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Article

Chemical Engineering beyond Earth: Astrochemical Engineering in the Space Age

Vassilis J. Inglezakis [1,*], Donald Rapp [2], Panos Razis [3] and Antonis A. Zorpas [4,*]

1 Department of Chemical & Process Engineering, University of Strathclyde, Glasgow G1 1XQ, UK
2 Independent Researcher, South Pasadena, CA 91030, USA; drdrapp@earthlink.net
3 Faculty of Pure and Applied Science, Department of Physics, University of Cyprus, 1st Panepistimiou Avenue, 2109 Aglantzia, P.O. Box 20537, Nicosia 1678, Cyprus; razis@ucy.ac.cy
4 Laboratory of Chemical Engineering and Engineering Sustainability, Faculty of Pure and Applied Sciences, Open University of Cyprus, Giannou Kranitiodi 89, Nicosia 2236, Cyprus
* Correspondence: vasileios.inglezakis@strath.ac.uk (V.J.I.); antonis.zorpas@ouc.ac.cy or antoniszorpas@yahoo.com (A.A.Z.)

Abstract: The Space Race in the second half of the 20th century was primarily concerned with getting there and back. Gradually, technology and international collaboration opened new horizons, but human activity was mostly restricted around Earth's orbit, while robotic missions were sent to solar system planets and moons. Now, nations and companies claim extraterrestrial resources and plans are in place to send humans and build bases on the Moon and Mars. Exploration and discovery are likely to be followed by exploitation and settlement. History suggests that the next step is the development of space industry. The new industrial revolution will take place in space. Chemical engineers have been educated for more than a century on designing processes adapted to the Earth's conditions, involving a range of raw materials, atmospheric pressure, ambient temperature, solar radiation, and 1-g. In space, the raw materials differ, and the unique pressure, temperature and solar radiation conditions require new approaches and methods. In the era of space exploration, a new educational concept for chemical engineers is necessary to prepare them for playing key roles in space. To this end, we introduce Astrochemical Engineering as an advanced postgraduate course and we propose a 2-year 120 ECTS MEng curriculum with a brief description of the modules and learning outcomes. The first year includes topics such as low-gravity process engineering, cryogenics, and recycling systems. The second year includes the utilization of planetary resources and materials for space resources. The course culminates in an individual design project and comprises two specializations: Process Engineering and Space Science. The course will equip engineers and scientists with the necessary knowledge necessary for the development of advanced processes and industrial ecologies based on closed self-sustained systems. These can be applied on Earth to help reinvent sustainability and mitigate the numerous challenges humanity faces.

Keywords: chemical engineering; astrochemical engineering; curriculum development; extraterrestrial environment; space engineering; sustainable education

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1. Introduction

Chemical Engineering (ChE) has evolved dramatically over the past thirty years, embracing advances in the broader areas of *nanotechnology*, *biotechnology*, and *computer science*. Bio-, info-, and nano- are not new concepts to ChE but the exponential development of these areas has had a profound effect on the evolution of the discipline. Nanotechnology was first introduced in 1959 with a lecture by the Nobel-prize-winning physicist Richard Feynman, entitled *There's Plenty of Room at the Bottom* (*Data Storage*), where he envisioned the possibility of directly manipulating individual atoms as a powerful form of synthetic chemistry [1]. ChE embraced nanotechnology in the 1990s; suitable modules were integrated into the curriculum and research has been evolving at an accelerating pace. In recognition of biology as an important science impacting ChE, a number of ChE departments changed their names to include some bio terms [1], such as Chemical and Biomolecular Engineering (e.g., Georgia Tech, Atlanta, GA, USA), Chemical and Biological Engineering (e.g., Princeton, NJ, USA), Chemical Engineering and Biotechnology (e.g., Cambridge, UK), and Chemical and Biomedical Engineering (e.g., Florida State University, Tallahassee, FL, USA). The new hybrid plays a key role in advancing bioprocesses, biomaterials, and biomedicine. In tandem, a revolution in process engineering was brought about by computers in the 1990s [2]. The increasingly powerful hardware and software created unimaginable opportunities. ChE is undergoing a transformation driven largely by the booming of data science [3]. A new term, i.e., Industry 4.0, has emerged to represent the fourth revolution that has occurred in manufacturing driven by digitalization. There is ample evidence that the next revolution in ChE will be data-driven and powered by artificial intelligence [3].

The potential human bases on the Moon and Mars are coming within the reach of our current technological capabilities and *Astropolitics* shapes national strategies worldwide [4]. Several disciplines have embraced the new opportunity; *Astrochemistry* deals with the chemical evolution occurring in space and it is a recognized field of research [5,6], *Space Chemistry* is defined as the performance of chemistry in space [6], *Astrobiology* is the study of life in the universe, *Space Biology* is aimed at addressing the basic questions regarding the extent to which gravity plays a role in the growth, morphology, and function of cells in the space environment [7], *Astropharmacy* and *Astromedicine* address the question of how human explorers can receive effective medical and pharmaceutical care in the context of space [8], and Civil Engineering is expanding towards the design and construction of lunar and Martian structures, habitats, and outposts [9]. ChE contributes to space industry as well in a number of ways; life support systems (LSSs), materials, energy systems, and propulsion are a few examples. However, as Lobmeyer and Meneghelli argued two decades ago, ChE has been laboring in the shadows of other disciplines, namely Physics and Mechanical Engineering [10]. The situation has not changed much since then. In *New Directions for Chemical Engineering* published by the U.S. National Academy of Sciences, bio and info are thoroughly discussed but space is absent [3]. In *Revisiting the Future of Chemical Engineering*, where some of the profession's thought leaders share their visions of the future of ChE, data science and biotechnology (among others) are identified as strong forces shaping the future of ChE; however, again, space is not considered [11].

Looking beyond the immediacy of current space projects, we envision a significant future expansion of space exploration and exploitation of space resources. We believe that the current ChE curriculum does not adequately prepare students for leadership in space engineering. We therefore created and present in this paper a new 2-year curriculum leading to an MSc in Astrochemical Engineering to fill this anticipated need. Section 2 discusses the role of ChE in space exploration. Section 3 discusses the differences between space and terrestrial processing, and interprets these as both challenges and opportunities. That is followed by Section 4, where the structure of the 2-year course is presented. The first year is on the theory and fundamentals of space engineering from the ChE perspective and the second year is dedicated to space exploration applications. The course comprises seven core modules, four modules for Process Engineering, and four for the Space Science specializations and a Design Project. An important part of space processing is so-called circular or cyclic systems, where spent outputs are reprocessed to produce new useful input materials. In typical terrestrial processes, such spent outputs are often discharged to the environment, where they typically pollute and require great effort to mitigate. Eventually, as these circular systems designed for space applications also become available for terrestrial applications, they will contribute to sustainability goals.

The 2030 Agenda of the United Nations (UN) revolves around the Sustainable Development Goals (SDGs), and to achieve the related objectives, scientific production should align with the SDGs' achievement [12]. Universities should try to make the most of the many opportunities that the SDGs offer, not only in the field of teaching and research, but also in their university extension activities [13]. This commitment in universities is advancing with the help of academics who individually include it in their disciplines and course design but consider that there is still a long way to go [14]. The innovative technologies built to push humanity into space can also support sustainable development on Earth. Many projects related to sustainable development across industries make use of space-based technologies and services to contribute to the goals. In particular, space technologies directly support Good health and well-being (SDG3), Affordable and clean energy (SDG7) and Industry, Innovation and infrastructure (SDG9) and Climate Action (SDG13). Also, according to UNESCO, five other SDGs have direct reference to Quality Education (SDG4), including SDG3 (Target 3.7) and SDG 13 (Target 13.3). Thus, by educating chemical engineers for space applications, the proposed curriculum is focused on fulfilling all these SDGs. The modules, and in particular the Circular Systems module of the proposed curriculum, bring together theoretical approaches and innovative knowledge by providing students with the skills and knowledge to apply sustainable development solutions in extraterrestrial environments.

Space was a central theme in science fiction for centuries, but it is only recently that fiction and reality have converged. Science fiction as an educational resource was recognized from the very beginnings of the genre, but its use in ChE education was first discussed in a paper published in *Education for Chemical Engineers* in 2011 [14]. In the science fiction book *Reach for the Stars* published in 2021 by John Wegener, Ethan Richards, a space traveler, was sponsored by NASA to study *Astrochemical Engineering* at UCLA; to the best of our knowledge, this is the first time the term was used. Hereby, we argue that it is time to make science fiction a reality and introduce *Astrochemical Engineering* into the ChE curriculum.

> *"There is a tide in the affairs of men*
> *Which, taken at the flood, leads on to fortune;*
> *Omitted, all the voyage of their life*
> *Is bound in shallows and in miseries.*
> *On such a full sea are we now afloat;*
> *And we must take the current when it serves,*
> *Or lose our ventures."*
>
> William Shakespeare, Julius Caesar (Act IV, Scene III, lines 218–224)

2. Space Exploration and Chemical Engineering

The contribution of ChE to space exploration is not new and can be traced in the literature back to 1979; Waldron et al. discussed the possibilities and conditions of constructing and operating processing plants in space using materials taken from the lunar surface [15]. They list a number of processes, such as the electrolysis of molten silica, carbothermic/silicothermic reduction, the carbon–chlorination process, NaOH basic-leach process, and HF acid leach. Life support systems, low-gravity processes, and the associated automated control systems have long been identified as areas where ChE can contribute [16]. In a conference paper published in 2001 [10], Lobmeyer and Meneghelli list cryogenics, ISRU, miniaturization, launchability, and power/process efficiencies as several areas where chemical engineers can provide support for the exploration of space. ChE played a central role in the development of propulsion systems and the latest major contribution is the development of solid oxide electrolysis of CO_2 to O_2 recently demonstrated on Mars [17,18]. Also, several ChE processes are used in the Environmental Control and Life Support System (ECLSS) developed by NASA. The ECLSS provides clean air and water to the International Space Station (ISS) crew and laboratory animals and it consists of two key components: the Water Recovery System (WRS) and the Oxygen Generation System (OGS) [19,20]. However, except for propulsion systems, fuels, and Life Support Systems, hardcore ChE such as chemical reactor engineering and separation processes has not been utilized in the core of space research. This is about to change as the advent of in situ resource utilization (ISRU) brings ChE to the forefront of space programs, and it is expected to grow significantly in importance over the coming decades.

The current cost of exploration and subsequent settlement in extraterrestrial environments is challenging but can be reduced by use of resources found in situ. ISRU is defined as the conversion of local resources at a space destination to provide useful infrastructure and commodities [18,21]. A seminal paper published in 1978 by Ash et al. presented a revolutionary detailed analysis of Mars ISRU and its benefits [22]. The current ISRU interests on the Moon and Mars concentrate on building shelters and the harvesting of subsoil water and atmospheric CO_2 for the production of methane, hydrogen, and oxygen [23]. However, there is untapped potential as the Moon and Mars hold a number of other useful materials such as oxides of silicon, aluminum, iron, and titanium; salts; hydrated minerals; and atmospheric N_2 and Ar [24,25]. Minerals that exist on Earth in very limited quantities are abundant on some meteorites and asteroids [18,26]. The new generation of chemical engineers should be able to capture and/or recover such critical minerals from extraterrestrial environments as these are essential to develop smart technologies. For materials that are not readily available, chemical engineers would have to recover them from waste or end-of-life equipment applying circular economy strategies [27]. Clearly, ISRU is incomplete without the development of processes that transform raw materials into useful products—this is what chemical engineers carry out on Earth. Indeed, ChE is recognized as one of the key disciplines involved in ISRU technologies [28]. Reverse water–gas shift and Sabatier reactions are prime examples of reactions utilizing CO_2, the main component of the Martian atmosphere [24]. These reactions are the basis of the era of small-molecule activation [29]. Another resource is the waste produced by humans, notably urine. The closed-loop nutrient cycle from human urine has attracted interest in the last decade and the number of papers published on bioregenerative life support systems is growing [30]. However, Earth technologies cannot simply be implemented on other planets and need to be adapted to each location. There is a gap both in terms of technology and finances stemming from the major differences on other planets regarding available resources and the physical environment in terms of gravity, temperature, pressure, and radiation conditions. As one recent example, consider the Mars Oxygen In Situ Experiment ("MOXIE") that has been converting CO_2 to O_2 on Mars for the past two years. This operates with a continuous flow reactor system, where a compressor pulls the Martian atmosphere through a filter to a higher pressure, and the flow passes through the cathode of a high-temperature electrolysis stack, where a portion of Martian CO_2 is converted to CO while a commensurate flow of oxygen occurs in the anode. However, an undesirable side reaction can also occur that would produce carbon that would clog up the cells and essentially destroy the electrolysis stack. The minimum voltage required for the side reaction is greater than the minimum voltage for oxygen production, so the voltages on the cells in the stack must be maintained above the minimum for oxygen production, yet below that for carbon formation. The essential technical background for MOXIE involves thermodynamics, electrochemistry, gas flow in various regimes, the filtration of dust particles, and thermal control. All of this must be carried out within the context of space constraints on mass, volume, power, and reliability. Most of the work was beyond ordinary ChE education and required special study to work effectively on the project. ChE education must evolve and equip engineers for the Space Age.

3. Challenges and Opportunities

Throughout history, scientists and engineers have been educated to think in terms of a 1 g environment, traditional training that must be updated to account for low-gravity environments [31]. Unit operations in microgravity are not a new topic in ChE; for instance, they were discussed in a paper published by Allen and Pettit in 1987 [32]. The authors view microgravity as an advantage in crystallization processes. However, microgravity complicates fluid handling and processes governed by density differences, such as the stratification and separation of gases and liquids, due to the absence of buoyancy [33,34].

In the absence of gravity, convection, sedimentation, and buoyancy become irrelevant and mixing is not spontaneous. Diffusion is the only way that molecular heat and matter can be transported, and microgravity conditions provide a unique opportunity to study processes decoupled from sedimentation [35]. Microgravity benefits the formation of alloys as the process is diffusion-controlled rather than gravity-controlled, encouraging molecules to be distributed evenly in the material, resulting in a more uniform structure. On the other hand, chemistry under microgravity cannot be performed in flasks because the solutions would not mix well and reactions would not be reproducible [36]. The predominance of diffusion is a challenge for heterogeneous catalytic processes as the absence of density-driven convection hinders phase separation [36]. Distillation, arguably the most important separation process in ChE, may be useless in space since microgravity removes two of the variables in boiling: convection and buoyancy. This means that the vapor phase of a boiling liquid does not rise and the usual model of convection currents that distributes heat in the liquid phase that we know on Earth is no longer valid. Two-phase boiling experiments have shown that reduced gravity considerably alters the flow patterns and heat transfer as compared to 1 g conditions [37]. Another example is electrolysis, where under 1 g, buoyancy leads to the detachment of gas bubbles from the electrode surface and a separation of oxygen and hydrogen gas bubbles from the liquid electrolyte, but under reduced-gravity electrolysis systems, this is hindered, resulting in a lower efficiency [20]. Due to the effect of microgravity on mixing in batch systems, continuous flow is considered the best operational mode in space. Flow chemistry studies reactions taking place in continuous flow in tubes rather than in a flask [38]. The first journal publications regarding the overall concept and promises of flow chemistry for microgravity applications were published in 2017 [36]. Although these effects are more intense in zero gravity and microgravity, they are important in reduced-gravity conditions found on terrestrial planetary bodies. Moreover, process integration to small compact systems is compulsory in space [35]. At the plant level, the integration of extraterrestrial industrial systems needs to be complete, and process intensification, a relatively new concept in ChE, represents a way to achieve more with less. This is relevant to the miniaturization of processes, e.g., microreactors—in other words, to put a plant on the scale of a small laboratory setup [39].

Beyond the profound effect of gravity, as Allen and Pettit argued in 1987 [32], low temperature and high vacuum are advantages that space offers rather than challenges. Indeed, space offers an infinitely available vacuum and extremely low temperatures, which are expensive and difficult to achieve on Earth. Vacuum technology is ubiquitous and typical applications include distillation, drying, sublimation, and filtration [40]. Low temperature is used to produce and transport immense quantities of gas mixtures [41]. Also, we know that some reactions can be accelerated by operating at temperatures below -150° K and some can even occur at temperatures below 10 K [42,43]. A challenge is the exposure of chemical reactions to the entire electromagnetic spectrum outside the Earth's atmosphere, which is likely to influence photocatalytic reactions and the stability of molecules due to higher UV radiation [36].

Sustainable development, as defined in the World Commission on Environment and Development's 1987 Brundtland report, should follow humans in the journey to space, considering circular economy principles [44]. A major challenge is to extract and transform the available in situ resources sufficiently in circular systems. The new concept of circular chemical processes is gaining traction [35]. In extraterrestrial environments, the objective is the development of an industrial ecology based on closed self-sustained systems with zero-discharge production processes. The knowledge acquired in extraterrestrial environments can be applied on Earth to help reinvent sustainability by developing new technologies, including smart ones that harness the power of chemistry to create sustainable products and processes. By studying the chemical properties of materials in space, scientists can identify new materials that are more resistant to environmental degradation. Furthermore, they can be used to create new processes for the production of energy, such as using solar power to create hydrogen fuel through a process known as artificial photosynthesis. Artificial photosynthesis can be an efficient alternative route to capture CO_2 and produce food and energy [45]. Hann et al. found a way to bypass the need for biological photosynthesis altogether and create food independent of sunlight by using artificial photosynthesis [46].

4. The Case for Astrochemical Engineering

In NASA's upcoming new mission "ARTEMIS II" [47], currently planned to be launched in November 2024, four astronauts will venture around the Moon, paving the way for future lunar missions. If we review the curriculum of the four astronauts, it will become apparent that nexus disciplines are needed for the next generations of engineers that intend to explore space. The commander spent hundreds of hours conducting valuable scientific research in areas such as Human Physiology, Medicine, Physical Science, Earth Science, and Astrophysics, and he studied Computer and Systems Engineering, with an MSc in Systems Engineering. The pilot holds a BSc in General Engineering, MSc in Flight Test Engineering, MSc in Systems Engineering, and MSc in Military Operational Art and Science. The other two members as specialists hold BSc degrees in Electrical Engineering and Physics and an MSc degree in Electrical Engineering and Space Science, as well as a PhD. The 17 members of the 2022 ESA astronaut class exhibit an amazing breadth of disciplines: Astronautical Engineering, Aerospace Engineering, Mechanical Engineering, Human Factors Engineering, Space Engineering, Physics, Astrophysics, Biotechnology, Neuroscience, Biomedical Engineering, Medicine, Transport Engineering, Military Technology, Electrical Engineering, and Astronomy. One of the class members studied Industrial Chemistry.

Beyond the standard Astronautical Engineering courses that focus on the design, development, and manufacturing of spacecrafts, there are a number of postgraduate courses related to space communications, data collection and processing, satellites, observation, and remote sensing. The *Technical University of Denmark* (Denmark) offers an MSc course in Earth and Space Physics and Engineering, with an astrophysics orientation and specialization primarily in the areas of instrumentation to observe the universe, data processing, and physical and mathematical modelling. The *University of Pisa* (Italy) offers a 2-year MSc of Science in Space Engineering course focused on aerospace engineering, instrumentation, and propulsion. Brno University of Technology (Czech Republic) offers a 2-year MSc course on Space Applications, which is an interdisciplinary association of electrical and mechanical engineering. *Gdansk University of Technology* (Poland) offers a 2-year MSc course on Engineering and Management of Space Systems and it is broader in scope, including robotics, gravity-related research, heat and mass transfer in zero gravity, space law, and several modules on applications of computer science. The ESPACE—Earth Oriented Space Science and Technology is a 2-year MSc course offered by the *Technical University of Munich* (Germany) positioned at the interface between space technology and the engineering and natural scientific use of satellite data. The 1-year Space Science MSc offered by *University College London* (UK) provides a broad understanding of all aspects of space science and space instrumentation, including modules on data, instrumentation, satellites and spacecrafts, planetary atmospheres, and astrophysics. The *University of Edinburgh* released a new master's course (1 year) on Astrobiology and Planetary Sciences targeting the development of knowledge on cometary and exoplanet science, investigating the origin, diversity, and behavior of planets, asteroids, and solar systems.

A course similar in spirit to the Astrochemical Engineering concept is the 4-year MEng course on Electronic Engineering with Space Science and Technology offered by the *University of Bath* (UK), focused on the design, operation, and building of electronic systems for the space environment. However, the modules offered do not seem to consider the environmental conditions found on terrestrial planets. In this paper, we propose a new ChE course, namely *Astrochemical Engineering* (120 ECTS), dedicated to enabling *space industry*, which is necessary for establishing self-sustaining communities on the Moon, Mars, and other solar system bodies. Astrochemical Engineering would have to answer the fundamental question of how terrestrial ChE processes can be optimized and/or transformed to adapt to, and benefit from, the conditions in space. In a paper entitled *Chemical Engineering Education in the Next Century,* Gillet argues that ChE has survived extremely well in a changing world by assimilating or developing new subjects into curricula, but there is a fear that this ability to adapt might go too far and might lead to its eventual demise [48]. We believe that ChE must adapt to the new trends without diluting its core and Astrochemical Engineering is seen as a stem of an evolving ChE discipline. Astrochemical Engineering (Figure 1) is a ChE course adapted to address extraterrestrial environments, typically characterized by high radiation and low gravity, pressure, and temperature.

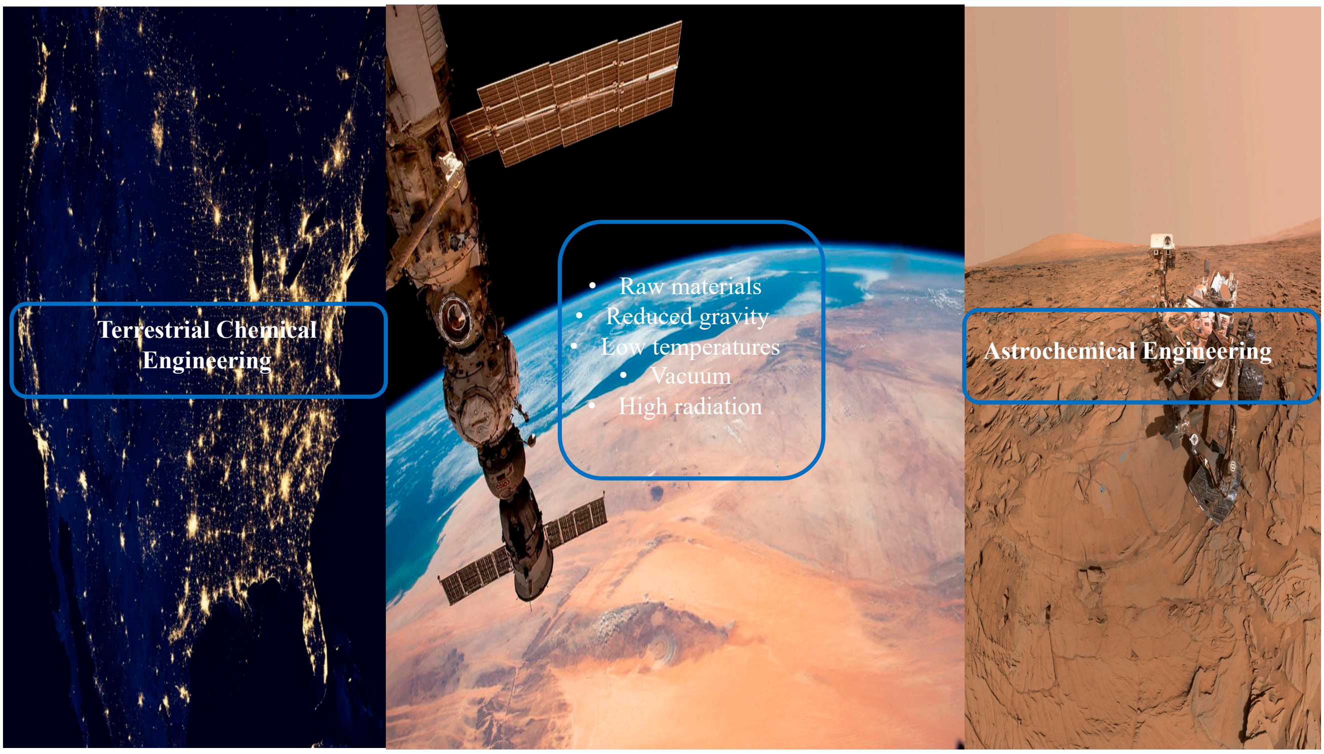

Figure 1. Astrochemical Engineering concept (images credit: NASA).

The 2-year MEng Astrochemical Engineering is a 120 ECTS course as presented below.

1st Year: Theory and fundamentals (60 ECTS)
Core modules (30 ECTS)

- Thermodynamics of terrestrial planets' and satellites' atmospheres and surfaces (7.5 ECTS): greenhouse effect, planetary atmosphere and climate, mass and heat flows, and case studies (Earth, Mars, Venus, Pluto, Titan, Triton, Enceladus, and Europa).
- Low-gravity process engineering (7.5 ECTS): the effect of gravity on transport phenomena and unit operations (boiling, flow, electrolysis, and crystallization).
- Principles of cryochemistry (7.5 ECTS): chemical reactions at low temperatures, in frozen systems, and at extremely low temperatures (<-150 °C).
- Programming (7.5 ECTS): numerical methods, open-source languages (Python), big data, machine learning, human–machine interfaces, the Metaverse environment, and gamification.
- Circular systems: circular economy, design for recycling, regenerative development remanufacturing, and reverse logistics for process optimization (7.5 ECTS).
- Design project I (7.5 ECTS).

Specialization: Process Engineering (15 ECTS)

- Fundamentals of cryogenic engineering (7.5 ECTS): the properties of materials and fluids in cryogenic conditions, cryogenic separation processes, the liquification of gases, cryogenic fluid storage and transfer, and cryogenic instrumentation.
- Process intensification (7.5 ECTS): equipment (microreactors, intensive mixing, and compact/microchannel heat exchangers) and methods (hybrid separations and reaction/separation integration).

Specialization: Space Science (15 ECTS)

- Energy production in space: solar energy, cosmic radiation, nuclear fission/fusion energy, artificial photosynthesis, energy production for life support systems, and carbon capture and utilization (7.5 ECTS).
- Space microbiology (7.5 ECTS): microbes in space, biochemical processes, synthetic biology and genetic engineering.

2nd Year: Space exploration applications (60 ECTS)
Core modules (45 ECTS)

- Martian in situ resource utilization (7.5 ECTS): atmospheric gas capture and purification, electrolysis (H_2O/CO_2), reactions for the production of useful substances (Sabatier, Fischer–Tropsch, reverse water–gas shift, and Haber–Bosch), and dust control and filtration systems.
- Materials for space applications: advanced composites (2D materials, graphene, carbon fiber, metal foams, aerogels, 3D-printed materials, and titanium composites), nanomaterials (carbon nanotubes; nanoscale sensors and actuators), and smart materials (shape memory alloys, self-healing materials, and bio-inspired materials) (7.5 ECTS).
- Design project II (30 ECTS).

Specialization: Process Engineering (15 ECTS)

- Lunar in situ resource utilization: polar ice, regolith, and fluid transfer under vacuum (pumps and compressors) (7.5 ECTS).
- Propulsion systems: methane–oxygen chemical propulsion, hydrogen storage and transport in space, solar electric propulsion, Xe, C60 and exotic propellants, nuclear thermal propulsion, nuclear electric propulsion, the storage and transport of cryogenic propellants on planetary surfaces, cryogenic propellants within aeroshells, and descent and ascent propulsion linkage (7.5 ECTS).

Specialization: Space Science (15 ECTS)

- Life support systems: human physiology and anatomy, life cycle assessment, instrumentation, and control systems (7.5 ECTS).
- Space agriculture (7.5 ECTS): plant science, farming technologies, the effect of reduced gravity, and genetic engineering.

The structure of the MSc provides the necessary transferable skills and ensures the learning outcomes (Figure 2) cover several pillars such as knowledge, comprehension, application, analysis, synthesis, and evaluation. The students will be equipped with solid theoretical knowledge and an understanding of applications, enabling them to operate in multiple contexts. The first year covers ChE fundamentals adapted to space conditions and applications, i.e., thermodynamics, transport phenomena, unit operations, and chemistry. The modules provide students with the tools needed to apply ChE in space applications. The circular systems module is of paramount importance in space and completes the set of core modules, ensuring that sustainability plays a central role in the curriculum [49]. In the second year, the approach is more specific and focuses on ISRU and materials needed for space applications. ISRU using the Mars paradigm as the planet offers a range of raw materials and appropriate, albeit challenging, conditions for the design of processes. Students can choose between two specializations in the first year, i.e., Process Engineering and Space Science, consisting of a total of four elective modules. The design project objective is the application of technical knowledge covered in the various teaching modules and it is divided into two phases: a group and an individual project. Bloom's taxonomy was used as a guide for the learning outcomes presented in Figure 2. As this is an advanced ChE course, it is best suited for students with ChE education. The course is designed to prepare a new generation of chemical engineers ready to work and innovate in the broader area of space industry.

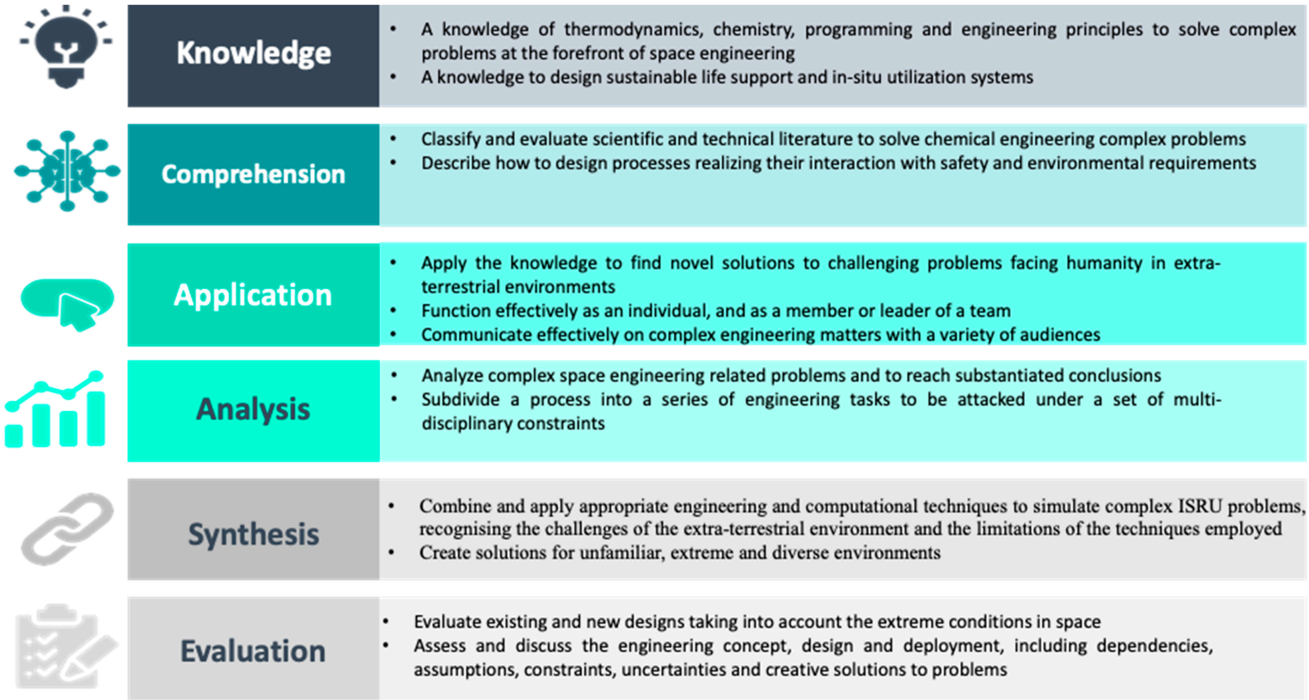

Figure 2. Learning outcomes of the course.

Education can be said to be part of an ongoing transition, which comprises opportunities and challenges. The proposed course competencies could vary depending on the institution and the evolving nature of the field. The course is multidisciplinary and concepts such as case-based learning (CBL) and problem-based learning (PBL), as a sustainable teaching practice, can be easily integrated [50]. Also, the proposed course contributes to SDG4 (Quality of Education) [51–53]. It links knowledge with real engineering problems through an interdisciplinary and cross-disciplinary approach to develop the competencies needed for building a sustainable future on Earth and beyond. It is relevant to mention that the notion of sustainability in Astrochemical Engineering is futuristic and one would have to look into the coming decades; it is difficult to make this specific in the year 2023.

5. Conclusions

Chemical Engineering education has passed through several significant stages of evolution, particularly in the incorporation of biological processes. We believe that Chemical Engineering education is poised for yet another evolution into preparation for operations in space, which we call Astrochemical Engineering. Chemical Engineering already plays a significant role in space technology via materials, environmental control, the reprocessing of waste materials, in situ resource utilization, and propulsion. These processes involve unique environmental conditions in gravity, radiation, and the need for recycling waste products under significant mass and power constraints. Individual chemical engineers have had to learn to adapt to these conditions ad hoc. We envision a significant future expansion in the global exploration and exploitation of space in which Chemical Engineering will play an increasing role, requiring targeted preparation at the university level. Looking beyond the immediacy of current space projects, we envision a significant future expansion of space exploration and the exploitation of space resources. We believe that the current Chemical Engineering curriculum does not adequately prepare students for leadership in space industry. We therefore created a new 2-year curriculum leading to an MS in Astrochemical Engineering to fill this anticipated need. Moreover, Astrochemical Engineering has much to offer to sustainability as space technologies can be used to solve problems on Earth. The proposed curriculum can support several SDGs, such as SDGs 3, 4, 7, 9, and 13.

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