postdoctoral researcher, P4S (Lister lab)

Nourishing the final frontier:

Revolutionising space food for long-term lunar and martian missions

A/Prof Sigfredo Fuentes + **Dr Claudia Gonzalez Viejo**, University of Melbourne

As preparations ramp up for NASA's Artemis missions to the Moon and Mars, one crucial question remains at the forefront of researchers' minds: What will astronauts eat during their extended missions away from Earth?

The physical challenges posed by prolonged microgravity—such as bone mass loss, vision impairment, and changes in taste and smell—underscore the need for nutritious, appealing, and less-processed foods.

In space, the human body undergoes a myriad of changes. Bone density declines rapidly, motion sickness often happens, and cardiovascular changes occur as the body adapts to microgravity. These factors, combined with the psychological stresses of isolation, highlight the need for meals that provide nourishment and wellbeing. Unfortunately, the current space fare, while nutrient-appropriate, is often high in sodium and lacks the vibrancy, visual appealing and flavour of food on Earth. This can lead to menu fatigue, diminishing appetite and heightening the risk of malnutrition.

Associate Prof Sigfredo Fuentes and Dr Claudia Gonzalez Viejo from the Digital Agriculture, Food and Wine and SpaceSense groups at the University of Melbourne are at the forefront of a revolutionary initiative to enhance astronauts' dining experiences. As CI and Postdoctoral Fellow, respectively of the ARC Centre of Excellence in Plants for Space, they are researching the differences in food perception between Earth and simulated space environments employing AI technologies. This will aid in developing digital twins to simulate how astronauts might perceive food and beverages made from products obtained from genetically modified plants in space.

Their innovative research includes developing appealing, nutritious 3D-printed foods that utilise carbohydrates, plant and animal proteins and fats sourced from genetically modified plants. These meals aim to fulfil astronauts' nutritional needs while being flavourful and visually enticing. Imagine appealing, appetising dishes that retain texture and freshness in space—a true game changer for astronaut dining!

Additionally, their research ventures into the realm of indulgent offerings, recognising that familiarity can provide psychological comfort during commercial space travels. Among their exciting innovations is the development of beer and wine for space. While consuming wine and beer for space in microgravity presents challenges, the development of these beverages could enhance social interactions among commercial travellers and long-term extraterrestrial settlers, making their time in space more enjoyable.

Long-term missions require a comprehensive approach to astronaut nutrition, where meals significantly influence physical and mental wellbeing. Understanding that adequate and enjoyable nutrition is essential, researchers are developing strategies to prevent weight loss and reduce menu fatigue, crucial factors during lengthy expeditions.

Imagine astronauts enjoying hearty, plant-sourced 3D-printed meals—think vibrant pastas, flavourful steaks, and delightful desserts crafted from space-suitable ingredients that look as good as they taste. Such food innovations not only enhance astronauts' experience but also ensure they receive vital nutrients to counteract health challenges in microgravity.

As we move closer to the reality of lunar and Martian exploration, success hinges on a thorough understanding of astronauts' nutritional needs and meal enjoyment. Researchers like A/Prof Fuentes and Dr Gonzalez Viejo are redefining the parameters of space food, improving the physical and mental wellbeing of astronauts while maintaining the connection to the pleasures of earthly living, just a bit different.

In this new era of space exploration, the integration of AI and 3D food printing reflects a commitment to transforming astronaut nutrition. By focusing on both sustenance and wellbeing, humanity's next leap into space promises to be powered by not just the technology that gets us there, but also by the nourishment that sustains us among the stars.

Above: Farmbot 3: Robotic farms (FarmBot, San Luis Obispo,CA, USA) located at the Student Precinct at the University of Melbourne, Parkville Campus. These FarmBots are used to grow plants for pick and eat to further assess their consumers acceptability in simulated space environments.

Left: ENose: Low-cost and portable electronic nose developed by the Digital Agriculture, Food and Wine research group (University of Melbourne) that, along with machine learning, is capable of predicting plant physiological data, pests and diseases, aromas and sensory responses from consumers.

Right: Immersive rooms that simulate Earth and space environments, the latter is complemented with a reclining chair that simulates the microgravity position.

Navigating the new era of space law

Prof Melissa de Zwart
The University of Adelaide

In 2023, NASA released a Report on 'Artemis, Ethics and Society: Synthesis from a Workshop'.

The key focus of that Report was to ask how NASA should identify and address the ethical, legal and societal implications of its plans to return to the Moon as part of the Artemis project. It has been over 50 years since humans last set foot on the Moon. In that time, there has been a dramatic change to the number and nature of uses of outer space. We have witnessed the growth of commercial space and the ongoing congestion of Low Earth Orbit. We have also seen the amazing capacity for international scientific co-operation and engagement with the International Space Station. Further, we are challenged by the increasing threats to the stability of peaceful uses of outer space.

On Earth we have witnessed the ongoing and dramatic effects of climate change on our environment, creating the need for novel approaches to food production. Above all, we have also recognised the importance of continued access to space for our daily lives.

However, in this context, there has been only limited consideration of the ethical and societal implications of space activities and how future activities should be planned to take account of these factors.

There has been a coherent body of international space law since the late 1960s, a set of five international treaties to which Australia is a party. The first and most important of these treaties, the Outer Space Treaty provides that the 'exploration and use of outer space...shall be carried out for the benefit and in the interests of all countries'. Space is deemed to 'be free for exploration and use by all States' including the freedom of scientific investigation. These freedoms are limited by the need to consider the effects of those activities on others, such as through the conduct of activities with 'due regard' and to avoid 'harmful contamination' to space and adverse changes to Earth. Further, states remain responsible for national space activities and for the authorisation and continuing supervision of the space activities of non-governmental entities.

The Centre's Processes program addresses the development and maintenance of a social licence to operate in space for Plants for Space, addressing issues of sustainability, diversity, inclusiveness, equity and responsibility. We have contributed to the Australian Space Agency's consultation on the development of an Australian sustainability of space activities policy. That submission highlighted the activities of Plants for Space in supporting human survival in space and on Earth, through the provision of food, supplements, building materials and other resources from plants, as well as support for human psychological and physical wellbeing.

Space provides us with the opportunity to develop novel, responsible and ethical approaches to sustainability challenges, for example, through the development of new means of production, green and renewable technology, such as zero-waste plants. Sustainability should also include the exercise of inclusive activities, such as recognition and embedding of indigenous knowledges with respect to plants, food and space. The concept of Sky Country embraced by groups such as Arnhem Land's Bawaka Groups, does not separate Earth and space, but rather regards all of Earth, space and beyond as one Country, one greater ecosystem requiring our care and respect.

Work is continuing on developing legal and ethical frameworks to support sustainable development of Plants for Space technologies and to contribute to global discussion of these issues.

Sustainability provides us with an opportunity to:

- Rethink existing practices and develop new ones;
- Consider social and ethical priorities;
- Encourage innovative solutions;
- Promote investment in green technologies;
- Address targeted investment in future technologies.

Opposite: An artist impression of a video conference between Earth and the Artemis Moon base.

Right: An artist impression of a futuristic Mars settlement where robots and people are managing vertical farms for growing produce.

Below: Prof Melissa de Zwart presenting at the inaugural P4S Conference on the topic of Space Law in Adelaide, 30 Ocober 2024.

Plant ingredients and foods to fuel activity in space and on Earth

Prof Sally Gras + Dr Lydia Ong
The University of Melbourne

Space food design

Success in space depends on the availability of nutritious and desirable food. As the distance from Earth increases, the regular resupply of pre-packaged food becomes unfeasible, making food production, preparation and storage increasingly important. Food needs to meet eight basic criteria for consumption in space, as described by NASA (Figure 1). Many of these criteria will be familiar to consumers. Food must be safe but also palatable to avoid menu fatigue, with a high variety of options that together offer optimal nutrition. Resource minimisation also presents a key challenge. The space environment is highly constrained, with limited energy, water, resources and crew time, requiring simple and effective solutions for the preparation and processing. Food that is stored must also be stable and retains its properties in the space environment. Practicality is also important, so foods can be consumed in the specific space environment, which could range from the low gravity environment of space travel to the reduced gravity environment of Mars.

While space presents a different environment to food processing on Earth, there are also shared objectives and parallels with the UN sustainable development goals. These include providing access to safe and nutritious foods to keep humans healthy (goal 2). Resource minimisation and circularity are also critical to space. These concepts are aligned with the need for sustainable industrial development and technological progress here on Earth (goal 9) and learnings obtained from a space environment are expected to help increase opportunities for sustainability on Earth.

The structure of plant ingredients and foods

Understanding the molecular structure of food is one of the key approaches taken by CI Prof Gras, Dr Ong and the P4S food structuring team, as they consider the design of food suitable for space. First, they are seeking to understand the arrangement of cells and location of protein, fibre and other components in selected plant materials. This arrangement, the relative proportions of different components and the interactions between these molecules determines the way plant materials behave, both as we consume and then digest these ingredients. Think, for instance, of the crunchiness and crisp texture of a celery stalk. The chemical and physical properties of the celery, including the presence of water molecules, determines the sensory experience. The arrangement of components also influences how they are processed by the body. The team will work collaboratively across the Centre with other teams led by CI A/Prof Fuentes, CI Prof Feinle-Bisset and CI Prof Kemps to assess the sensory, psychological and gastrointestinal impact of plant ingredients and foods.

The molecular properties of plant ingredients also impact food preparation and processing, including the possible range of different food structures that can be created. Food structure then further impacts on enjoyment and digestibility. The team is currently assessing how food crops that could potentially be grown reliably in space could be used to make a variety of food types. Initial plant ingredients include water spinach (Figure 2). Other potential crops like duckweed and crops previously grown in space, such as lettuce, will also be explored.

Microscopy is one of the best ways to assess the structure of plant ingredients and plant-based foods. The team is applying a range of techniques, including cryo scanning electron microscopy (Figure 3) and confocal laser scanning microscopy (CLSM; Figure 4), to better understand plant structure before and after processing. CLSM, for instance, can be used to visualise mesophyll cells within a

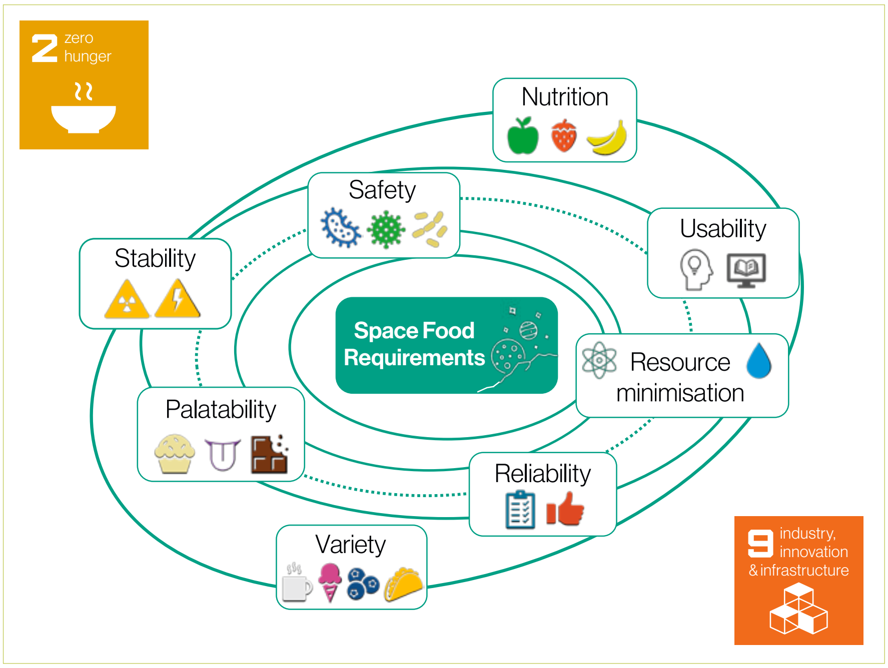


Figure 1

whole water spinach leaf, together with the distribution of chloroplasts within the cells (shown in green in Figure 4). These images also show the lipid components within the plant cell wall and the guard cells surrounding the stomatal pore (shown in red in Figure 4).

Processing offers the opportunity to change, or destructure, plant ingredients and can be followed by restructuring to make plant-based foods (Figure 4). On Earth, plant proteins may be fractionated and purified to produce ingredients, such as leaf protein Rubisco, which can be used to make gels and food analogues. These multi-step processes may not be feasible in space but developing methods for the minimal processing of plant-based ingredients will be key to food variety.

Figure 2

Long term storage solutions

The team will consider the risks of long-term food storage to nutrition and product stability and the opportunities for technology to address these challenges. Current state of the art solutions from food processing on Earth include freeze-drying, frozen storage and powder production (Figure 5). The team will seek to understand the differences between Earth and space storage and apply engineering strategies to develop novel storage solutions.

Summary

This project will help to create sustainable food systems for deep space exploration, whilst providing alternative ingredients and applications in space and on Earth. By better understanding the constraints on food growth and production in a constrained environment we will be in a better position to support life on Earth.

References

Douglas, G. L., Zwart, S. R., & Smith, S. M. (2020). Space Food for Thought: Challenges and Considerations for Food and Nutrition on Exploration Missions. J Nutr, 150(9), 2242-2244. https://doi.org/10.1093/jn/nxaa188

Figure 4

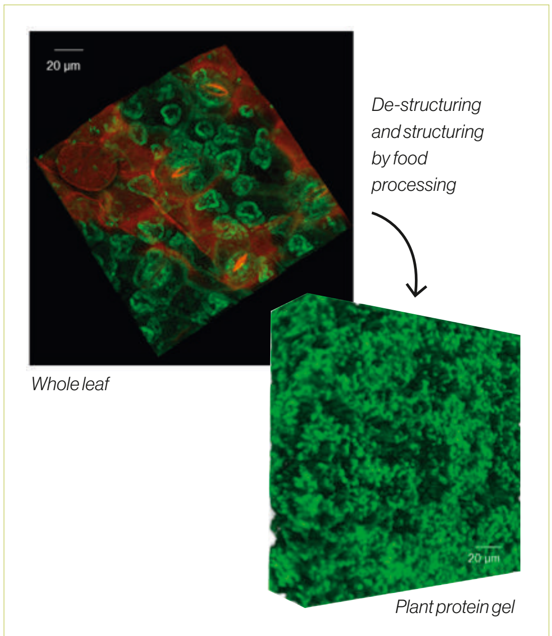


Figure 3

Figure 5

Figure 1. Space food requirements (Image adapted from Douglas et al. (2020)) and the United Nation sustainable development goals.

Figure 2. Cultivating water spinach at the P4S Latrobe University node.

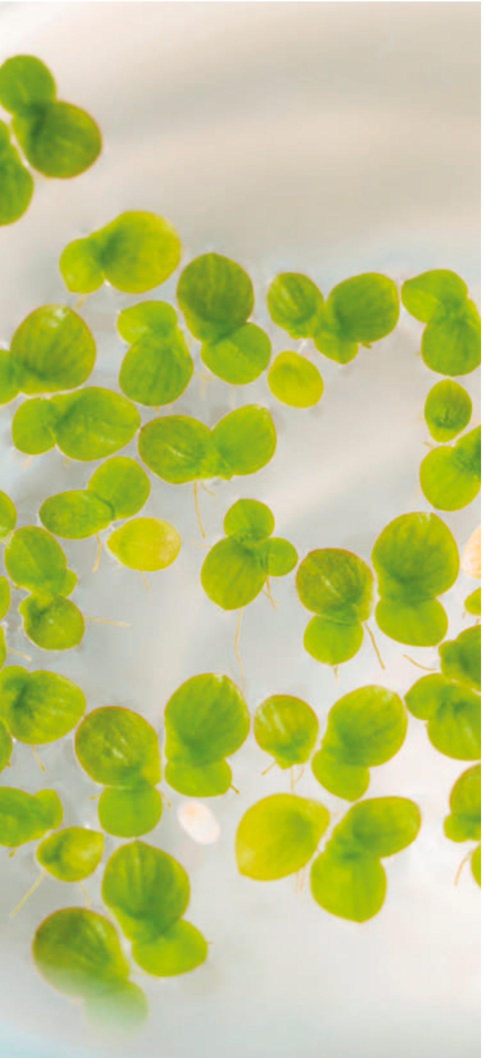
Figure 3. Cryo scanning electron microscopy at The Bio21 Institute, at the P4S University of Melbourne node.

Figure 4. The structure of a water spinach leaf observed by CLSM (left). This arrangement may be destructed and restructured with food processing to create a protein gel (right).

Figure 5. Long term storage options for leaves: freeze-drying (left), freezing (top right) and powder production (bottom right). Photo credit: frozen leaf and powder from iStock.

Making an impact: Insights from our Centre members

“How does your work support our aims of enabling human space travel and sustainable food production on Earth?”



Dr Kenneth Sim

Flinders University

Plant-based foods present a promising, sustainable solution to feeding people both in space and on Earth. While nutritional value and production feasibility are often prioritised in this pursuit, consideration of consumer-related psychology can be overlooked. My work broadly examines the psychology associated with consuming plant-based foods. On Earth, psychology helps us identify the barriers to people adopting more plant-based sources of nutrition amidst diverse consumer options. In space, where food choice is limited, psychology instead explores how consuming plant-based foods can support mental wellbeing.

Dr Caterina Selva

University of Adelaide

I study the fundamental and molecular development of duckweed, a group of tiny aquatic plants known as water lentils, to understand how they grow, store nutrients, and most importantly, how they flower and produce seeds. This knowledge will give me and other scientists the tools to modify duckweed to make it produce valuable substances such as nutrient supplements, pharmaceuticals, and bioplastics. This is essential to fulfil nutritional requirements and sustainably produce bioresources in resource-limited environments both on Earth and in space.

Dr Lydia Ong

The University of Melbourne

My work involves the design of food products that provide complete nutrition using minimal processing and plant resources.

Understanding the structure of raw plant ingredients and how they respond to processing helps us to create a variety of palatable food textures to avoid menu fatigue. Our team also considers how food can be stored to ensure safety and stability during deep space exploration. The knowledge gained will help us to feed astronauts in space, as well as helping to develop sustainable approaches to feed the growing population on Earth.

Kate Nakashima

The University of Melbourne

My research investigates the growth of two species of strawberry in a hydroponic system starting from seed or runner cuttings. The aim is to understand which approach produces the most fruit and the least non-usable material such as roots. Human space travel requires edible plants to be optimised for enclosed systems because waste is costly to manage. In addition, increasing our knowledge of strawberry's response to hydroponic systems supports the efficiency of non-traditional forms of horticulture on Earth.

Dr Van Duc Long Nguyen

The University of Adelaide

Our work supports human space travel by developing smart systems to grow food efficiently in places where resources are limited. By combining experiments with computer models (digital twins), we can predict and optimise plant growth, ensuring astronauts have a reliable and nutritious food supply. On Earth, these solutions enhance sustainable agriculture by maximising crop yields while using less water and energy. This advances both space exploration and food security on Earth, addressing the challenges of growing population and changing climate.

Anshul Phaugat

La Trobe University

Picture this: growing fresh, crunchy mini cucumbers and hearty peanuts in a controlled environment that could work on Mars—or in your own backyard. That's exactly what I'm working on! As a 24-year-old PhD researcher, I'm diving into the science of creating perfect growing conditions for plants in extreme environments. By tweaking light, temperature, and nutrients, I'm turning these crops into space-ready superstars: nutritious, high-yielding, and built to thrive where nothing else can. It's not just about feeding astronauts—it's about using these futuristic farming techniques to revolutionise agriculture on Earth, too. Who says you can't dream big and make it happen?

Florence Ly

The University of Western Australia

Food production on Earth and in space relies on healthy, high yield plants that can produce essential nutrients. However, instructing plants to generate useful products can be very demanding on the plant's energy and resources. My work focusses on enhancing the production of nutrients in specific parts of the plant, such as the fruit, at specific times. This reduces the strain on the whole plant and preserves its overall health for efficient production of nutrients in our food.

Chigozie Ofoedu

The University of Adelaide

My research supports P4S by optimising protein-enriched duckweed production in limited spaces, ideal for space missions where traditional protein sources are unfeasible. I am also developing novel methods to extract duckweed protein for diverse food applications, addressing astronauts' dietary needs and preventing food fatigue. This work contributes to the P4S mission by advancing zero-waste, controlled-environment plants that provide complete nutrition, ensuring humans can sustain health during space exploration.

Looking forward to 2025

As we step into 2025, the horizon is brimming with possibilities. This year promises to be a transformative one, with fresh challenges, innovations, and trends shaping the world around us. P4S will explore many new opportunities and here are some of the exciting activities we can look forward to in the coming year.

Plants

- Characterise the molecular properties of duckweed, including its cell wall and nutritional profiles.
- Test duckweed's responses to microgravity and space launch conditions.
- Develop plant tissue analysis protocols for lunar samples from the Artemis III mission.
- Build ISS-like hardware for plant growth monitoring under various conditions.
- Modify lettuce to improve protein and stress resistance.
- Improve tomato, lettuce, and strawberry growth and micronutrient content in space-based systems.
- Study strawberry gene expression and antioxidant profiles.
- Optimise mini-cucumbers and peanuts for hydroponic growth systems.

Products

- Create a platform for sharing gene circuitry information across the Centre.
- Develop stable duckweed transformation platforms and produce PHB plastic in plants.
- Enhance nutritional content in plants, focusing on vitamins and omega-3s.
- Establish a gene atlas for tomato trichomes and investigate bioactive compound production.
- Explore new plant-derived products, including biopharmaceuticals and beverages.
- Develop food structures and digestibility benchmarks for space-based foods.
- Examine sensory properties of plant-based foods in simulated space environments.

Processes

- Create digital twins using advanced technology for improved predictions in plant growth.
- Conduct sustainability studies, including techno-economic, life-cycle, circularity and ESG assessments.
- Develop legal, ethical, and environmental frameworks for genetically modified plants in space.
- Design and model supply chains for space farming and sustainability.

Above: Jonathan Diab, University of Adelaide, Below: Prof Michelle Watt and Cassie Watts, University of Melbourne, Opposite: Prof Volker Hessel, University of Adelaide, and Modupe Adebowale, University of Adelaide.

People

- Develop teaching materials aligned with the Australian National Curriculum.
- Deliver professional learning programs for teachers and engage industry sectors.
- Begin studies on the impact of P4S education programs.
- Support early career researchers and PhD students with interdisciplinary training.
- Launch the P4S 'Action Learning' mentoring program.

Governance

- Recruit postdoctoral researchers and PhD students to meet target capacity by 2025.
- Promote collaboration through seminars, research updates, and the Annual Conference.
- Continue quarterly meetings with the P4S Advisory Committee to review strategic direction.
- Build on equity, diversity, and inclusion efforts through a dedicated committee.

Public engagement

- Create engaging content to communicate the Centre's impact and research.
- Strengthen the Centre's online profile through social media and digital communications.
- Participate in the International Astronautical Congress 2025 and National Science Week.
- Engage with remote communities in the Northern Territory through local events.

Plants for Space Outreach

Plants for Space is committed to sharing their missions and research with a broad audience, through a range of outreach projects and public awareness efforts.

Teacher engagement

626
Secondary School Teachers

348
Primary School Teachers

In 2024 high impact was achieved in collaboration with partners and across all nodes, through the following programs and events:

- Martian Garden National Science Week,
- simple seeds,
- plant life on Mars,
- Growing Beyond Earth,
- engagement week following the Plants for Space Centre Launch.

Other engagement included a range of visits, public speaking activities and conference presentations, including but not limited to:

Visits from dignitaries at the Plants for Space headquarters including:

- NASA officials Ms Rebecca Levy (Office of International and Interagency Relations), Ms Sandra E. Connelly (Deputy Associate Administrator/ Science Mission Directorate) and Dr Mitch Schulte, Program Scientist, Mars Exploration Program.
- The Governor General of Australia, The Honourable Ms Sam Mostyn AC
- His Excellency Mr Maris Saisamponga, Minister for Foreign Affairs of the Kingdom of Thailand.

Public speaking opportunities and points of engagement through:

- More than 40 public talks, including events at Pint of Science, the Adelaide Club, and the International Space Centre.
- The Royal Adelaide Show, with over 1400 connections made with the general public over the course of nine days of visibility at the event, and an interview for local ABC radio.
- Multiple career engagement and networking opportunities, including presentations at the Royal Agricultural Society Discover Ag event in Sydney and the STEAM Careers forum, which was face to face but also online with a total of 7,100 students tuning in for this through the Science Gallery Careers Forum.
- Over 120 points of media attention, including several tv, radio and podcast interviews.

Prof Michelle Watt, University of Melbourne

Kate Nakashima
STEAM Careers Forum

The Martian Garden for National Science Week

Plants for Space presented 'The Martian Garden' as an interactive series of public events that explored how to select and adapt plant species to survive and thrive on Mars; supporting sustainable new ecosystems off-world and guiding novel approaches on Earth.

Innovative and immersive experiences propelled participants into tending a Space Garden and making new future foods.

The Martian Garden events were hosted during National Science Week in Victoria, South Australia and Western Australia (across our nodes, in metro and regional locations), reaching more than 3,000 members of the public. Even Australia's first astronaut Katherine Bennell-Pegg visited us at Melbourne's Scienceworks museum. As a National Science Week event the Martian Garden also received a broad range of media attention, including interviews on local ABC stations and short articles in local newspapers.

Simple Seeds

Plants for Space collaborated with Magnitude.io, Fizzics Education and SARDI (South Australian Research and Development Institute) to engage with students and teachers across four countries for the astrobotany Simple Seeds challenge. In five Australian states students performed simultaneous in class-ISS plant growth challenge and collected experimental data, to study and compare results obtained in classrooms across the world and on the ISS!

Schools were able to participate with the Simple Seeds programs on several levels, with growing chambers ranging from home-made soda bottle environments to state-of-the-art Exolabs, but all students joined in for a weekly webinar which included invited speakers from Plants for Space. SARDI provided Medicago seeds for the project both for the classroom Exolabs, as well as the ISS growing chambers, ensuring experimental design to be off to a good start to compare results to plants being grown off-Earth and on. A range of schools shared their results regularly through social media, proving a great overview of the scientific outcomes of the project.

Katherine Bennell-Pegg and P4S CI Prof Mathew Lewsey at Scienceworks in Melbourne

The Simple Seeds project provided a great way for students to meet researchers, normalise STEM approaches and problem solving, and show the benefits of international collaboration and intercultural learning in space research.


WA Open Day

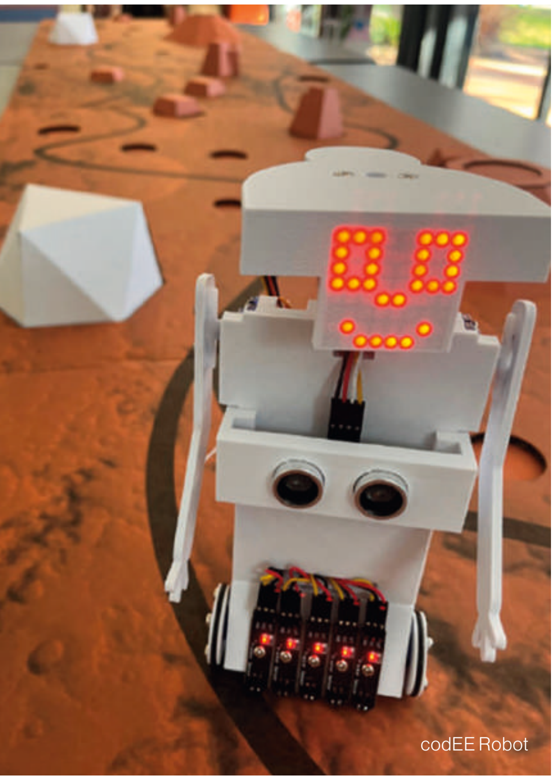
Shenton Park and Kings Park open day 'Gardening for the Future'

At the UWA node two successful open days showcased Plants for Space to industry, with a specific focus on agriculture and horticulture. This event was a good opportunity for P4S researchers and staff – from PhD to Chief Investigator and admin – to highlight the Centre's missions and individual research projects.

The outreach 'vertical farm' set up provided an engaging backdrop for open discussion on how Plants for Space will provide support for more sustainable food production on Earth.

Plant life on Mars

The year is 2030 and an international group of astronauts has just landed on Mars. To support health and wellbeing on this long-term mission, tasty, fresh plants are grown in carefully monitored space labs. Astronauts carefully monitor resource supply and demand for sustainable production. A meteorite storm requires the plant-bot to pick and deliver the food to astronauts but can it make it through the Mars terrain unscathed?


codEE Robot

This scenario challenged secondary school students and teachers across Victoria to run term- or semester-long projects in schools, together with Plants for Space researchers, the Victorian Space Science Education Centre (VSSEC), and undergraduate mentors as part of their STEM curriculum. Students were tasked with growing a highly nutritious plant-based food (duckweed) in different temperature and light conditions and monitor plant growth and health.

Furthermore, they were asked to build a 'codEE' robot, design and attach a carrier for the robot to hold plants and code the robot to navigate a Mars map back to base.

The challenge embodied STEM skills to solve the challenge of automated food production in space, and highlighted the interdisciplinary needs in space research. Students interested in space, agriculture and food careers from 15 schools in metropolitan Melbourne and regional Victoria joined in, and three teacher professional learning events were held to support the program.

Growing Beyond Earth

Growing Beyond Earth is a citizen science program created by NASA and Fairchild Tropical Botanic Gardens in Miami and the Australian program extends this collaboration to Plants for Space, Royal Botanic Gardens Victoria, the La Trobe Institute for Agriculture and Food, and Melbourne Archdiocese of Catholic Schools.

The program engages students to test the durability, production and sustainability of various crops in grow boxes, with the aim of uncovering species that have potential to be grown successfully in space.


Engagement week

In 2024, 8 schools in Victoria and Tasmania ran the program with students gaining experience in running their own experiments, planting the seeds in pots and media that match the NASA Vegetable Production System (Veggie).

Students present their findings in showcase events to researchers from Plants for Space, NASA and the Royal Botanic Gardens, giving them the opportunity to engage with the real-world scientists leading this work, and even new plants being tested on the ISS.


Growing Beyond Earth growbox

Engagement week following Centre Launch

Following on from the Plants for Space Centre Launch the SA node engaged with industry, media and high school students during an engagement week.

An engaging Mars environment was set up to introduce the audience to the future of astrobotany and what we can learn from this for on-Earth applications in sustainable food production and controlled environment grow facilities. More than 100 visitors came through the exhibition space during this engagement week.

Industry engagement included networking opportunities for existing and potential new Centre partners, whereas the media engagement day presented the opportunity for a long Q and A with Centre Director Prof Matthew Gilliham. Students were introduced to Plants for Space on two separate days through our immersive Mars plant-growing facility, followed by a series of interactive hands-on sessions on feeding astronauts for deep space exploration, sustainable food systems featuring edible insects, how plants can be grown in space for food, medicine, and even bioplastics and the impact of Plants for Space on sustainability on Earth.

In the Media

A/Prof Jennifer Mortimer, University of Adelaide

Plants for Space shared several press releases in 2024, in collaboration with the media teams of their respective universities. Announcements included exciting grants, upcoming nation-wide events and the launch of the first Plants for Space payload of duckweed aboard Mapheus-15.

Furthermore, Plants for Space researchers recorded 62 radio interviews, 7 podcast episodes, 5 tv appearances and 52 newspaper, print and online articles.

Highlights of Plants for Space media releases include:

Plants to be grown on the Moon when humans return (3 April 2024):

NASA has announced that when humans take their first steps back on the Moon after 50 years during the Artemis III mission, astronauts will cultivate and return lunar-grown plants to Earth for the first time.

Known as Lunar Effects on Agricultural Flora (LEAF), the project will collect plant growth and development data that will help scientists understand the use of plants grown for both human nutrition and life support on the Moon and beyond.

Slated for a September 2026 launch, the consortium of partners who will pioneer this initiative includes a core group from the Australian Research Council Centre of Excellence in Plants for Space, headquartered at the University of Adelaide.

The project is led by Space Lab Technologies and involves the University of Adelaide, La Trobe University, and NASA Kennedy Space Center, all P4S partners, as well as the United States Department of Agriculture, University of Colorado Boulder, and Purdue University, with additional analysis to be conducted by the P4S node at the University of Western Australia.

UK-US-Australia collaboration scales plant growth in preparation for space exploration, and funding gives plants in space a growth boost (8 April 2024)

Martians, dinosaurs headline National Science Week 2024 (12 May 2024. Minister for Industry and Science)

La Trobe finalist in NASA Space Food competition (7 August 2024)

Build a Martian Garden for National Science Week (7 August 2024)

Potential future space-farers will discover how to grow plants for interplanetary travel, as part of a National Science Week event held by the University of Adelaide's ARC Centre of Excellence in Plants for Space (P4S).

The Martian Garden is an immersive experience which delves into the challenges and innovative solutions required for growing plants in space to ensure a nutritious and varied food supply to sustain the physical and mental wellbeing of future off-world inhabitants.

Attendees will be guided through four interactive "research" stations – Space Garden, Space Plants, Space Robots and Space Food – with Mars rovers roaming outside.

Australian duckweed launches into space (13 November 2024)

The ARC Centre of Excellence in Plants for Space, headquartered at the University of Adelaide, has sent its first payload of duckweed into space, jumping aboard a sounding rocket launched by the German Aerospace Centre (DLR) as part of its MAPHEUS 15 mission.

The MAPHEUS 15 sounding rocket was successfully launched at 7:38am (UTC) on Monday, 11 November, and contained 21 scientific experiments from organisations all around the world.

The University of Adelaide's MiniWeed experiment, conducted in collaboration with DLR and Melbourne's La Trobe University, will test how altered gravity affects duckweed – a plant identified as a potential food source for astronauts.

Dr Lieke van der Hulst, University of Adelaide

Leading sustainable innovation in space and on Earth

At the heart of P4S is a commitment to ethical, sustainable innovation that benefits both space exploration and life on Earth.

Our Cultural Charter guides our values, behaviours, and interactions, ensuring that every aspect of our work is grounded in responsibility and integrity.

Key Commitments of P4S:

Sustainable space habitation and benefits for life on Earth

- Promote sustainable, ethical, and responsible use of plants for food, pharmaceuticals, materials, and psychological wellbeing.
- Partner with industries on Earth to co-design products and processes, ensuring sustainable outcomes for space and Earth environments.
- Educate on waste management and resource use in space habitats, applying the latest global practices.
- Generate different types of food that appeal to a range of users; that are cognisant of different cultural norms; and are edible and digestible by as wide a range of people as possible.
- Learn from Indigenous cultures and practices including cultures that live in remote and extreme environments and embed culturally appropriate practices into our relationship with Earth and space.
- Meet, apply, shape and evolve ethical, health and legal requirements for production of plant products in space or in contained environments on Earth.

Research excellence and integrity

- Adhere to the highest standards of research excellence and integrity as outlined by the ARC Centres of Excellence scheme objectives and ARC Research Integrity Policy.
- Foster cross-disciplinary collaboration, teamwork and cooperation to achieve world class impact.

A diverse, supportive and co-operative team

- Celebrate creativity and achievements through regular events and communications.
- Support each other through formal and informal mentorship and training.
- Apply inclusive practices in recruitment and communications, fostering a culture of kindness, inclusion, and respect.

Promoting and supporting Australian science, education, and industry

- Engage schools, universities, and industry in urban, regional and rural environments to promote the vision of P4S and inspire future Australian scientists and engineers.
- All education and engagement activities to reflect diversity and inclusion, and ensure that our work promotes Australia's role as a global leader in science and sustainability.

> “Our Cultural Charter guides our values, behaviours, and interactions, ensuring that every aspect of our work is grounded in responsibility and integrity.”

Above: Dr Lieke van der Hulst, Communications and Engagement Officer, engages with students at the University of Adelaide.

Right: Dr Ryan Coates from the University of Western Australia discusses innovations in enhancing protein nutrition in plants.

Below: Ms Bhargavi Solanki from La Trobe University examines duckweed under the microscope.

> “P4S is more than just research; it’s about creating a better, safer future, driven by the incredible potential of plants in space. We’re committed to staying responsible and transparent, making sure our work stays in line with the changing needs of society.”

Developing technologies for on-Earth sustainability

Our diverse team brings together a wide range of researchers in disciplines across plant science, nutrition, food science, engineering, psychology and space law.

Professor Matthew Gilliham

Director

University of Adelaide

"The goal of P4S is to re-imagine plant design and bioresource production, through the lens of space, to enable off-Earth habitation and provide transformative solutions to improve on-Earth sustainability."

Professor Sally Gras

Deputy Director

University of Melbourne

"Collaboration of those involved in P4S will create new technologies and capabilities in plant modification and biomanufacturing to translate research into a variety of applications. This will stimulate both new process and product development for domestic and international markets. We will pursue innovation in plant processing and food structuring that, together with sensory and digestive assessments, will help develop a plant-based food industry for space and Earth."

Professor Melissa de Zwart

Deputy Director

University of Adelaide

"By training more than 400 researchers, P4S will produce the next generation of internationally connected and industry-focused experts and accelerate the growth of the burgeoning national and international CEA and biomanufacturing industries."

Professor Christine Feinle-Bisset

Chief Investigator
University of Adelaide

"I love being a scientist for many reasons - one of them is seeing the excitement in young students when embarking on new projects and the wonder about what they might discover in the process."

Professor Volker Hessel

Chief Investigator and Program Leader
University of Adelaide

"We have simulated a mix of six to eight crops that deliver all the required nutrients that an astronaut needs, which is different from what people need on Earth. While there are dozens of crops that can fulfil an astronaut's nutrient requirements, we needed to find those that could pack a punch and deliver the calories needed in smaller portions that could be grown in a small space."

Associate Professor Kim Johnson

Chief Investigator and Program Leader
La Trobe University

"Supporting life in space is a huge challenge but also offers amazing opportunities for innovation and creativity. I love being able to work with people from all different areas –science, engineering, chemistry, law and psychology - to come up with solutions for better quality of life in space and sustainability on Earth."

Professor Eva Kemps

Chief Investigator and Node Leader
Flinders University

"Investigating human-plant interactions (i.e., caring for and eating them), will optimise the overall wellbeing of astronauts involved in space missions. The to-be-developed plant-based food products and their effects on human nutrition, cognition and mood will also have important implications for Earth in terms of addressing food insecurity and environmental sustainability."

Professor Mathew Lewsey

Chief Investigator, Program Leader and Node Leader
La Trobe University

"Growing plants on Mars is one of the biggest sustainability challenges you can imagine. There's no (readily available) water, food, fertiliser; no materials to build anything. If we can solve those problems to grow enough food for a small settlement on Mars, we can apply those sustainability solutions on Earth."

Professor Ryan Lister

Chief Investigator and Program Leader
University of Western Australia

"Our new synthetic gene circuit technologies enable us to program gene activity for precisely when and where it is needed in a plant. We'll use these to reprogram plants for the controlled environments of space missions and vertical farming industries on Earth. These synthetic circuits will allow us to add new cell functions and behaviours in plants, such as enhanced disease and stress tolerance or on-demand production of pharmaceuticals or biomaterials."

Professor Harvey Millar

Chief Investigator and Program Leader
University of Western Australia

"Growing plants as food in space stations or a future Lunar base requires robust processes to ensure crops are available on-time and in the expected quantity to meet demand. The collaboration between plant scientists and space technology providers from the UK, Australia, and the US aims to create new commercial options for automating plant growth at scale in space and on Earth."

Associate Professor Jenny Mortimer

Chief Investigator and Node Leader
University of Adelaide

"We are excited to reach this first step of launching a sample of Wolffia australiana in a sounding rocket experiment with our collaborators at the DLR. We are currently analysing the impact of the altered gravity on the plant biology on the retrieved samples, with a focus on early gene expression responses."

Associate Professor Sigfredo Fuentes

Chief Investigator
University of Melbourne

"We know food tastes different in space. We want to understand how astronauts can avoid menu fatigue, using the best plant-based foods that will stimulate tastebuds and satisfy sensory and nutritional needs."

Professor Ian Small

Chief Investigator and Node Leader
University of Western Australia

"Many of the challenges needed for long-term life on Moon and Mars are also faced by agriculture on Earth and need to be researched to advance the efficiency of plant-based foods for example increasing fertiliser use efficiency."

Professor Matthew Tucker

Chief Investigator
University of Adelaide

"The Centre (P4S) is looking for plants that can grow well and reproduce on demand in constrained spaces such as outer space; and one of those plants is duckweed. Duckweed is intriguing since it has these properties where it can grow in quite stressful conditions under limited water, perhaps even polluted water."

Professor Michelle Watt

Chief Investigator and Node Leader
University of Melbourne

"Our research will examine the role of plant roots in space and seek to improve key measures of plant efficiency, such as harvest index, allowing us to use all plant parts in resources we grow in space and here on Earth."

Prof Harvey Millar, University of Western Australia

P4S Centre Partners

GAIA Project Australia

GAIA Project Australia have developed innovative cultivation systems through cutting-edge research on plant growth and nutrition both for space, as part of the NASA-CSA Deep Space Food Challenge, and for Earth. Our partnership is focussing on optimising food production for space environments and offering valuable research opportunities for students, advancing both space-based agriculture and Earth applications in controlled environment farming.

University of California, Berkeley

UC Berkeley are bringing their world-leading expertise in engineering biology to advance high-efficiency, zero-waste plant production systems for space habitats to P4S. Our work with UCB's researchers in genomics and space engineering is fostering innovative plant designe and biomolecule production to create transformative solutions for sustainability in both space and on Earth.

University of California, Davis

UC Davis are pioneers in biochemical engineering and plant-based biopharmaceutical production which they bring to P4S, enhancing the development of sustainable, high-efficiency plant systems for space exploration.

University of Wisconsin-Madison

The University of Wisconsin-Madison has extensive expertise in spaceflight plant biology, particularly through partner investigators who have led recent experiments on the International Space Station. This collaboration is providing new insights into space biology, with applications in bioregenerative life support systems and agricultural innovations for both space and Earth environments.

Rice University

Rice University is initially contributing to P4S through its expertise in team dynamics and psychology in space. Building on its longstanding relationship with NASA, Rice is advancing the development of sustainable space agriculture and bioregenerative life support systems to support P4S's space exploration efforts.

University of Cambridge

The University of Cambridge's Department of Plant Sciences is driving advancements in plant productivity, particularly in controlled environments. By utilising the expertise of partner investigators and collaborating with industry leaders, Cambridge is contributing to pioneering research on plant circadian rhythms and nutrient management for space agriculture.

University of Nottingham

The University of Nottingham is leveraging its expertise in agricultural, environmental, plant, and food sciences. As a member of the Russell Group, Nottingham is internationally recognised for its research excellence and global partnerships. This collaboration is building upon the University's strengths in plant science and sustainable agriculture, supporting efforts to advance space-based food production and Earth sustainability.

YURI

YURI is developing biological products such as pharmaceuticals, nutritional products, and new materials using plants in simulated microgravity and space. In collaboration with P4S, YURI brings its expertise in microgravity research and engineering solutions, providing flexible, on-demand platforms, including mini-bioreactors and greenhouses, to support the goals of space biomanufacturing.

ETH Zurich

ETH Zurich is advancing sustainable food production for space exploration in collaboration with P4S, particularly in the food products sector. Through its Institute of Food, Nutrition, and Health, ETH Zurich is contributing innovative solutions in food science, food science, food structure and texture design, to support P4S efforts to address the challenges of feeding humans in space, and improving the sensory experience for plant based foods on Earth.

Andy Thomas Space Foundation (ATSF)

ATSF is supporting space education and outreach, inspiring young people to pursue STEM careers. Through school programs and public events, ATSF is showcasing the research and challenges addressed by space-related scientific fields, including those of P4S, helping ignite curiosity and promote the importance of space science.

Dr Joanna McMillan

Dr Joanna McMillan is contributing her expertise in nutrition and health to enhance food production for space exploration. With her background in nutrition science, she is helping develop innovative solutions to improve the nutritional content, efficiency, and sustainability of food, with applications that extend beyond space to address global food security and wellness.

Victorian Space Science Education Centre (VSSEC)

VSSEC incorporates cutting-edge research from P4S into its educational programs for primary and secondary students. By leveraging discoveries in space agriculture, VSSEC updates its curriculum and develops new programs focused on space exploration and food production challenges.

One Giant Leap Australia

One Giant Leap Australia is delivering space and agriculture-focused STEM programs for primary and secondary school students in collaboration with P4S. With its expertise in space education and established relationships with global space agencies, it is expanding outreach to inspire the next generation of students to pursue careers in STEM and space science.

The Botanic Gardens and State Herbarium (BGSH) of South Australia

BGSH is advancing scientific understanding of plant systems in space and promoting public engagement with space botany in collaboration with P4S. By integrating research into educational programs and digital platforms, BGSH is contributing to public communication and outreach, fostering a deeper connection between the public and the future of space agriculture.

Department of Primary Industries and Regions (PIRSA-SARDI)

SARDI is enhancing the development of novel plants and food processing systems for space exploration. By contributing expertise in plant nutrition, food processing, and innovative growing systems, SARDI is advancing space agriculture research while supporting South Australia's food and plant industries through PhD student co-supervision and collaborative projects.

Bioplatforms Australia

Bioplatforms Australia is leveraging its expertise in 'omics research infrastructure to generate critical data needed for plant redesign and biomolecule production projects in collaboration with P4S. Through financial support, internships, and strategic collaborations, Bioplatforms is contributing to the development of high-efficiency plant production systems while providing opportunities for students to engage with leading biotechnology initiatives.

Twist Bioscience Corporation

Twist Bioscience is supporting the development of plants with enhanced nutritional value and biosynthetic potential through its advanced synthetic DNA tools and biomanufacturing capabilities. This collaboration is helping accelerate innovations in food sustainability and bioengineering for both space and terrestrial applications.

*denotes project partners

Defence Science and Technology Group (DSTG)

DSTG is exploring innovative solutions in food, nutrition, and human performance in closed environments, such as space and submarines. This partnership builds on existing research and provides opportunities for work-based PhD students and internships, supporting DSTG's strategic goals to strengthen Defence capabilities.

**APPN (formerly APPF)*

Advancing plant production systems for space exploration and Earth sustainability, APPN is enhancing its globally leading research infrastructure in sensing, imaging, and analytics to develop controlled environment agriculture technologies, including vertical farming. This collaboration is enhancing plant growth and biofactory production for both off-Earth and terrestrial applications.

AXIOM Space

Axiom Space is developing plant-based solutions in microgravity using its commercial space station as a platform. In collaboration with P4S, this partnership aims to assess the effectiveness of innovative plant systems and processes, advancing space exploration and Earth-based sustainability through frequent access to low-Earth orbit.

**DLR (The German Aerospace Centre)*

DLR is advancing bioregenerative life support systems, focusing on nitrogen recycling to support plant growth for off-Earth habitation. This collaboration combines DLR's expertise in aerospace medicine and closed-loop systems with P4S's research on sustainable plant systems, enhancing space exploration and agricultural sustainability on Earth.

AGRF

AGRF is aligning its cutting-edge genomics platforms with global sustainability challenges. Through its collaboration with P4S, AGRF is developing plant solutions for space exploration and aims to deliver significant benefits for agriculture and climate resilience on Earth.

Australian Space Agency

The Australian Space Agency (ASA) and P4S are collaborating to foster innovation and growth in the local space sector. By leveraging ASA's leadership in coordinating civil space activities across government and its commitment to aligning space policy and initiatives nationally, P4S is helping strengthen South Australia's position as a leader in the global space industry.

SpaceLab Technologies

SpaceLab Technologies are advancing sustainable space food production, contributing to technologies that support off-Earth habitation and improve life on Earth. By combining its expertise in space agriculture with space research, this partnership is driving innovation in plant growth and productivity.

Vertical Future

Vertical Future is applying its expertise in controlled environment agriculture to advance space-based food production systems. The partnership focuses on optimising vertical farming techniques for space environments, driving innovations in sustainable food production for space missions and Earth-based applications.

Saber Astronautics

Saber Astronautics are providing next-generation spaceflight operations expertise and software to support mission design and space operations. This collaboration optimises plant growth and sustainability in space environments, advancing research in space agriculture.

South Australia Space Industry Centre (SASIC)

SASIC is supporting the growth of South Australia's space sector by focusing on food production in space. Leveraging the state's expertise in agriculture for resource-constrained environments, this partnership supports South Australia's Space Sector Strategy and promotes innovation, research excellence, and workforce development for both space and Earth applications.

NASA

NASA is collaborating with P4S to create transformational advances in space crop production, which are critical for feeding and supporting long-term space exploration. This partnership is advancing food systems for space missions and supporting NASA's efforts for crewed Mars missions in the 2030s, with advice and consulting from NASA's experts.

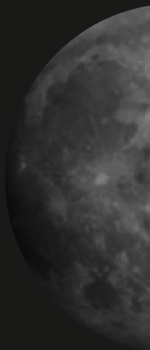
Food IQ

FoodIQ is collaborating with P4S to provide science-backed food and nutrition insights, helping develop sustainable, nutritious food systems for space exploration and Earth applications.

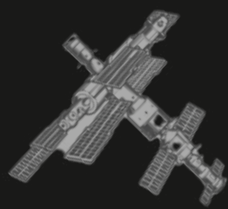
INRAE

INRAE is addressing the unique challenges of feeding humans on the Moon, combining its expertise in sustainable agriculture and food systems with P4S's research to assess and improve the digestibility and nutritional value of novel plant based foods developed for space and earth applications.

Interdisciplinary Collaboration



Molecular Plant Science	The University of Adelaide; The University of Western Australia
Plant Physiology	The University of Melbourne; NASA
Plant Pharma	La Trobe University; UC Davis University of California
Plants as Bio-Resources	UC Berkeley
Controlled Env. AG.	vertical future; appn Australian Plant Phenomics Network; GAIA PROJECT AUSTRALIA PTY LTD
Systems Engineering	The University of Adelaide; Space Lab; Saber Astronautics; Axiom Space; DLR; Yuri
Food Structuring	The University of Melbourne; University of Nottingham UK | CHINA | MALAYSIA; Australian Government Department of Defence Science and Technology; dr Joanna McMillan
Food Processing	ETH zürich



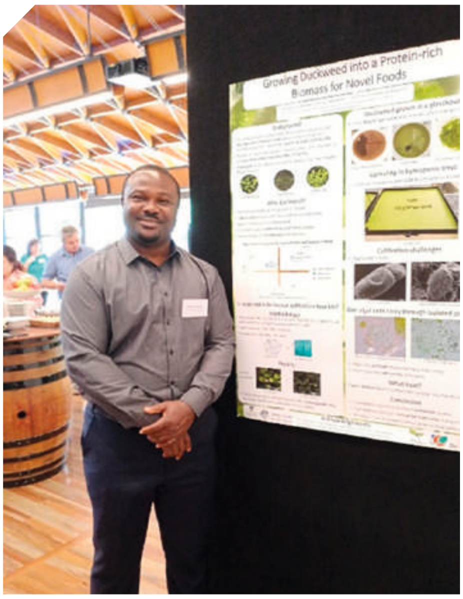
P4S CENTRE PARTNERS

Digestion	The University of Adelaide; FOODiQ global; INRAE; Government of South Australia Department of Primary Industries and Regions; SARDI South Australian Research and Development Institute
Single Cell 'Omics	The University of Western Australia; La Trobe University; Bioplatforms Australia
Gene Editing	The University of Western Australia; UC Berkeley; TWIST Bioscience; agrf
Law and Policy	The University of Adelaide; Australian Space Agency; South Australian Space Industry Centre
Education	VSSEC; The Andy Thomas Space Foundation; One Giant Leap Australia
Outreach	NASA; Botanic Gardens and State Herbarium; Dr Joanna McMillan
Psychology	Flinders University; Rice University; NASA
Sensory Science	The University of Melbourne; The University of Adelaide; University of Nottingham UK | China | Malaysia

Grants

At Plants for Space, we are excited to highlight the incredible achievements of our members. In 2024, they were awarded a number of grants that recognise their innovation and drive. These grants not only celebrate their hard work but also provide the resources needed to push their projects forward.

Researcher/s	Awarding Organisation	Funds awarded
A/Prof Jenny Mortimer, Dr Bo (Weasley) Xu, Prof Matthew Gilliham	SA Genomics Centre - South Australian Multiomics Framework Initiative	$81,000 Research funding
Dr Bo (Weasley) Xu	Waite Research Institute - Elizabeth MacMeikan Trust	$24,600 Research funding
Prof Matthew Gilliham, A/Prof Jenny Mortimer, Prof Matthew Tucker	Bioplatforms Australia (Plant Synthetic Biology facility)	$8,500,000 NCRIS funding
Prof Matthew Gilliham, A/Prof Jenny Mortimer, Prof Harvey Millar, Sumen Rai, Prof Alex Webb, Prof Bernadette McCabe, A/Prof Cheryl McCarthy, Jennifer Bromley, Jana Stoudemire	International Bilateral Fund – UKSA Phase 2	GBP£1,500,000 Research funding
Prof Mathew Lewsey	Bioplatforms Australia (Plant Synthetic Biology facility)	$4,500,000 NCRIS funding
Prof Matthew Gilliham, A/Prof Jenny Mortimer	iLaunch Trailblazer Program through the University of Southern Queensland	$1,289,538 Research funding
Dr Caterina Selva	American Society of Plant Biologists	USD$575 Travel award
Dr James Lloyd	University of Western Australia - Clifford Bradley Robertson and Gwendoline Florence Robertson fund UWA's International Space Centre - Internal funding support	Fellowship $5,000
Chigozie Ofoedu	Adelaide Graduate Research School	$1,000 Travel grant
Dr Alison Gill	Graduate Women SA Trust Fund	$5,000 Postdoctoral travel grant
Dr Claudia Gonzalez Viejo	University of Melbourne - ECR Grant 2024	$40,000 Research funding
Prof Volker Hessel, Dr Le Yu	John Shaw Legacy - Philanthropic grant - Legume Growth in Microgravity	$25,000 Research funding
A/Prof Jenny Mortimer, Prof Matthew Gilliham, Prof Matthew Tucker	Australian Wine Research Institute - Friendship Fund	$25,000 Research funding
Dr Alex Ware	Biotechnology and Biological Sciences Research Council (BBSRC) Fellowship	GBP £420,000
Anshul Phaugat	Australian Plant Phenomics Network Defence Science Institute	$10,000 Research project funding $15,000 HDR Top up grant



Clockwise from top left: Dr Claudia Gonzalez Viejo at the inaugural conference and launch of the ARC Centre of Excellence in Plants for Space, Dr James Lloyd presenting his work on synthetic gene circuits for plants, and how they can be engineered plants for space, Dr Alison Gill at Vertical Future in Bishop's Stortford UK, looking behind the scenes of their vertical farm manufacturing, R+D, and working farm facilities, Prof Volker Hessel and Dr Le Yu (UoA) visiting LTU to conduct a life cycle assessment study for La Trobe's pilot and NASA-awarded (Gaia) closed environmental systems, Chigozie Ofoedu at the Waite Research Institute presenting his research on sustainable protein, highlighting its potential to tackle prevailing environmental and resource challenges.

Awards & Achievements

Prof Matthew Gilliham

- Finalist for 2024 South Australian Scientist of the Year.
- Clarivate's Highly Cited Researchers list for 2024.
- Finalist for Academic of the Year in the Australian Space Industry Awards 2024.
- University Outstanding Achievement Award in the category of Excellence in Research (Academic).

Thomas Cobbinah

- Best Poster award at the Australian Society of Plant Scientists 2024 Conference (ASPS2024) in Melbourne, Victoria.

Prof Mathew Lewsey

- La Trobe University's 2024 Vice-Chancellor's Cultural Qualities Award for Innovation. Winner: Leafy 2.0 team - Prof Mat Lewsey. This award acknowledges their ground breaking work on smart farm technology, in collaboration with P4S partner Gaia Project Australia Pty Ltd.

A/Prof Jennifer Mortimer

- ASPS Jan Anderson Award. In recognition of Prof Jan Anderson's life and achievements in photosynthesis research as a pioneering female scientist, this award acknowledges talented female plant science researchers.
- Promoted to Prof (University of Adelaide) as of 1 January 2025.
- Bruce Stone Award for excellence in Plant Polysaccharide Biochemistry.

Dr James Lloyd

- Winner of UWA School of Molecular Science's Mid-Career Research Award (annual award) for contribution to excellence in research.
- Staff exchange with the University of Leeds, UK to develop climate-smart plants with Dr Suruchi Roychoudhry.

Dr Farley Kwok van der Giezen

- Awarded the Perth Protein Group (PPG) grant, Farley, an early career researcher, will have the opportunity to travel to and present their research at the ComBio conference. The PPG, a special interest group of the Australian Society for Molecular Biology and Biochemistry (ASBMB) in Western Australia, offers this grant every two years.

Dr Alison Gill

- Federation of European MicroBiological Societies - FEMS Early Career Travel Grant.
- Graduate Women SA Trust Postdoctoral Grant - 2024.

Dr Troy Miller

- International Space Centre, UWA - Space Research Support Scheme.
- AUD$5,000 to support space related research, particularly to develop cross-node collaboration.

Dr Adriane Piechatzek

- Most Highly-Cited Researcher 2024 ECR Category - Waite Research Institute.

Leni Campbell-Clause

- Lugg Travel Award. The purpose of the travel award is to assist a student undertaking a postgraduate research degree in biochemistry.

NASA's Deep Space Food Challenge

- Gaia Project Australia Pty Ltd, an Australian start-up and partner of the ARC Centre of Excellence in Plants for Space, was international runner-up in NASA's Deep Space Food Challenge at The Ohio State University, competing against international contenders.

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1: Prof Matthew Gilliham (centre) receiving his finalist nomination for SA Scientist of the Year, 2: Thomas Cobbinah (3rd from Right) among other ASPS attendees, 3: The Leafy 2.0 team, P4S Chief Investigator Prof Mathew G Lewsey pictured far right, 4: A/Prof Jennifer Mortimer, 5: Dr Farley Kwok van der Giezen - the University of Western Australia, 6: Dr Alison Gill showcasing P4S Research, 7: From L-R, World-renowned gravitational biologist Dr Jens Hauslage (P4S Partner DLR),Dr Adriane Piechatzek and Charlotte Bampton, 8: Dr Troy Miller presenting at the 2024 P4S Conference, 9: Dr James Lloyd, 10:Leni Campbell-Clause is part of the P4S team looking to re-design plants to provide astronauts with all the nutrition they need, 11: Robyn Gatens (Director, International Space Station and Commercial Spaceflight Divisions, NASA) and Trent Smith (Research Advisor, Space Crop Production, NASA) with Gaia project team members.


1
2024 SA Science Excellence + Innovation Awards


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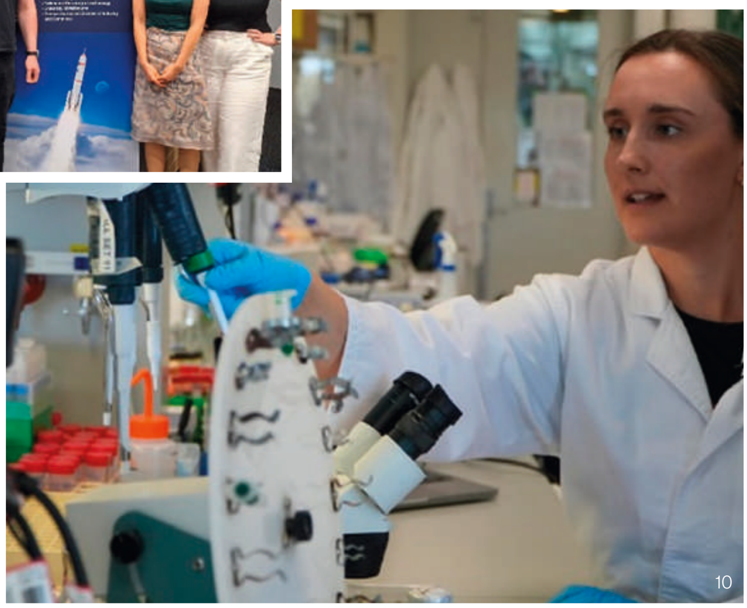
DR ALI GILL


5


8


7
VICTORIAN MICROGRAVITY AND SPACE LIFE SCIENCE CONSORTIUM

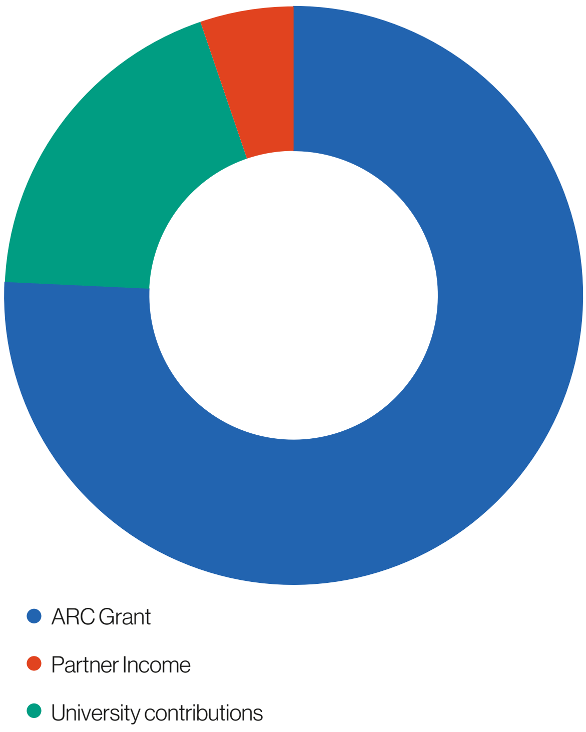

9


10

Financial Statement

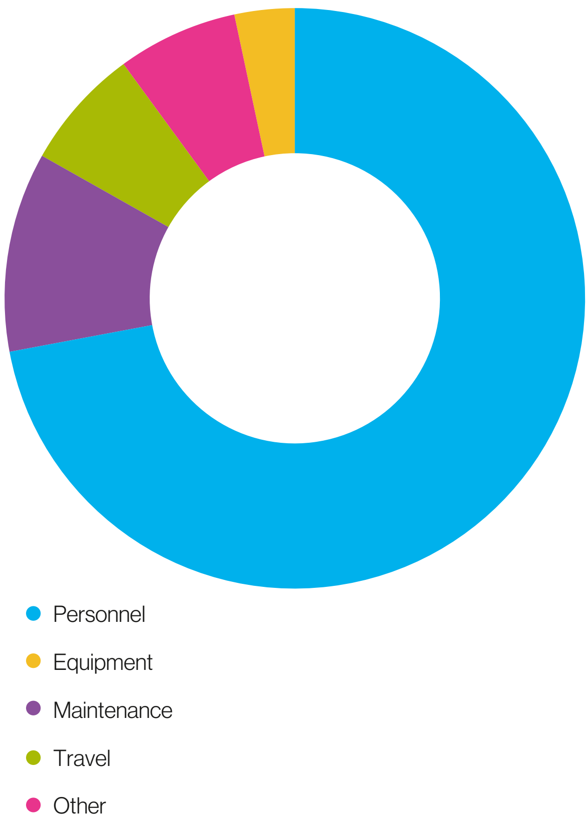
Income

Income	2024
ARC Grant	$5,578,652.80
Partner Income	$385,000.00
University contributions	$1,401,972.00
Total	**$7,367,648.80**



Expenses

Expenditure	2024
Personnel	$2,474,476.01
Equipment	$114,996.42
Maintenance	$382,002.62
Travel	$232,773.06
Other	$230,205.89
Total	**$3,434,454.00**



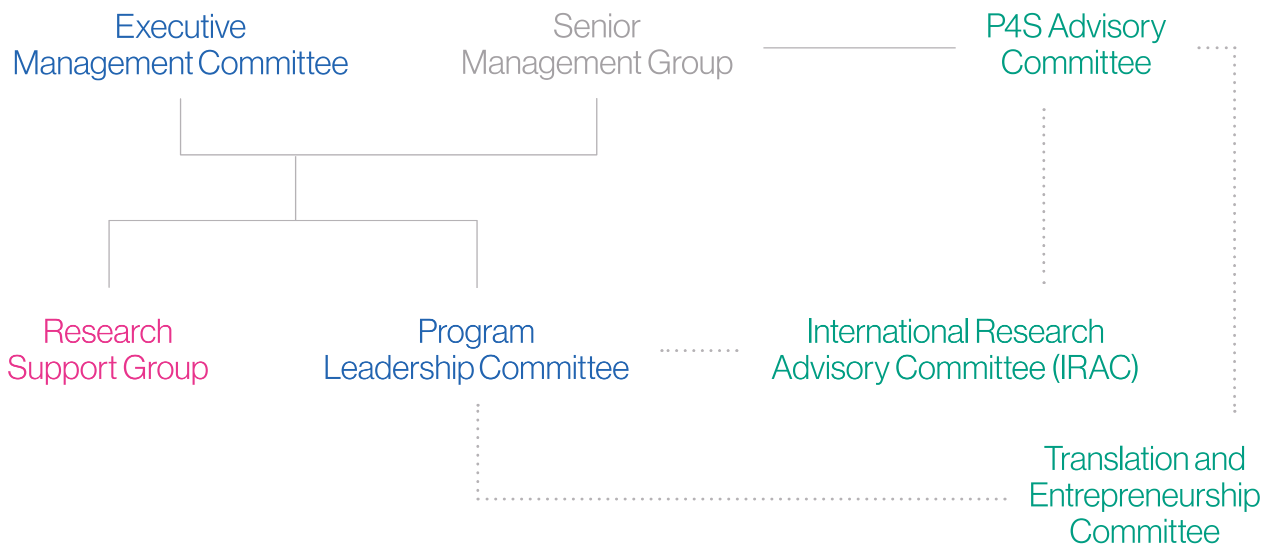
Developing technologies for on-Earth sustainability

By pushing the boundaries of plant science and technology, **PLANTS FOR SPACE** is helping to create a more sustainable and resilient future.

Governance

P4S governance structure and framework are designed to facilitate agility, delivery of outcomes and connectivity to the international Space agriculture community. P4S' internal committees and decision-making processes incorporate control measures of the P4S risk management plan to continuously monitor and manage the performance of Centre projects, succession planning and appropriate management and allocation of Centre funds across the Centre.

P4S' external committee structure links independent expert strategic, industry and academic advice to P4S' research programs to help shape the objectives and direction of the Centre and ensure the Centre's activities remain relevant to broader international industry and academic trends and demands. Inclusion of early- and mid-career researchers (EMCRs) in internal committees supports the professional development and succession planning activities of the Centre.



= Early and Mid-Career Researcher (EMCR) Inclusion

= External

At the forefront of innovation, Chief Investigators and members of the Executive Management Committee of the ARC Centre of Excellence in Plants for Space

Executive Management Committee (EMC)

Prof Matthew Gilliham* (Chair)

Prof Melissa de Zwart*

Prof Sally Gras*

Dr Richard Harvey

Prof Mathew Lewsey*

Prof Harvey Millar*

Prof Ryan Lister*

Prof Volker Hessel*

A/Prof Kim Johnson*

Prof Ian Small

Prof Michelle Watt

A/Prof Jenny Mortimer

Prof Eva Kemps

Prof Matthew Tucker

A/Prof Sigfredo Fuentes

Prof Christine Feinle-Bisset

Dr Gioia Massa

Dr James Lloyd
(alternating EMCR representative)

Dr Bo Xu
(alternating EMCR representative)

Jonathan Diab
(alternating HDR student representative)

Kate Nakashima
(alternating HDR student representative)

**Denotes Program Leadership Committee Leads*

Senior Management Group (SMG)

Prof Matthew Gilliham (Chair)

Prof Melissa de Zwart

Prof Sally Gras

Dr Richard Harvey

Research Support Group (RSG)

Dr Richard Harvey

Dr Rebecca Vandeleur

Dr Lieke van der Hulst

Ms Nikki Hodge

Ms Sandra Clavijo

Mrs April Harris

Ms Cassie Watts

Dr Linda de Melis

Ms Amy Griessl

P4S Advisory Committee (PAC)

Prof Steven Freeland (Chair)

Dr Jitendra Joshi

Dr Shannon Walker

Ms Carey Taylor

Dr Brett Biddington AM

Prof Fiona Cameron

Prof Anna Koltunow FAA FTSE

International Research Advisory Committee (IRAC)

Prof Anna-Lisa Paul

Dr Raymond Wheeler

Prof Birger Lindberg Møller

Prof Harjinder Singh

Ms Sally McPhee

Translation and Entrepreneurship Committee (TEC)

Prof Matthew Gilliham (Co-chair)

Prof Sally Gras (Co-chair)

Prof Jay Keasling

A/Prof John Coulton

Dr Michael Millan

Dr Aude Vignelles

Dr Judy Halliday

Dr Natalie Curach

Dr Richard Harvey

Key Performance Indicators

Performance Measure	2024 Target	2024 Actual
1. Number of research outputs		
· Journal articles	10	19
· Conference presentations	18	25
- Of which, invited presentations	8	23
2. Quality of research outputs		
· Publications in Q1 journals within specified fields as defined by CiteScore	8	20
· Number of publications in journals in top 5% of field by CiteScore	0	8
· Citations of P4S papers	35	50
· Publications with co-authors from POs	8	4
· Publications with co-authors from 2 or more P4S nodes	5	4
· Awards/prizes	0	17
3. Number of workshops/conferences held/offered by the Centre		
· P4S workshops	1	14
· External meetings supported	1	2
4. Number of training courses held/offered by the Centre		
· Training workshops	3	6
· Equity and Diversity campaigns	1	3
5. Number of additional researchers working on Centre research		
· Postdoctoral researchers	15	18
- Of which, Fellows	1	1
· Honours/Masters students	6	10
· PhD Students	15	24
· Undergraduate interns	30	16
· Associate Investigators	9	6
· National visitors to P4S nodes	5	13
· International visitors to P4S nodes	3	15
6. Number of postgraduate completions		
7. Number of mentoring programs offered by the Centre		
· Mentoring activities/workshops	2	1
· External/industry PhD internships	3	3

Performance Measure	2024 Target	2024 Actual
8. Number of presentations/briefings		
· To the public	20	35
· To government	2	11
· To industry/business/end-users	10	68
- Of which, non-PO industry/business/end-users	2	48
9. Number of new organisations collaborating with, or involved in, the Centre	1	1
· Of which, from target regions		
10. Number of female research personnel	45%	54%
· Senior Management Group	45%	50%
· Chief Investigators	45%	47%
· EMCRs	45%	50%
· Students	45%	49%
· Research support and professional staff	45%	70%
P4S-specific KPIs		
· New grants won by P4S staff and students	3	13
· P4S alumni in academia		
· P4S alumni in industry/government		
Public inspiration		
· Number of students engaged by P4S education and engagement activities (incl. school events, public events and as a result of teacher professional development)	15,000	120,000
· Teachers trained in P4S-hosted workshops	20	974
· Press releases	7	12
· Website hits	10,000	24,962
· Social media reach	5,000	96,878
Translation		
· Uptake of technologies by industry		
· Technologies used in CEA/Space		
· P4S spin-out companies		

Publications

Book Chapters

de Zwart, M and Lisk, J (2024), 'The Effect of Space Tourism, of the Concept of "Astronaut" Under International Law', in S. Bhat B. (ed), Space Tourism, Routledge, Oxon, pp. 28-41.

de Zwart, Melissa (2024), 'Hybrid and Grey Zone Operations in Outer Space', in M. Regan and A. Sari (eds), Hybrid Threats and Grey Zone Conflict: The Challenge to Liberal Democracies, Oxford University Press, Oxford, pp. 289-316.

Fuentes, S., Tongson, E. and Viejo, C.G., (2024), 'Artificial intelligence and Big Data revolution in the agrifood sector', in A. Hassoun (ed), Food Industry 4.0, Elsevier, London, pp. 171-188.

Journal articles

Cahn, J., J. P. Lloyd, I. D. Karemaker, P. W. Jansen, J. Pflueger, O. Duncan, J. Petereit, O. Bogdanovic, A. H. Millar and M. Vermeulen (2024). "Characterization of DNA methylation reader proteins in Arabidopsis thaliana." Genome Research 34(12): 2229-2243.

Campos Assumpcao De Amarante, M., L. Ong, F. Spyropoulos, S. Gras and B. Wolf (2024). "Modulation of physico-chemical and technofunctional properties of quinoa protein isolate." Food Chemistry 457: 140399.

Conneely, L. J., B. Hurgobin, S. Ng, M. Tamiru-Oli and M. G. Lewsey (2024). "Characterization of the Cannabis sativa glandular trichome epigenome." BMC Plant Biology 24(1): 1075.

Doolan, O., M. G. Lewsey, M. Peirats-Llobet, N. Bricklebank and N. Aberdein (2024). "Micro computed tomography analysis of barley during the first 24 hours of germination." Plant Methods 20(1): 142.

Edwards, R. A., X. Y. Ng, M. R. Tucker and J. C. Mortimer (2024). "Plant synthetic biology as a tool to help eliminate hidden hunger." Current Opinion in Biotechnology 88: 103168.

Escribà-Gelonch, M., S. Liang, P. van Schalkwyk, I. Fisk, N. V. D. Long and V. Hessel (2024). "Digital Twins in Agriculture: Orchestration and Applications." Journal of Agricultural and Food Chemistry 72(19): 10737-10752.

Fuentes, S., S. Ortega-Farías, M. Carrasco-Benavides, E. Tongson and C. G. Viejo (2024). "Actual evapotranspiration and energy balance estimation from vineyards using micro-meteorological data and machine learning modeling." Agricultural Water Management 297: 108834.

Garcia-Daga, S., S. J. Roy and M. Gilliham (2024). "Redefining the role of sodium exclusion within salt tolerance." Trends in Plant Science.

Gonzalez Viejo, C., N. Harris, E. Tongson and S. Fuentes (2024). "Exploring consumer acceptability of leafy greens in Earth and space immersive environments using biometrics." npj Science of Food 8(1): 81.

Govil, S., N. V. D. Long, M. Escribà-Gelonch and V. Hessel (2024). "Controlled-release fertiliser: Recent developments and perspectives." Industrial Crops and Products 219: 119160.

Hong, U. V. T., M. Tamiru-Oli, B. Hurgobin and M. G. Lewsey (2024). "Genomic and cell-specific regulation of benzylisoquinoline alkaloid biosynthesis in opium poppy." Journal of Experimental Botany: erae317.

Hoyos, M. V., V. Hessel, E. Salas, J. Culton, K. Robertson, A. Laybourn, M. Escribà-Gelonch, N. Cook and M. de Zwart (2024). "Supply Chain Sustainability in Outer Space: Lessons to Be Learnt from Remote Sites on Earth." Processes 12(10): 2105.

Huang, S., M. R. G. Roelfsema, M. Gilliham, A. M. Hetherington and R. Hedrich (2024). "Guard cells count the number of unitary cytosolic Ca^{2+} signals to regulate stomatal dynamics." Current Biology.

Khan, M. A., G. Herring, J. Y. Zhu, M. Oliva, E. Fourie, B. Johnston, Z. Zhang, J. Potter, L. Pineda, J. Pflueger, T. Swain, C. Pflueger, J. P. B. Lloyd, D. Secco, I. Small, B. N. Kidd and R. Lister (2024). "CRISPRi-based circuits to control gene expression in plants." Nature Biotechnology.

Liew, L. C., Y. You, L. Auroux, M. Oliva, M. Peirats-Llobet, S. Ng, M. Tamiru-Oli, O. Berkowitz, U. V. T. Hong, A. Haslem, T. Stuart, M. E. Ritchie, G. W. Bassel, R. Lister, J. Whelan, Q. Gouil and M. G. Lewsey (2024). "Establishment of single-cell transcriptional states during seed germination." Nature Plants 10(9): 1418-1434.

Morgan, M. F., J. Diab, M. Gilliham and J. C. Mortimer (2024). "Green horizons: how plant synthetic biology can enable space exploration and drive on Earth sustainability." Current Opinion in Biotechnology 86: 103069.

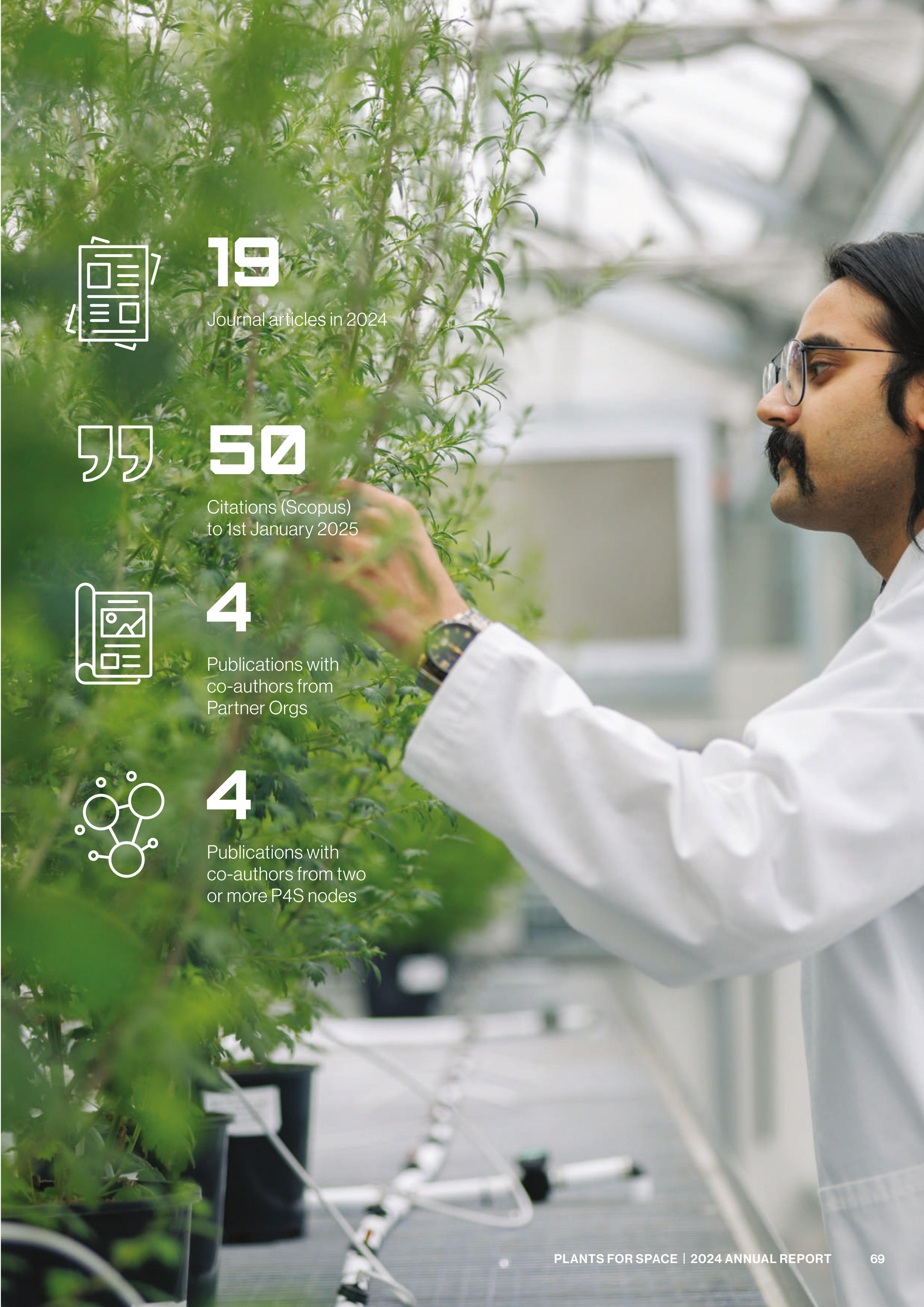
Piechatzek, A., X. Feng, N. Sai, C. Yi, B. Hurgobin, M. Lewsey, J. Herrmann, M. Dittrich, P. Ache, T. Müller, J. Kromdijk, R. Hedrich, B. Xu and M. Gilliham (2024). "GABA does not regulate stomatal CO_2 signalling in Arabidopsis." Journal of Experimental Botany 75(21): 6856-6871.

Viejo, C. G., N. Harris and S. Fuentes (2024). "Assessment of changes in sensory perception, biometrics and emotional response for space exploration by simulating microgravity positions." Food Research International 175: 113827.

Wu, Y., S. W. Henderson, R. R. Walker, M. C. Shelden and M. Gilliham (2024). "Expression of the grapevine anion transporter ALMT2 in Arabidopsis roots decreases the shoot Cl^-/NO_3^- ratio under salt stress." Journal of Experimental Botany.

Industry papers

Watt, M and Millar, H (2024) Australian strawberries join new mission to inhabit space while turbo charging sustainability innovations, Australian Berry Journal



19

Journal articles in 2024

50

Citations (Scopus)
to 1st January 2025

4

Publications with
co-authors from
Partner Orgs

4

Publications with
co-authors from two
or more P4S nodes

Members

Centre Director

Prof Matthew Gilliham, University of Adelaide

Deputy Director

Prof Melissa de Zwart, University of Adelaide
Prof Sally Gras, University of Melbourne

Chief Operating Officer

Dr Richard Harvey, University of Adelaide

Chief Investigators

Prof Christine Feinle-Bisset, University of Adelaide
A/Prof Sigfredo Fuentes, University of Melbourne
Prof Volker Hessel, University of Adelaide
A/Prof Kim Johnson, La Trobe University
Prof Eva Kemps, Flinders University
Prof Mathew Lewsey, La Trobe University
Prof Ryan Lister, University of Western Australia
Prof Harvey Millar, University of Western Australia
A/Prof Jenny Mortimer, University of Adelaide
Prof Ian Small, University of Western Australia
Prof MatthewTucker, University of Adelaide
Prof Michelle Watt, University of Melbourne

Postdoctoral Researchers

Dr Ryan Coates, University of Western Australia
Dr Lee Conneely, La Trobe University
Dr Fleur Dolman, University of Adelaide
Dr Alison Gill, University of Adelaide
Dr Zheng (Tommy) Gong, University of Adelaide
Dr Claudia Gonzalez Viejo, University of Melbourne
Dr Adil Khan, University of Western Australia
Dr Farley Kwok van der Giezen, University of Western Australia
Dr James Lloyd, University of Western Australia
Dr Troy Miller, University of Western Australia
Dr Van Duc Long Nguyen, University of Adelaide
Dr Marina Oliva, University of Western Australia
Dr Lydia Ong, University of Melbourne
Dr Adriane (Adri) Piechatzek, University of Adelaide
Dr Caterina (Cate) Selva, University of Adelaide
Dr Kenneth Sim, Flinders University
Dr Frazer Thorpe, La Trobe University
Dr Bo (Weasley) Xu, University of Adelaide
Dr Le Yu, University of Adelaide

Masters Students

Ms Yunti Ge, University of Adelaide
Ms Yujia (Cora) Liu, University of Adelaide
Ms Kate Nakashima, University of Melbourne
Mr Xiao Yu (Josh) Ng, University of Adelaide
Ms Bhargaviben (Bhargavi) Solanki, La Trobe University
Mr Bingxi (Bring) Wang, University of Melbourne
Mr Anxing (Andy) Zhang, University of Adelaide

Honours Students

Ms Natalie Chan, University of Adelaide
Mr Levi McKenzie, University of Adelaide
Ms Jiayue Wang, La Trobe University

PhD Students

Mrs Modupe Adebowale, University of Adelaide
Mr Javad Anjom Shoae, University of Adelaide
Ms Leni Campbell-Clause, University of Western Australia
Ms Cadell Canute, University of Adelaide
Ms Yiwen Chen, University of Adelaide
Mr Thomas Cobbinah, La Trobe University
Mr Jonathan Diab, University of Adelaide
Mr Ryan Edwards, University of Adelaide
Mr Elliott Fourie, University of Western Australia
Mr Sebastian Garcia Daga, University of Adelaide
Mr Patrick Gong, University of Western Australia
Ms Gabrielle Herring, University of Western Australia
Mr Harish Jadhav, University of Western Australia
Mr Mohammad (Alex) Karami, University of Adelaide
Ms Shu Liang, University of Adelaide
Ms Florence Ly, University of Western Australia
Mr Matthew Morgan, University of Adelaide
Ms Sampurna Mukherjee, University of Adelaide
Mr Chigozie Ofoedu, University of Adelaide
Mr Anshul Phaugat , La Trobe University
Mr Akshat Raghuvanshi, La Trobe University
Ms Amy Viljoen, University of Western Australia
Ms Xingyi (Raven) Zhou, University of Adelaide
Ms Jia Yuan (Meggie) Zhu, University of Western Australia

Undergraduate Students

Mr Ian Cullen, La Trobe University
Ms Angelica Rossi, La Trobe University
Mx Hugo Watson, University of Melbourne

Professional Staff

Mr Douglas Bair, La Trobe University
Ms Sandra Clavijo, La Trobe University
Dr Linda De Melis, University of Melbourne
Ms Amy Griessl, University of Adelaide
Mrs April Harris, University of Western Australia
Ms Nikki Hodge, University of Adelaide
Dr Janine Oldfield, University of Melbourne
Dr Lieke van der Hulst, University of Adelaide
Dr Rebecca Vandeleur, University of Adelaide
Ms Cassie Watts, University of Melbourne

Research Assistants

Dr Ane Aldalur Soto, University of Melbourne
Mr Jacob Calabria, University of Melbourne
Ms Penelope Fitzgerald, University of Adelaide
Mrs Sarah Hollitt, Flinders University
Ms Selena Wiesel, University of Melbourne
Ms Charlotte Bampton, University of Adelaide
Mr Chao Ma, University of Adelaide
Ms Wendy Sullivan, University of Adelaide

Partner Investigators

Prof Adam Arkin, University of California, Berkeley
Dr Jennifer Bromley, Vertical Future
Ms Jackie Carpenter, One Giant Leap Australia Foundation
Dr Janine Croser, South Australian Research and Development Institute
Prof Jennifer Doudna, University of California, Berkeley
Dr Didier Dupont, INRAE
Ms Christine Escobar, Space Lab Technologies
Dr Flávia Fayet-Moore, FOODiQ Global
Prof Ian Fisk, University of Nottingham
Prof Simon Gilroy, University of Wisconsin- Madison
Mr Nadun Hennayaka, GAIA Project Australia
Prof Jay Keasling, University of California, Berkeley
Dr Gioia Massa, NASA
Prof Karen McDonald, University of California, Davis
Dr Joanna McMillan
Prof Raffaele Mezzenga, ETH Zürich
Ms Sumen Rai, SASIC
Prof Eduardo Salas, Rice University
Prof Alex Webb, University of Cambridge

Associate Investigators

Dr Stephanie Watts-Fawkes, University of Adelaide
Dr José Colmenero-Flores, Instituto de Recursos Naturales y Agrobiología
Ms Jess Bunchek, DLR
A/Prof John Coulton, University of Adelaide
A/Prof Sue Bastien, University of Adelaide
Prof Rainer Hedrich, University of Adelaide

24 PhD Students

15 Chief Investigators

19 Postdoctoral Researchers

8 Research Assistants

10 Professional Staff

3 Undergrad Students

3 Honours Students

7 Masters Students

The Gallery

Top left: P4S Centre Director, Prof Matthew Gilliham warmly welcomes NASA Administrator Senator Bill Nelson.

Top right: Col Pam Melroy, Senator Bill Nelson, Enrico Palermo and Dr Megan Clark AC.

Above: P4S Prof Kim Johnson exhibiting at Nihonbashi Space Week in Japan.

Left: P4S Postdoctoral research fellow, Dr Claudia Gonzalez Viejo, speaking at the European Low Gravity Research Association Symposium 2024, Liverpool, UK

Above: Her Excellency the Hon. Ms Sam Mostyn AC, Governor-General of the Commonwealth of Australia and Honourable Catherine Branson AC SC with P4S Chief Investigator Associate Prof Jenny Mortimer.

Right: Prof Melissa de Zwart at the Space Industry Working Group as part of the Asia Pacific Regional Space Agencies Forum.

Below: Prof Matthew Gilliham joined the Australian delegation to the European Astronaut Centre, Cologne Germany in 2024

Bottom right: JAXA President Dr Hiroshi Yamakawa and Senior Vice President Mr. Yasuo Ishii visit the UoA EXTERRES Laboratory.

Acronyms and abbreviations

Instutions

AGRF	Australian Genome Research Facility
APPN	Australian Plant Phenomics Network
ARC	Australian Research Council
ASA	Australian Space Agency
Axiom	Axiom Space
BGSH	South Australia Botanic Gardens
BPA	BioPlatforms Australia
DLR	German Aerospace Centre
DSTG	Defence Science and Technology Group
ETH Zurich	Eidgenössische Technische Hochschule Zürich
Flinders	Flinders University
GAIA	GAIA Project Australia
INRAE	Research for Agriculture, Food and Environment
LTU	La Trobe University
NASA	National Aeronautics and Space Administration
OGL	One Giant Leap Australia Foundation
PIRSA	Department of Primary Industries and Regions, South Austalia
RICE	Rice University
Saber	Saber Astronautics
SASIC	South Australian Space Industry Centre
Space Lab	Space Lab Technologies, LLC
Twist	Twist Bioscience
UC Davis	University of California, Davis
UCB	University of California, Berkeley
UoA	University of Adelaide
UoC	University of Cambridge
UoM	University of Melbourne
UoN	University of Nottingham
UW Madison	University of Wisconsin-Madison
UWA	University of Western Australia
VF	Vertical Future
VSSEC	The Victorian Space Science Education Centre
Yuri	Yuri GmbH

General

AI	Associate Investigator
CI	Chief Investigator
CoE	Centre of Execellence
COO	Chief Operating Officer
COSPAR	Committee on Space Research
ECR	Early Career Researcher
EDI	Equity, Diversity and Inclusion
EMC	Executive Management Committee
EMCR	Early and Mid-Career Researcher
EXTERRES	The Extraterrestrial Environmental Simulation laboratory
HDR	Higher Degree by Research
IRAC	International Research Advisory Committee
KPI's	Key Performance Indicators
LEAF	Lunar Effects on Agricultural Flora
P4S	Plants for Space
PAC	P4S Advisory Committee
PDRA	Postdoctoral Researcher or Postdoctoral Research Associate
PI	Partner Investigator
PLC	Program Leadership Committee
PO	Partner Organisations
RSG	Research Support Group
SMG	Senior Management Group
TEC	Translation and Entrepreneurship Committee


LI-COR
LI-600
LI-COR

PLANTS FOR SPACE

ARC CENTRE OF EXCELLENCE

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Chief Operating Officer
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