TERRA

IGEM 2025

TERRA – Survey

an Analysis

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Introduction

When planning our project at the crossroads of biotechnology, synthetic biology, and environmental design, we understood at the very beginning that our work would benefit profoundly from public input. Our central aim was to ground our research in real-world perspectives by systematically exploring how the public understands, reacts to, and engages with the topics we address.

The primary motivation for launching our survey was to learn how well-known and accessible concepts such as **rare earth elements, red mud, algae, and synthetic biology** are among the general public. We sought not only to gauge baseline knowledge, but also to uncover which aspects of our project might require additional explanation or outreach.

Our target audience included a **broad demographic, across multiple countries** and age groups. This diversity was essential for ensuring that our findings offered a representative reflection of the wider community.

By distributing our survey in multiple languages, we enabled residents from a wide range of countries to participate anonimously. This approach not only increased our sample's diversity, but also allowed us to observe whether the topics of our project are being discussed, taught, or prioritized differently across cultural and national boundaries To enable broad and fair participation, each language version of our survey, **English, German, French, and Turkish,** was initially distributed within one family and one friend group chat by a different team member, ensuring regional and linguistic representation. Each team member could then monitor how their respective version circulated within these networks, allowing us to trace both reach and feedback.

From the outset, we anticipated that surveying the community would not only give us a **snapshot of public awareness** around our research themes, but also help us identify **knowledge gaps, misunderstandings, or areas of concern**.

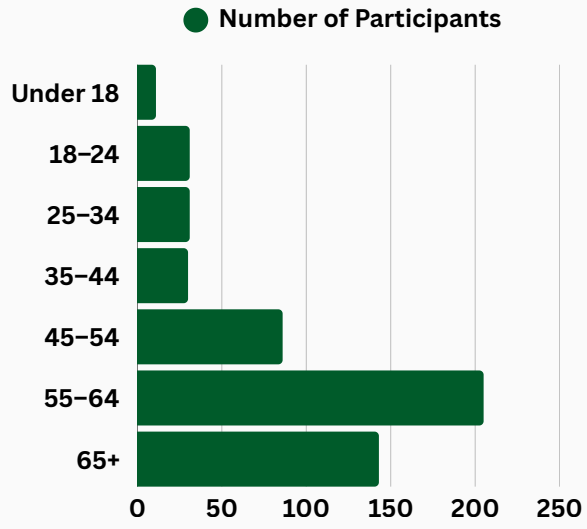
Finally, in crafting our questions, we drew inspiration from precedent educational surveys [1,2] and designed two main types: general questions to probe overall familiarity with our topics, and perception questions, which we asked after providing a brief description of our proposed project and methodology. This structure allowed us to compare initial knowledge and attitudes with informed reflections following a short educational primer.

Statistics

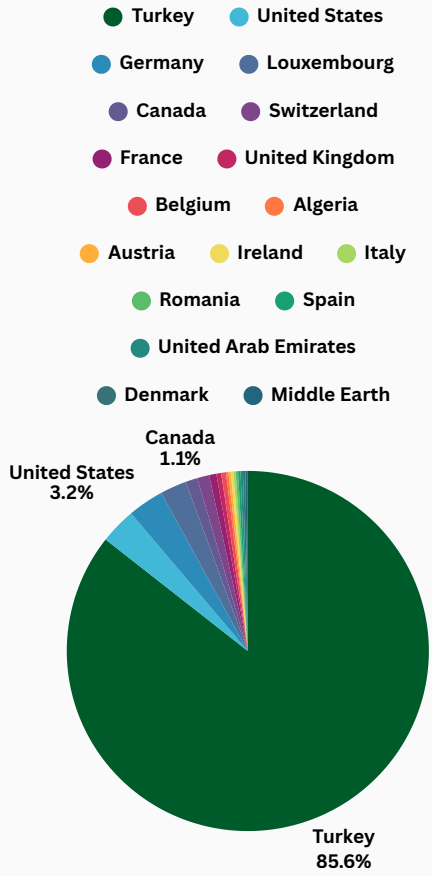
Number of Participants

In total, we had 549 participants summed over all four renditions of the survey.

Distribution of Age Groups



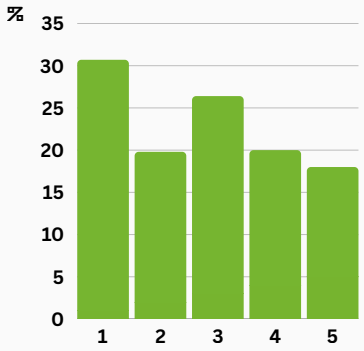
Distribution of Countries



Despite efforts to evenly distribute the survey by limiting the number of group chats the survey initially reached, there is a notable imbalance in participation among language speakers, especially between Turkish and other languages. We observed that the majority of our participants demonstrated remarkable enthusiasm in completing the survey, however Turkish-speaking participants actively shared it within their communities.
This response pattern highlights the importance of tailoring outreach efforts to engage diverse linguistic and cultural groups effectively, an insight that will guide our future engagement strategies to build an even wider, more inclusive community.

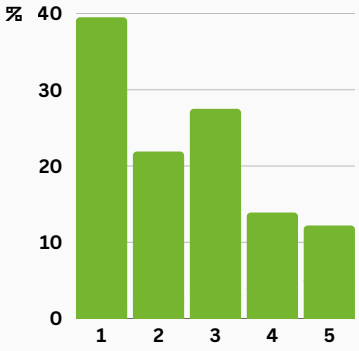
Results

Q1. How familiar are you with the term “rare earth elements”?



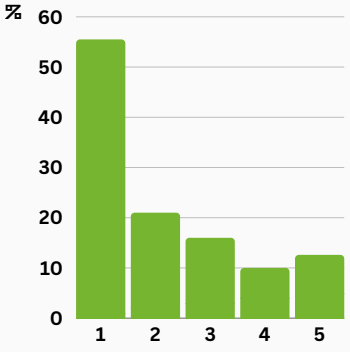
1 = not familiar
5 = very familiar

Q3. How familiar are you with the term "synthetic biology"?



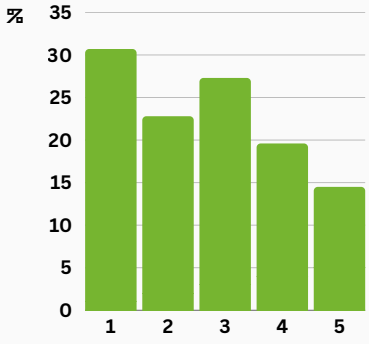
1 = not familiar
5 = very familiar

Q2. How familiar are you with the term “red mud”?



1 = not familiar
5 = very familiar

Q4. How familiar do you feel with the environmental and social challenges linked to mining and production of raw materials (REEs and aluminium)?

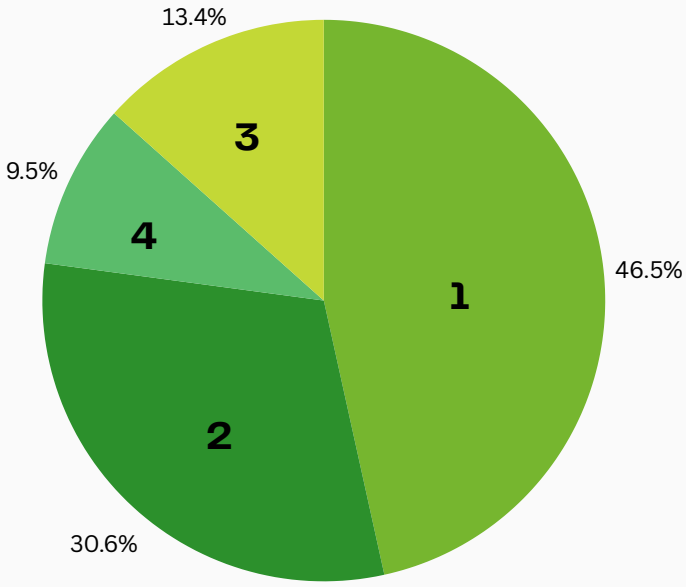


1 = not familiar
5 = very familiar

- **General awareness of rare earth elements and synthetic biology is low to moderate.**
- **Public familiarity with “red mud” is very limited.**
- **Responses to awareness of challenges connected to mining, rare earths, and aluminum production are skewed toward the lower-to-middle end of the spectrum, showing that many people feel only a little to somewhat informed.**
- **Combined, the data indicate that there is a significant knowledge gap in the general public regarding both the scientific and social context of red mud and regarding rare earths,and synthetic biology the tendency is still towards a lack of familiarity, yet there seems to be more information in circulation. This highlights the importance and relevance of clear science communication and engagement.**

To address the following questions, our intention was to gain a nuanced understanding of how participants perceived our project after a brief introduction. For this reason, we deliberately placed these questions after providing concise explanations of key concepts, supplementing each with targeted factual statements. By structuring the survey this way, we aimed to ensure that even those with no prior knowledge of rare earth elements, red mud, or synthetic biology would be able to assess our project with a more objective and informed perspective.

Q5. When developing solutions for challenges posed by red mud production and REE dependencies in global markets, which two priorities do you consider most important?



The results highlight a strong public preference for environmental protection and sustainable resource recovery over strictly economic or market-focused goals. This suggests that community support for new technologies will be strongest if these values remain central to project design and implementation.

1. **Protect the environment and local communities**
2. **Recover valuable resources for technology sustainably**
3. **Make the process economically viable**
4. **Reduce global dependence on mining**

Q6. What is your initial reaction to our project idea including your concerns? Utilising algae, whose ability to capture rare earth elements from red mud is enhanced through genetic engineering.

As this was an open-ended question, we received 410 written responses, many of which echoed the kinds of concerns we had hoped participants would share. Following are the six primary concerns most frequently raised by our respondents. Some of these mirrored questions we had been grappling with since the beginning of the project, while others offered valuable new dimensions that have enriched our own perspectives. Seeking to bridge this newly engaged community with the expert voices we interviewed, we set out to gather information and provide answers addressing these major concerns, including those related to TERRA's role in bioremediation, as well as questions of sustainability, scalability, and beyond.

Fate and safety of the algae after metal uptake:

Many respondents are concerned about what happens to the genetically engineered algae once they have accumulated rare earth elements (REEs). There is a worry that unless the contaminated biomass is responsibly managed, the pollution problem could simply be shifted or return in a different form.

Risk and containment of genetically modified organisms (GMOs):

There is significant apprehension about the use of genetically modified algae. Concerns focus on the possibility of escape, unintended ecological impacts, potential colonization of natural environments, and whether the solution could cause new risks greater than those it seeks to address.

Environmental impact and long-term effects:

Numerous participants questioned the broader ecological consequences of deploying engineered algae, specifically, the long-term effects on soils, water, flora, and fauna, as well as secondary contamination or unforeseen ecological disruptions.

Technical feasibility, efficiency, and scalability:

Respondents frequently asked whether the proposed technology can function effectively at scale, whether the process is viable in real-world conditions, what the recovery rates and efficiencies would be, and if it could be broadly implemented within existing industrial systems.

Sustainability of production and disposal:

Questions were raised regarding the sustainability of producing, maintaining, and eventually disposing of genetically engineered algae, the resource requirements for their production, as well as the management of any by-products or side streams resulting from the process.

Social and economic viability, stakeholder adoption, and industry costs:

Participants voiced concerns about the practical adoption of the technology, who will ultimately use this approach, whether industries will be open to investing in it given cost structures, and how systemic change can occur in sectors that have historically been difficult to shift.

Fate and safety of the algae after metal uptake

To address this concern, we rely on our planned workflow as well as direct input from leading researchers:
Dr. Mathieu Renaud, an ecotoxicologist, highlights that thorough risk evaluation must combine chemistry, toxicity assays, and studies of the living algal community to detect unintended risks from any by-products or residual waste. He underscores the ongoing need for site-specific, long-term monitoring to ensure true environmental safety.

Environmental chemist **Prof. Kathrine Fenner** recommends focusing on the primary peptide or protein used in recovery, in this case, the TFD protein, since the parent molecule is generally most relevant for risk. She also advises predictive modeling to anticipate where transformation products may end up in the environment and advocates using rapid cell-based bioassays to detect toxicity in waste streams pre-release.

Aquatic systems expert **Dr. David Janssen** notes that environmental risks are typically low while systems are contained within well-managed treatment plants. However, he calls attention to the need for responsible post-process handling, cautioning that carefully managing algae biomass is vital to prevent accidental re-release of recovered metals into natural water systems.

Bringing together these expert recommendations, our workflow for algal REE-recovery is designed to maximize safety: after REE accumulation, **algae are incinerated to ash for secure metal recovery, minimizing environmental exposure**. The **modular bioreactor architecture further ensures encapsulation of genetically engineered algae**, with flexible onsite deployment to suit a range of industrial settings.
By integrating careful testing, robust planning, and close attention to environmental context, we establish a practical and responsible foundation, for all stakeholders engaged in safe, sustainable resource recovery.

Risk and containment of genetically modified organisms (GMOs)

Environmental impact and long-term effects

To address concerns about risk, containment, and long-term environmental effects of genetically modified organisms (GMOs), we combine intentional engineering with direct insights from expert researchers.

Lucas Boldrini of IBBIS underscores that biosafety and biosecurity "should be an integral part of the project, similar to a feature built into the design." He highlights the importance of embedding continuous risk assessment within project workflows, using international benchmarks such as ISO biosafety standards, robust sequence screening tools, and active engagement with policymakers. This approach creates a culture "where risk reduction is consistently applied and prevents it from being overlooked," ensuring alignment with evolving European legislative initiatives such as the ISO policies.

Prof. Dr. Axel Schippers, geomicrobiologist, notes that the "main concern arises from using genetically modified organisms, which are subject to strict regulations and public scrutiny. Full containment in mining-like conditions would be difficult, though the harsh chemical environments used in such processes are unlikely to support harmful microbial growth. Standard monitoring and compliance with biosafety regulations are essential, but from a biological perspective, the environmental risk is low compared to conventional mining hazards". Regular compliance and robust monitoring are thus indispensable.

Dr. David Janssen, who investigates aquatic systems, emphasizes that ecosystem impacts are minimized when engineered algae stay within well-managed, closed facilities. He cautions that "if the engineered algae were to escape into the natural environment and thrive, overaccumulation could become problematic," hence strong containment and post-process controls are vital.

Aligned with the EU's evolving **ISO policies** [3] **and the Zero Pollution Action Plan** [4]**,** our workflow ensures that engineered organisms remain encapsulated within modular, flexible bioreactors. This platform meets both legal standards and the spirit of **"biosafety by design"** advocated by our experts. We remain committed to **proactive risk assessment, continuous monitoring, and transparent policymaker and stakeholder engagement** to ensure that advances in GMO-based recovery science proceed safely, responsibly, and in accordance with Europe's biosafety and biosecurity ambitions.

Technical feasibility, efficiency, and scalability

Sustainability of production and disposal

To address technical feasibility, scalability and the sustainability of production and disposal, we construct our approach around expert perspectives from technical and environmental fields.

Prof. Dr. Axel Schippers points to the challenge posed by red mud's high alkalinity and acid demand, highlighting that "biological methods are best suited after chemical leaching has simplified the waste matrix." He emphasizes the necessity of "integrating process engineering and economic feasibility from day one," ensuring that biological solutions contribute meaningfully to sustainable metal recovery instead of simply shifting the burden elsewhere.

Prof. Dr. Cathleen Zeymer and **Dr. Florian Leiss-Maier** observe that while the TFD protein holds "strong lanthanide affinity and robustness in moderate pH," questions remain about its selectivity and operational lifetime, especially when immobilized or displayed for repeated use. They stress that realistic industrial matrix tests and careful planning for recovery, recycling, or safe disposal of spent protein are crucial for closing the sustainability loop.

Dr. Michal Shoshan advises beginning with "stepwise complexity testing," as shortened and modified peptides can offer selectivity benefits but may pose challenges in production, stability, and downstream separation. She recommends the optimization of metal-binding constructs before addressing host organism/environment compatibility.

With these expert insights, our workflow considers **a design for safe, modular deployment.** The system favors **integrated chemical-biological steps that minimize secondary waste and enable secure, defined recovery and disposal pathways.** By placing sustainability at the center and embracing ongoing testing, recycling, and life-cycle planning, our strategy supports responsible, scalable metal recovery, reducing environmental harm now and in the future.

Social and economic viability, stakeholder adoption, and industry costs

To address the concern of social and economic viability, stakeholder adoption, and industry costs, we rely on our workflow as well as direct insights from leading researchers and practitioners:

Dr. Marie Perrin of REEcover stresses that overcoming market and policy hurdles requires very high selectivity to drive down operational costs, early industrial partnerships to secure supply and scale, and robust life cycle analysis even when standardization is a challenge.

Kevin Rouff of Studio ThusThat underscores that economic, legislative, and public perception barriers are often the primary obstacles to adoption. They highlight the value of design, local context, and storytelling in creating collaborations that bridge the gap between science, industry, and society.

Prof. Dr. Axel Schippers warns that without careful integration with transport, mixing, and cost models, it is unlikely to survive industrial scaling, adding that biological solutions can complement, rather than replace, established hydrometallurgical routes.

Finally, **Lucas Boldrini of IBBIS** emphasizes that early, ongoing engagement with policymakers and proactive alignment with emerging standards are crucial steps to smooth the pathway for real-world adoption and credibility.

By integrating these recommendations, namely, **prioritizing cost-effectiveness, open collaboration, and policy alignment** our project aims for broad stakeholder acceptance and long-term social and economic impact.

By integrating these recommendations, namely **prioritizing cost-effectiveness, open collaboration, and policy alignment**, our project emphasizes the need for **rigorous techno-economic analysis, life-cycle assessment, and supply-chain-level feasibility.** This perspective supports practical hybrid strategies that combine chemical pretreatment with biological recovery, increasing both technological acceptance and real-world applicability. Taken together, these measures position our project for broad stakeholder acceptance and durable social and economic impact.

Closing Remarks

Our objectives in designing this survey were guided by a strong commitment to science communication, meaningful community engagement, and genuine outreach. From the very beginning, we envisioned our survey *as a platform for authentic dialogue, a bridge fostering exchange*.

The concerns voiced by participants during the survey echoed our own priorities, reinforcing that our approach has always placed public perspectives, environmental stewardship, ethical considerations, and safety at its core. Notably, the majority of respondents demonstrated a clear understanding of our project's aims, which affirms our goal of transparent and effective science communication. While our initial aim was to inform a broader audience about these pressing issues, the survey experience was deeply reciprocal: we, in turn, gained new perspectives and insights from the community.

Our analysis reflects more than statistics; it captures the emotional landscape expressed in participants' comments, their engagement, curiosity, support, hope, and even joy. **Through their words, we witnessed a budding sense of community, unified by curiosity and optimism around the idea of transforming waste into a resource through biology**. It is this shared enthusiasm that signals the emergence of a community invested in **reimagining waste not as a hazard to be ignored, but as a narrative that can inspire renewed relevance**.

Looking ahead, it is our wish and intention to continue nurturing this community, remaining open to further exchange and collaboration. This study owes its existence, and is ultimately dedicated, to the participants themselves. They have demonstrated that **public perceptions of "waste", so often dismissed and marginalized, can shift dramatically when people are invited into the story and given a role in its renewal.**

In closing, we are honored to share the words of a few participants who, through their comments, have truly touched our hearts and reminded us of the transformative power of dialogue and shared curiosity.

"I was surprised. It seemed interesting. I started thinking about it…"

"Cela a l'air passionant, avec un reel enjeu environnemental".

"Projeniz çok değerli açıkçası başarılı olmanızı diliyorum :)"

"It's the first time I'm getting interested in this and learning about it."

"Kreativ, wichtig, erstaunt von den Algen"

Many thanks, iGEM 2025 ETH Team

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