A project truly succeeds when it addresses a real-world need, delivering meaningful impact for its users. To ensure we achieve this, we’ve actively engaged a diverse range of stakeholders, aligning their insights to shape our vision into something that can genuinely drive change and make a difference.

As our project aims to solve the issue of resource constraints in space travel, we have interacted with various space organizations, and scientists in the field. Our project deals with both bacteria and diatoms, and as such, we have taken input from experts in each, as well as those in reactor design and modeling our project.

To move beyond the strictly proof-of-concept stage, we have interacted with experts in the biotechnology industry, in order to understand both the needs of industry, and the niche that we could occupy in it. No project involved in potential terraforming could be complete without considering the ethics of both terraforming and the project itself. For input on the ethicality of our project, we spoke with ethics and safety experts.

We strongly believe that science is ultimately for humanity as a whole. In that context, one of the end users is the general public, from whom we have sought opinions, in order to understand the needs and ideas of the people.

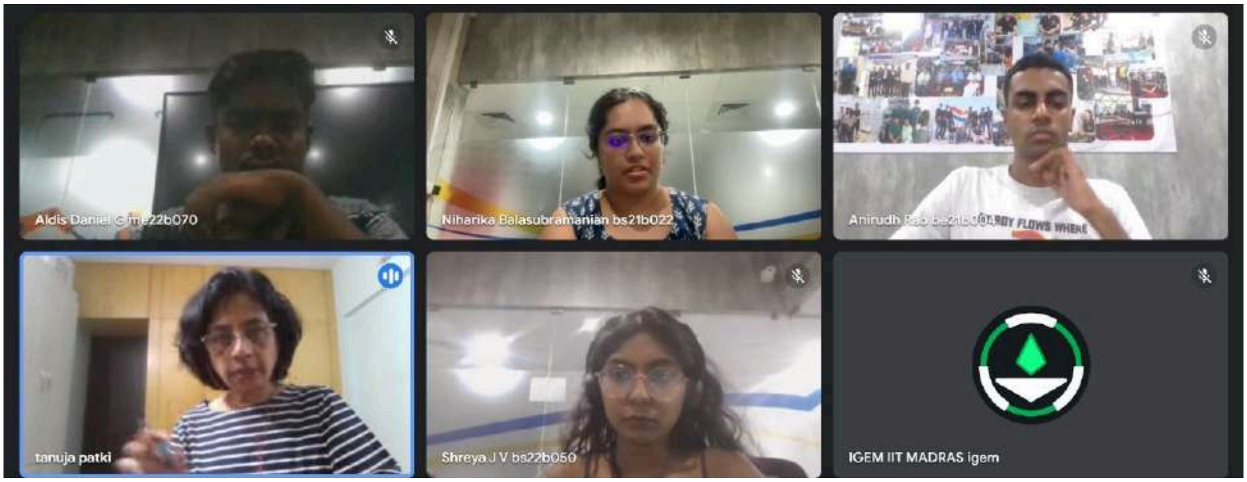
Space Organisations

Tanuja Patki, Payload Engineer, ISRO

We discussed the challenges and strategies for designing biological systems for Mars with Mrs. Tanuja Patki, a Payload and Design Engineer at the Indian Space Research Organisation’s Satellite Centre. The extreme conditions on Mars, such as low atmospheric pressure, minimal oxygen, cold temperatures, and toxic perchlorates in the soil, require that bioreactors effectively insulate the organisms from these. Radiation is a significant concern, both during space travel and on Mars itself, which lacks a protective atmosphere. Shielding or engineering organisms to withstand radiation will be essential for long-term survival.

Weight constraints for the bioreactors are critical, so materials like magnesium or aluminum, as well as honeycomb structures, offer lightweight yet durable solutions. Existing space missions, such as those sending microorganisms and fruit flies, provide valuable lessons on survival in space and how these systems perform under the effects of reduced gravity and radiation. The potential use of Mars' water sources and efficient resource recycling could sustain life over time.

Finally, we recognized the need for careful material selection to avoid active maintenance, save energy, and ensure that biological systems are housed in environments suitable for survival. These insights are key to optimizing microbial transport in space and ensuring long-term sustainability in extraterrestrial environments.



J. "Bob" Balaram, Chief Engineer, Jet Propulsion Laboratory, NASA

Dr. Balaram is an Indian-American scientist and engineer currently working for NASA. He is known for being the pioneer and Chief Engineer behind the Ingenuity project that built an autonomous helicopter as part of the Mars 2020 mission. We had an opportunity to interact with him during one of his periodic visits to our Institute, which he is an alumnus of.

We discussed with him about considerations that would come into play if we were to implement our project idea in reality. Considering the requirements of a bioreactor, he highlighted the need to balance radiation shielding while enabling the use of sunlight for our photosynthetic organisms. This has been incorporated into our reactor design where we chose to keep the reactor underground for shielding and used a light tube to deliver sunlight

To design a robust system that can be tested and deployed extraterrestrially, he stressed the need for analysis of failure scenarios for every subsystem and to ensure it fails in a non-catastrophic manner and thus, it was important to design with reliability, simplicity and reparability in mind.

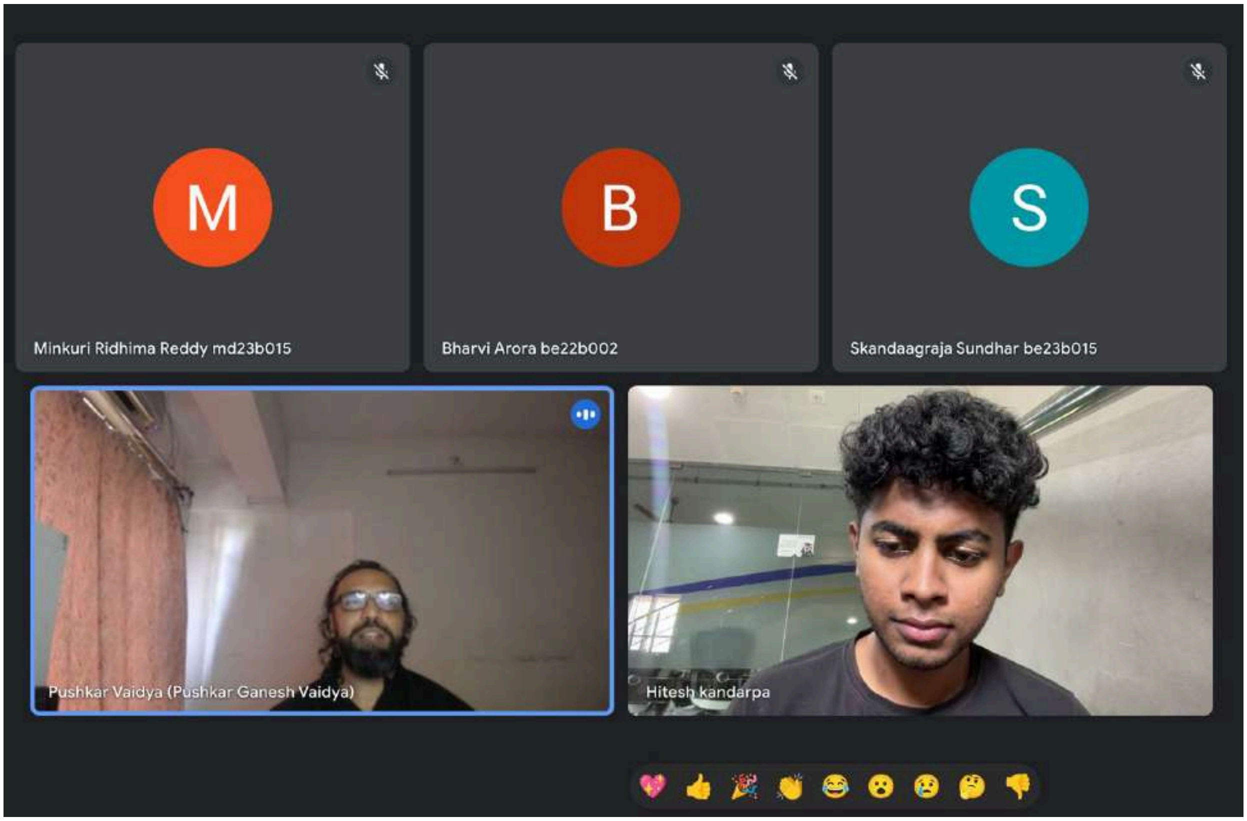
He also highlighted the fact that we were proposing the production of substances that would be ingested by humans - therefore requiring an analysis of intermediaries in the production pathways that could cause issues if the product treatment failed. We plan to fulfill this in our future work where we would implement a kill switch into the bacteria to mitigate biosafety concerns.

Pushkar Vaidya, Head, Indian Astrobiology Research Foundation

Pushkar Ganesh Vaidya is the Head of the Indian Astrobiology Research Foundation and an independent scientist working in astrobiology, the study of the origin, evolution, and distribution of life in the universe. He has delivered numerous lectures & workshops, hosted conferences & webinars, and authored several articles, books, courses & research papers about space, particularly astrobiology.

Mr. Pushkar briefed us about the COSPAR (Committee on Space Research) guidelines, which aim to prevent harmful biological contamination of space environments and Earth. They classify missions based on their potential for contamination, with strict protocols for planetary protection.

He also emphasized that for a project involving synthetic biology on Mars, following COSPAR guidelines would ensure that biological experiments do not introduce Earth microbes or genetically engineered organisms that could disrupt Mars' potential ecosystems, affect future studies of Martian life, or pose a threat if returned to Earth. He told us that these protocols are vital for preserving the scientific integrity of space environments. Our team has ensured to adhere to these guidelines at all stages of our projects.

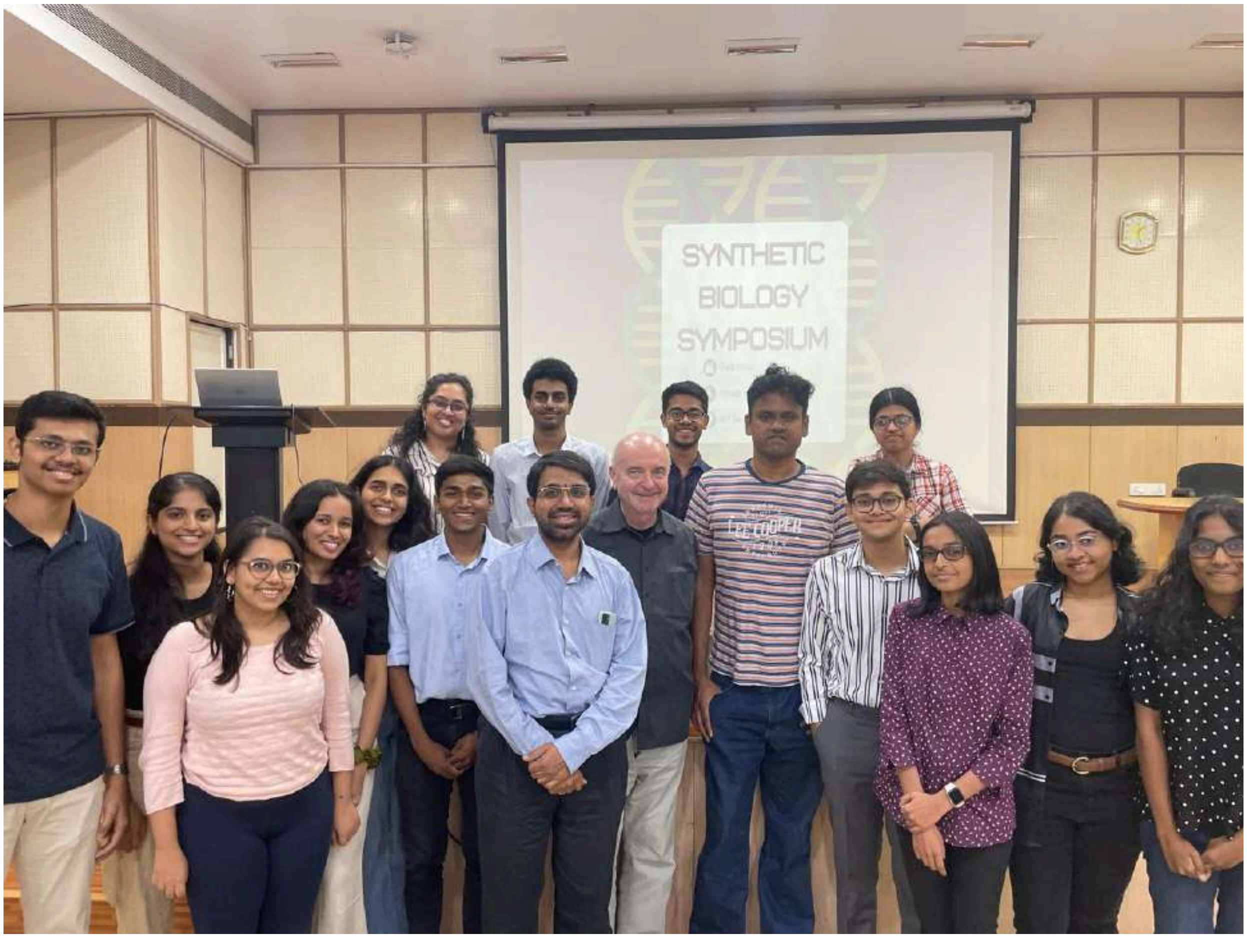


Academia

Dr. Victor de Lorenzo, Lead Researcher, National Biotechnology Center, Spain

Dr. de Lorenzo is a member of the EMBO Council, the American Academy of Microbiology (AAM) and the European Academy of Microbiology (EAM). Given his expertise in the field of synthetic biology, our team approached him for advice regarding the choice of bacteria in the system. He suggested the use of the bacteria Pseudomonas for its flexibility in using multiple substrates, and its nature as a soil bacterium, making it suited for our regolith-based culture.

The pathways involved in the solubilization of silica were identified in the bacterium *Pseudomonas fluorescens* from literature, which is why it was chosen as the bacterium in the co-culture.



Dr. Smita Srivastava, Professor, IIT Madras

Dr. Smita Srivastava is a Professor at IIT Madras, in the Department of Biotechnology. She works on rationally integrating bioprocess and cellular engineering principles to maximize the yield and productivity of high-value metabolites (like phytochemicals) from microbial and plant cell based production platforms.

We discussed the process of diatom transformation, and Dr. Srivastava advised that we choose a diatom-specific vector, rather than a general plant one, as transformation efficiency rates are low, due to decreased penetration through the siliceous cell wall. We accordingly attempted assembly with a diatom specific vector, although it was ultimately not successful.

Dr. K Chandraraj, Professor, IIT Madras

Dr. K. Chandraraj, a professor in the Department of Biotechnology, specializes in microbial growth within soil environments. Given that our project pivots on the survival of *P. fluorescens* in Martian regolith, we sought his expertise. Our discussion with him centered on two queries:

designing an experiment to test bacterial growth on Martian soil simulant quantitatively and determining how to inoculate the bacteria without contamination.

In response to our queries, he suggested an experiment design involving spread plating, manually counting colonies (CFU) after set intervals, and plotting daily growth data. He also recommended doing around 2-3 serial dilutions so that the bacterial count is reduced substantially in the plates. To avoid contamination, he suggested that we autoclave every piece of equipment used in the experiment, including spatulas.

Dr. Baskar R, Professor, IIT Madras

Dr. Baskar R is a Professor at IIT Madras, at the Department of Biotechnology. He works on phytochemical volatiles and their impact on gene expression and activity.

We consulted him on assessing limonene presence in the transformants. He recommended that we use GC-MS analysis to identify the presence of limonene, as it would likely be more accurate than any other chemical test that could be conducted on a bacterial extract. Additionally, we asked for his expertise in guiding us with the diatom transformation.

Dr. G K Suraishkumar, Professor, IIT Madras

Dr. G K Suraishkumar is a Professor at IIT Madras, working on algal biotechnology and bioreaction engineering. He is also part of the ExtraTerrestrial Manufacturing (ExTeM) group at IIT Madras.

We validated our project ideation and co-culture setup with him. He suggested that we avoid using microgravity based experiments in the scope of our project, as it is well established in literature that yields are standardly greater in microgravity, and is thus unlikely to be a factor causing negative effects to consider at this stage.

We have thus considered only standard gravity throughout the experiment. We also took input from Dr. Suraishkumar on the proposed reactor design we have suggested in our future planning.

Dr. Karthik Raman, Professor, IIT Madras

Dr. Karthik Raman is one of India’s pioneering systems biologists who also caught onto the synthetic biology wave very early on. The team met up with him on several occasions to discuss their future directions in terms of how to phrase their problem statement, how to approach international stakeholders, etc.

He also guided the model team during their work with a genome-scale metabolic model. As part of the network architecture analysis, the team used Metquest, an in-house Python package developed by Dr. Raman himself. We also actively collaborated with members of his Computational Biology lab, particularly in the community modeling department.

Dr. Maziya Ibrahim, who was part of Dr. Karthik's team that modeled a microbial community at the International Space Station (ISS), helped us maneuver through the nitty-gritties of the MICOM community model.

Dr. Sathyan Subbaiah, Professor, IIT Madras

Dr. Sathyan Subbaiah is a Professor at IIT Madras, in the Department of Mechanical Engineering. He is the head of the ExtraTerrestrial Manufacturing (ExTeM) team at IIT Madras.

We discussed our plan for silicon solubilization using biological means with Dr. Subbaiah, who suggested that to give our project added accuracy and replicability, we should use an actual Martian Regolith simulant, rather than relying on earth soil. To incorporate the proof of Martian efficacy, we tested the silicon solubilization on the Martian regolith simulant successfully.

Dr. Sangram Bagh, Professor, Saha Institute of Nuclear Physics

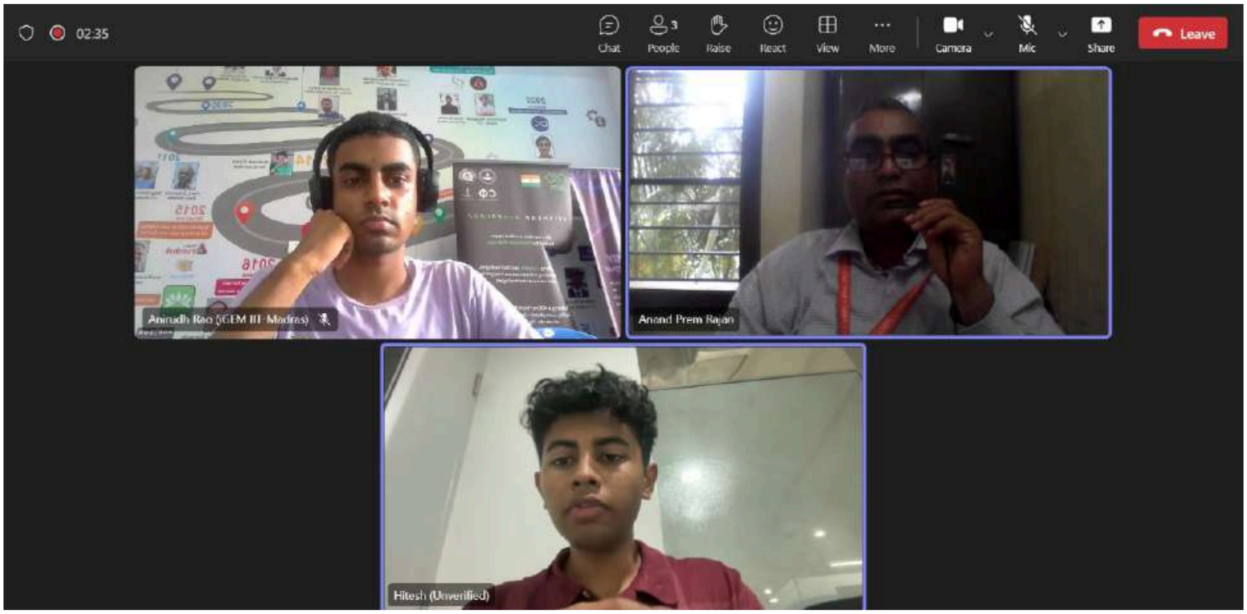
Prof. Sangram Bagh is an associate professor at Saha Institute of Nuclear Physics, Kolkata. He is an experienced synthetic Biologist who has several projects in Space Synthetic Biology.

Given his expertise, we consulted him on our overall project design to identify any gaps in our understanding of biological processes under space conditions. He provided valuable insights, particularly regarding scale-up factors such as light intensity control, pH regulation, and mechanical stirring—all of which we carefully integrated into our reactor scale-up design to suit the Martian environment.

Dr. Anand Prem Rajan, Professor, Vellore Institute of Technology

Dr Anand Prem Rajan is a Professor at VIT Vellore, working on diverse systems as a geobiologist. He has experience working with both diatoms and Pseudomonas, making him an excellent candidate to consult for our project.

He suggested that we sterilize the regolith used in our co-culture, as we had not considered the contaminating aspects of the regolith simulant in culture, and it was unlikely to have components that would be damaged by autoclaves. We have accordingly used autoclaved simulant in all experiments.



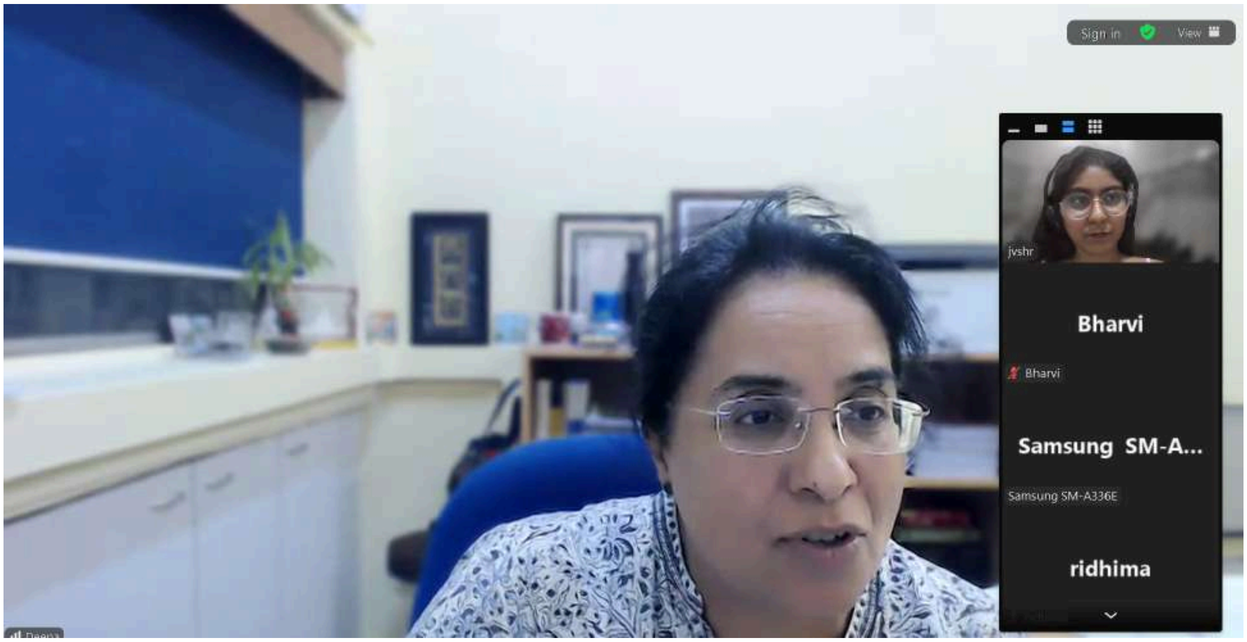
Dr. Deepa Khushalani, Professor, Tata Institute of Fundamental Research

Dr. Deepa Khushalani, Head of the Department of Chemistry at Tata Institute of Fundamental Research, was consulted for her expertise in silicon nanoparticles to gain deeper insights into the chemical reaction mechanisms underlying our experiment aimed at quantifying soluble silicic acid.

We presented our project concept, detailed our approach for silicon quantification, and discussed the challenges we were encountering. Dr. Khushalani pointed out that monosilicic acid is unstable, potentially leading to unreliable data. She recommended utilizing X-ray diffraction and gravimetric analysis for more accurate quantification.

Additionally, our discussions with her led us to realize that the time delay between the formation of silicates by bacteria and our quantification experiment could be a limiting factor for correct estimation as silicates form polymers rapidly in solution. The meeting helped us positively redirect our efforts towards coming up with an alternate experimental design.

Based on her recommendation, we determined that correlating the increase in diatom growth rate with the presence of bacteria in the soil would be the most effective approach to demonstrate our proof of concept.



Dr. Maike Lorenz, Curator, Culture Collection of Algae (SAG), University of Göttingen

SAG Göttingen is a consortium that acts as an algal type culture collection for a variety of micro- and macroalgae. While we were having issues maintaining the microalgal culture, we reached out to Dr. Maike Lorenz, the Curator of SAG, and implemented her updated culture recommendations in order to maintain the culture successfully.

Policy Experts

Nikos Kolisis, PhD Student, University of Athens

As part of our efforts to evaluate the ethical considerations surrounding our project, we engaged in a discussion with Nikos Kolisis, a PhD student specializing in the Philosophy of Law at the National and Kapodistrian University of Athens. We consulted his expertise owing to his prior experience in the field of bioethics. Our conversation focused on the ethics of space exploration, the moral implications of synthetic biology in extraterrestrial environments, and broader concerns about resource allocation and GMOs.

Mr. Kolisis highlighted that decisions surrounding the allocation of resources to space exploration are largely determined by policy-makers and national priorities. He emphasized that while there are significant social issues on Earth, space exploration could lead to advancements in technology that benefit various industries, including healthcare.

On the subject of Martian territorial ownership and whether humanity has the right to develop technologies in space, Mr. Kolisis suggested this is more of a legal question tied to whether exploration is approached with a colonizing attitude. He noted that these decisions are often made by state actors and private companies, rather than individuals or small research teams like ours.

We also addressed concerns regarding genetically modified organisms (GMOs) and the public's perception of their safety. Mr. Kolisis acknowledged the stigma but highlighted that our ISRU-based approach adds ethical merit. He further stated that ethical considerations surrounding GMOs would focus on empirical safety protocols and the protection of sentient life. As long as our work ensures that no sentient beings are harmed, there are no substantial ethical objections to our project.

Finally, we explored the idea of sentience and whether organisms like algae could be considered sentient. Mr. Kolisis pointed out that while sentience in biotechnology is a complex topic, our project does not involve enslaving or mistreating species. Instead, we are creating new organisms to support human survival in extreme environments. However, he stressed the importance of showing respect for nature and being mindful of critical voices in the field to ensure that ethical considerations are properly addressed.

This conversation provided valuable insights, reaffirming our commitment to ethical responsibility as we continue our work.

Dr. Arvind Gupta and Rear Admiral Deepak Bansal

During a visit to the Centre for Innovation (CFI) at IIT Madras, we had the opportunity to meet with Dr. Arvind Gupta, Director of the Vivekananda International Foundation (VIF), a policy think tank, who expressed great interest in our project, “cosmobiome”.

Dr. Gupta emphasized the growing importance of biotechnology and synthetic biology in India's scientific landscape and strongly supported our initiative. He encouraged us to think beyond research, urging our team to seek opportunities for commercialization and real-world application of our work. Rather than allowing the project to remain as research output, he advised us to engage with relevant bodies, such as the Department of Biotechnology under the Government of India, to explore pathways for future development and implementation.

In addition to Dr. Gupta’s insights, we also had a fruitful interaction with Retired Rear Admiral Deepak Bansal, a Strategic Advisor to the Armed Forces and member of the CODISSIA think tank, which is supported by the NITI Aayog, the Government of India’s public policy think tank. RAdm. Bansal shared his interest in synthetic biology and the work of iGEM, offering suggestions for expanding our outreach. He encouraged us to present our project at larger national forums and policy-making platforms, including events hosted by the VIF. His advice reinforced the importance of integrating innovative projects like ours into national dialogues and strategic planning.

These conversations not only boosted our confidence in the potential of our project but also provided us with critical guidance on how to make a tangible impact beyond the academic realm.

Alonso Flores, Safety and Security Program Officer, iGEM Foundation

Alonso Flores is a safety and security program officer at the iGEM foundation, and helped us review the bioethics and safety aspects of our project.

Our primary takeaway from our conversation with Mr Flores would be that our primary direction of biosafety needs to be a containment based strategy, rather than a contamination-reduction type. He was of the opinion that since there is no microflora on Mars, and would likely have no contamination risk on our proposed reactor. Accordingly, we have designed both our future reactor and kill switch in such a way that it primarily acts as a leakage-reduction strategy.

General Public

Team IIT-Madras Space Survey

As part of our Integrated Human Practices initiatives, we conducted a comprehensive survey to gauge public perception towards space exploration and space synthetic biology. Our goal was to understand the views, concerns, and expectations of the general public regarding these cutting-edge fields. To make the survey accessible to a larger audience, we translated our survey into three Indian languages - English, Hindi, and Tamil.

The survey covered various aspects, including:

1. The perceived necessity and importance of space exploration
2. Expected benefits and priorities in space exploration
3. Opinions on extraterrestrial habitation and colonization
4. The role of biotechnology in space exploration
5. Ethical considerations in space exploration and genetic modification
6. Accessibility and commercialization of space endeavors
7. Potential impacts of space exploration on life on Earth

We received responses from a diverse group of participants, providing us with valuable insights into public opinion. The data collected offers a nuanced picture of how people view the intersection of synthetic biology and space exploration, as well as the broader implications of these fields for humanity's future.

Our survey results reveal a generally positive attitude towards space exploration, with most respondents considering it essential for humanity's progress. However, the data also highlights important ethical concerns, particularly regarding genetic modification and the treatment of potential new planetary environments. There is a clear preference for maintaining space exploration as a primarily scientific and technical endeavor, balanced with responsible and ethical practices.

These findings not only inform our project but also contribute to the broader discussion on the role of synthetic biology in space exploration. By understanding public perception, we were able to better address concerns, focus on prioritized applications, including space medicine, and work towards responsible innovation in this exciting field. The detailed analysis that follows provides an in-depth look at the survey results, offering valuable insights for researchers, policymakers, and anyone interested in the future of space exploration and synthetic biology.

A summary of our results can be found here:

(Embed PDF - Space Survey Summary.pdf)

iGEM Space Village Meet

We participated in the iGEM Space Village Meetup conducted on 28th August, 2024. It was an amazing opportunity for us to get to know about the projects of other teams, receive feedback and discuss some common hindrances.

One of the valuable feedbacks we integrated from the meeting was about the need to give importance to proving our hypotheses using well-constructed experiments. Since our project revolves around co-culture success and silicon mobilization, we put considerable effort into testing our system. We focused a lot on assessing whether it performed as expected according to our hypotheses.

All India iGEM Meet

The All India iGEM Meet, held at the Indian Institute of Science Bangalore, was more than just a precursor to the final Jamboree event in Paris. It was an informal yet competitive event where iGEM teams from across India came together to exchange ideas, receive feedback from field experts, and most importantly, build meaningful connections.

From in-depth discussions on metabolic modeling with IISER-TVM that closely aligned with our own project, to exploring transformation protocols with IIT Bombay, to engaging with IISc on gene identification techniques, to discussing protein sub-unit algorithms, the exchange of knowledge was seamless and unrestricted. This sort of open dialogue is often not as easy to come by. We shared advice, gained new perspectives, and even explored potential visits and collaborations with other teams.

These interactions were not limited to just project discussions. Human practices, sponsorship strategies, and even fun conversations on bioethics and poster presentations brought us closer to the iGEM community. By the end of the event, we didn't just have better projects, we had stronger relationships, critical feedback from ambassadors and panel members, and a renewed sense of purpose for our project. The All India iGEM Meet reinforced the importance of connection and collaboration, the two key pillars that drove the success of our project.

Industry

Tenshi Kaizen

Most pharmaceutical manufacturing happens vis-a-vis traditional abiotic methods - large reactors, conveyor belts and standardized operating procedures. To see what niche biomanufacturing fills and to get opinions about our novel drug production techniques, we decided to visit Tenshi Kaizen Pvt Ltd, an Indian pharmaceutical manufacturer.

Tenshi Kaizen has a unique state of the art machine that produces rapid orally disintegrable paracetamol. We interacted with the R&D departments, process engineers and plant directors learning about the various steps that go into converting raw materials into fully packaged products. Chandan Kumar, the Team Lead showed us their lyophilization set-up, the in-house water plant for cooling, the storage units and the packaging factory line.

We spoke with the scientists about the potential for biological chassis to be used en masse for commercial manufacturing and received valuable inputs as to how to translate our methods from a proof of concept in a lab to a technique that can gain widespread industry acceptance. We also discussed how the reactor could be set up in order to be easily incorporated into existing industry standards, and incorporated these suggestions into our reactor design.

AstraZeneca

AstraZeneca is a global biopharmaceutical company that focuses on the discovery, development, and commercialization of innovative therapeutics. With a strong commitment to science and research, they operate across multiple therapeutic areas. The company emphasizes sustainability and efficiency in its manufacturing processes, integrating cutting-edge technology with pharmaceutical production.

During our conversation with industry experts from AstraZeneca, we explored the potential of dual biomanufacturing, where both *P. tricornutum* and *P. fluorescens* would be genetically engineered to produce multiple products of interest. We received insightful pointers on the feasibility and the factors to be taken into account during its implementation.

We also discussed possible applications for the co-culture system in biomanufacturing, including the production of monoclonal antibodies and pharmaceuticals like acetaminophen.

Through our discussions, the experts highlighted that while achieving these objectives would require additional time, manpower, and cross-disciplinary collaboration, the concept held potential applications in their field. While we were able to acknowledge the fascinating future directions this project could take, we were forced to acknowledge that these were not within the scope of our project in its current form. We, however, designed our co-culture system in keeping with these ideas, making sure the future dual biomanufacturing was a possibility.