Konzeptstudie über die potenzielle Gewinnung von Nährstoffen für Algen und Pflanzen auf der Marsoberfläche

Concept study on the potential extraction of nutrients for algae and plants on the surface of Mars

Bachelorarbeit von
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Abstract

Bio-regenerative life support systems are of major significance to the feasibility of future crewed space exploration missions. Within this thesis, the extraction of elements that can be used as nutrients for organisms used in bio-regenerative life support systems from minerals present on the Martian surface was studied. The organisms were defined as higher plants, green algae, and cyanobacteria due to their inclusion in numerous current concepts. Nutritional needs of these organism were categorized into two groups, macronutrients, and micronutrients. A representative global characterization of the Martian surface's mineral abundancies was presented. The required nutrients potassium, calcium, magnesium, sulphur, iron, sodium and silicon are all present within mineral abundancies on the Martian surface. Processes to extract these elements were compiled and evaluated for their applicability under the conditions on the Martian surface. An Analytical Hierarchy Process analysis was chosen to conduct the evaluation. The available data of the examined extraction processes did not allow an analysis according to the proposed Analytical Hierarchy process framework. The processes were presented and evaluated in text. Possibilities for extracting the elements required by higher plants, green algae and cyanobacteria used in bio-regenerative life support systems from Martian minerals exist but need to be expanded upon to accommodate the conditions on the Martian surface. Recommendations and considerations for future research and development are discussed.

Kurzfassung

Bioregenerative Lebenserhaltungssysteme sind für die Durchführbarkeit künftiger bemannter Raumfahrtmissionen von großer Bedeutung. Im Rahmen dieser Bachelorarbeit wurde die Extraktion von Elementen, die als Nährstoffe für Organismen in bioregenerativen Lebenserhaltungssystemen verwendet werden können, aus den auf der Marsoberfläche vorhandenen Mineralen untersucht. Anhand ihrer Präsenz in zahlreichen aktuellen Konzepten, wurden die Organismen höhere Pflanzen, Grünalgen und Cyanobakterien als zu betrachtende Organismen ausgewählt. Der Nährstoffbedarf dieser Organismen wurde in zwei Gruppen eingeteilt: Makronährstoffe und Mikronährstoffe. Eine repräsentative globale Charakterisierung der Mineralvorkommen auf der Marsoberfläche wurde vorgestellt und erläutert. Die benötigten Nährstoffe Kalium, Kalzium, Magnesium, Schwefel, Eisen, Natrium und Silizium sind auf der Marsoberfläche in großer Menge vorhanden. Verfahren zur Extraktion dieser Elemente wurden zusammengestellt und auf ihre Anwendbarkeit unter den Bedingungen auf der Marsoberfläche bewertet. Eine Analytische Hierarchieprozess Analyse wurde als Bewertungsmethode ausgewählt. Die verfügbaren Daten der untersuchten Extraktionsprozesse ließen keine aussagekräftige Analyse anhand der erarbeiteten Analytical Hierarchy Process Struktur zu. Die Prozesse wurden in Textform dargestellt und bewertet. Die Möglichkeiten zur Extraktion von Elementen, die von höheren Pflanzen, Grünalgen und Cyanobakterien in bio-regenerativen Lebenserhaltungssystemen benötigt werden, aus Mineralien auf der Marsoberfläche sind vorhanden. Um den Bedingungen auf der Marsoberfläche gerecht zu werden besteht weiterer Forschungsbedarf. Empfehlungen und Erwägungen für zukünftige Forschungs- und Entwicklungsarbeit werden erläutert.

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List of abbreviations

AHP	Analytical Hierarchy Process
APXS	Alpha-Particle X-ray Spectrometer
BLSS	Bio-regenerative life support system
BLSSs	Bio-regenerative life support systems
CI	Consistency Index
CR	Consistency Ratio
CRISM	Compact Reconnaissance Imaging Spectrometer for Mars
ISRU	In-Site Resource Utilization
MCDM	Multi Criteria Decision Making
MELiSSA	Micro-Ecological Life Support System Alternative
MOXIE	Mars Oxygen In-Situ Resource Utilization Experiment
PBR@LSR	Photobioreactor at the Life Support Rack
RI	Random Index
TES	Thermal Emission Spectrometer
Veggie	Vegetable Production System
ZARM	Center for Applied Space Technology and Microgravity

1 Introduction, Motivation and Outline

Future long-duration missions into the solar system, finally culminating on Mars, will require a fresh food supply to supplement crew diets, which means growing crops in space [1].

A spacecraft needs at least 9 months to reach Mars [2]. During long-term missions, it is impossible to continuously send resupplies to astronauts. Therefore, concepts for bio-regenerative life support systems (BLSSs) are being researched as a possible continuous source of resources such as oxygen and nutritional edible biomass. A critical aspect of long-term missions is sustainability. The concept of In-Situ Resource Utilization (ISRU) is about using local resources to their full extent and in turn lessen the dependence on resupply missions from earth. Improving sustainability for crewed missions on the surface of Mars means using local resources to generate consumables on site [3].

Most current BLSSs concepts include plants and algae as a component, either to produce oxygen or for them to be used as biomass for the consumption by astronauts in extraterrestrial habitats.

The analysis conducted by *Schubert, 2018* focused on an in depth analyses on greenhouse modules designed for producing higher plants, sometimes called vascular plants, for human space exploration missions [4]. The higher plants of said greenhouse modules primarily served as food. 27 different types of higher plants were carefully selected, analyzed, and compared against each other according to numerous criteria. There is no one singular crop that serves as the perfect candidate to be consumed as biomass. The choice of crop to be used as biomass depends heavily upon, but is not limited to, whether the considered mission is a short-term or a long-term mission. The 27 crops that possessed favorable characteristics for greenhouse modules in the context of a crewed space exploration mission were a selection of leafy greens, fruits, vegetables, herbs or types of wheat crops such as cabbage, strawberries, bell pepper and bread wheat.

Plant growth systems and ground demonstrators such as the “EDEN ISS” greenhouse in Antarctica [5], the Vegetable Production System (Veggie) [1, 6] as well as its successor, Advanced Plant Habitat [6–8] onboard the International Space Station represent further efforts on researching the cultivation and use of higher plants in extraterrestrial BLSSs.

The summary presented in *Niederwieser et al., 2018* lists every experiment conducted in space utilizing algae at the time of the paper’s publication [9]. Most experiments either investigated green algae such as the *Chlorella* genus or cyanobacteria, which are also called blue-green algae and many of them focused on the algae’s capability and performance to revitalize air, recycle water, or serve as a biomass source. The implementation of green algae and cyanobacteria into BLSSs concepts for extraterrestrial mission scenarios has been further investigated by experiments such as the Photobioreactor at the Life Support Rack (PBR@LSR) onboard the ISS [10] and research on the use of *Arthrospira*, also known as *Spirulina*, to produce oxygen and edible biomass through use of the “Artemiss” reactor as part of the Micro-Ecological Life Support System Alternative (MELiSSA) [11, 12]. The Center for Applied Space Technology and Microgravity (ZARM) at the University of Bremen is specifically focusing on the production of oxygen on the Martian surface through the use of the cyanobacteria genus *Anabaena* [2, 3]. It is suggested that the cyanobacteria genus could even be cultivated in Martian soil.

The algae genera *Arthrospira sp*., *Chlamydomonas sp*., and *Chlorella sp.* Have been classified as remarkably suited to serve as model organisms for space applications due to their cultivational flexibility and robustness [13]. All of these genera are either green algae or cyanobacteria.

The aim of this thesis is to evaluate the potential use of Martian soil for nutrient supply for higher plants, green algae and cyanobacteria used in concepts for BLSSs. The nutritional requirements of these organisms will be discussed and outlined within an adequate scope. Cultivation techniques of plants and algae are scientific fields on their own and will be considered only in appropriate detail. A representative overview of the global mineral distribution on the surface of Mars will be presented and synergy possibilities with the required nutrients for higher plants, green algae and cyanobacteria identified. Processes targeting the extraction of elements required as nutrients for higher plants, green algae and cyanobacteria will be presented and evaluated according to the amount and detail of available data. The evaluation criteria will be defined and explained with the help of an Analytical Hierarchy Process (AHP) framework.

2 Nutritional requirements of higher plants, green algae, and cyanobacteria

Higher plants, green algae, and cyanobacteria require several elements to complete a full life cycle and in turn produce edible biomass and oxygen. These elements can be classified into macronutrients and micronutrients. The prefixes “macro” and “micro” do not indicate the importance of the nutrients, but the relative amount consumed by a batch of plants in a given timeframe. Both macro-and micronutrients are essential for proper growth.

In practice, predetermined nutrient solutions which cover all nutritional requirements of a given group of plants are applied during cultivation. One of the most common of these solutions is the so called “Hoagland solution” [14] used for the cultivation of higher plants. During the cultivation process, one species or batch of plants might require more or less of a certain nutrient. The specific nutritional requirements are then determined by observing deficiency and superabundance symptoms. Factors that may impact the exact nutritional requirements are stage of growth, atmospheric conditions, pH value of the water used for cultivation, the techniques used for cultivation and more [14, 15].

These highly specific and situational nutritional requirements during cultivation processes will not be further accounted for within the scope of this thesis. The nutrients required by higher plants, green algae and cyanobacteria, will be classified into macro-and micronutrients, but not differentiated any further.

2.1 Macronutrients, micronutrients and beneficial elements of Higher Plants

The individual elements that make up the macro-and micronutrients of higher plants have been clearly defined in previous works. Additionally, so-called beneficial elements which are favorable to the prosperity of higher plants during certain stages of growth and conditions have been identified. Beneficial elements can help the plants grow more efficiently. However, the applicational possibilities of these elements are highly dependent on the higher plant in question and the cultivational circumstances. The beneficial elements listed in Table 1 will not be considered further within the scope of this thesis and are solely listed as an illustrative example of the wide variety of elements that different species of higher plants may also benefit from but not necessarily require depending on the circumstances. The macro-and micronutrients listed in Table 1 are required by all higher plants during any stage of growth and are therefore the elements that will be considered as nutritional requirements for higher plants within this paper.

Table 1: Macro-and micronutrients required by higher plants and elements that can benefit the growth of higher plants during certain stages of growth as described in [15].

Macronutrients	Micronutrients	Beneficial elements
Nitrogen (N)	Iron (Fe)	Sodium (Na)
Phosphorus (P)	Copper (Cu)	Silicon (Si)
Potassium (K)	Zinc (Zn)	Vanadium (V)
Calcium (Ca)	Manganese (Mn)	Selenium (Se)
Magnesium (Mg)	Molybdenum (Mo)	Cobalt (Co)
Sulphur (S)	Boron (B)	Aluminum (Al)
	Chlorine (Cl)	Iodine (I)
	Nickel (Ni)	

Three absolutely essential resources for the growth of higher plants are of course hydrogen (H) in the form of water (H_2O), acids, and bases, as well as carbon (C) and oxygen (O_2). Carbon and oxygen are usually acquired from the surrounding atmosphere through the process of photosynthesis.

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2 \quad (1)$$

The Martian atmosphere is very rich in carbon dioxide (CO_2) [16] which is required for the photosynthesis process, displayed in reaction (1). ISRU technologies such as the Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE) are already utilizing the compound's abundance to produce oxygen on the Martian surface using solid oxide electrolysis [17]. Hydrogen is commonly obtained by higher plants through the absorption of water.

The extraction of water and oxygen from local resources as well as the utilization of CO_2 found within the atmosphere are areas of research essential for the sustainability of future extraterrestrial missions on the surface of Mars but will not be encompassed within this concept study.

An essential requirement for the photosynthesis process and therefore the proper growth of higher plants is light. "Nutrients cannot take the place of sunshine" [14]. Ensuring proper lighting is a critical aspect of the cultivation of higher plants but will not be considered further within the scope of this thesis.

2.2 Macronutrients and micronutrients of green algae and cyanobacteria

The nutrients required by green algae and cyanobacteria can also be classified as macro-and micronutrients. The macro-and micronutrients required for proper growth of green algae are listed in Table 2.

Table 2: Macro-and micronutrients required for the proper growth of green algae [18].

Macronutrients
Nitrogen (N)
Phosphorus (P)
Potassium (K)
Calcium (Ca)
Magnesium (Mg)
Sulphur (S)
Sodium (Na)
Chlorine (Cl)

Micronutrients
Iron (Fe)
Copper (Cu)
Manganese (Mn)
Molybdenum (Mo)
Boron (B)
Nickel (Ni)
Vanadium (V)
Cobalt (Co)
Silicon (Si)
Selenium (Se)

The macro-and micronutrients required for the proper growth of cyanobacteria are listed in Table 3.

Table 3: Macro-and micronutrients required by cyanobacteria [19].

Macronutrients
Nitrogen (N)
Phosphorus (P)
Potassium (K)
Calcium (Ca)
Magnesium (Mg)
Sulphur (S)
Carbon (C)

Micronutrients
Iron (Fe)
Copper (Cu)
Manganese (Mn)
Molybdenum (Mo)
Boron (B)
Nickel (Ni)
Cobalt (Co)
Zinc (Zn)
Chlorine (Cl)

Like for higher plants, carbon, oxygen and hydrogen also count as essential nutrients for green algae and cyanobacteria and will also not be considered for potential extraction for the same reasons discussed in chapter 2.1. The same applies to the provision of a light source.

As can be seen from Table 2 and Table 3, the nutritional requirements for green algae and cyanobacteria are very similar. The most striking difference is the requirement of chlorine as macronutrient for green algae while cyanobacteria require chlorine merely as a micronutrient.

3 Martian Regolith Composition and Characteristics

In this chapter, the mineral compositions present on the Martian surface will be presented and evaluated in regards to the nutritional requirements of higher plants, green algae and cyanobacteria.

The analysis of *Bandfield, 2002* used data from the Thermal Emission Spectrometer (TES) instrument onboard the Mars Global Surveyor space probe to characterize the mineral abundancies on the entire surface of Mars [20]. While instruments with higher resolution than the TES instrument such as the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) onboard the Mars Reconnaissance Orbiter spacecraft exist, this analysis provides the most extensive characterization on a global scale. Instruments with higher spectrographic resolution such as CRISM are limited to a smaller area and therefore not yet suitable for global mineralogic mapping. The minerals chosen for spectrographic comparison with the TES instrument data by *Bandfield, 2002* are of a relatively wide compositional range and the entire surface of Mars is considered, rather than specific locations.

Detailed investigations of small specific locations exist, such as for example the analysis of a location within the Namib Dune of the Bagnold Dune Field by Alpha-Particle X-ray Spectrometer (APXS) analysis of the CheMin instrument onboard the Mars Science Laboratory rover Curiosity [21].

While local investigations are good at providing ground truth for observations and studies conducted on the basis of data collected by satellites and spacecraft outside of the Martian atmosphere, they do not necessarily help at characterizing the global trends of mineral distributions and abundancies. Of course, the specific mineral concentrations will differ from one location to another. However, the aim of this study is to evaluate whether or not ISRU extraction processes could fundamentally benefit the nutritional requirements of plants and algae used in BLSS concepts. Should previously undetected localized abundancies of relevant minerals be discovered, this thesis can be used as a foundation to be built upon for further research and feasibility analyses.

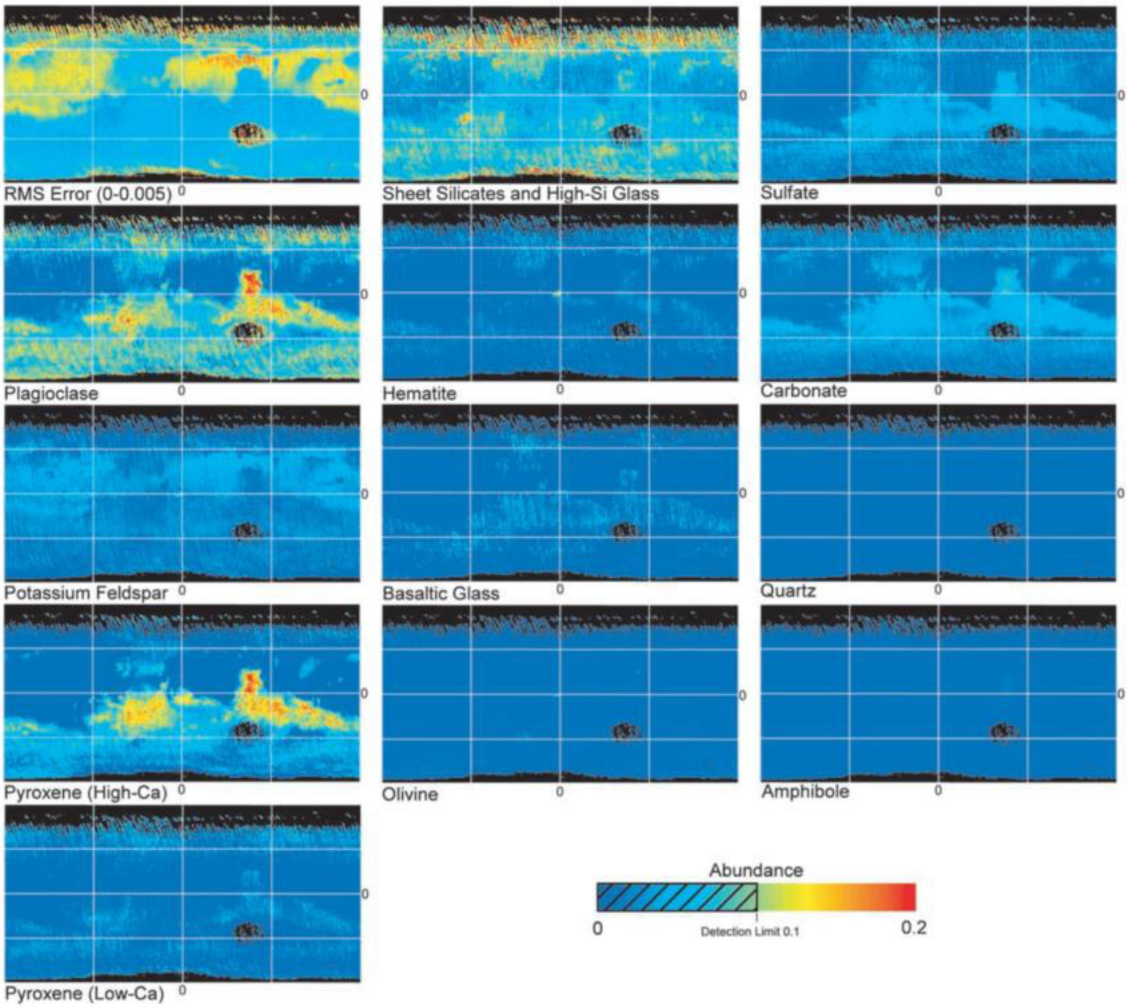

Figure 1: One pixel per degree binned global mineral concentration maps. The scale ranges from blue (concentration = 0) to red (concentration ≥ 0.2) except the RMS error image, which is 0 to 0.005 in emissivity from blue to red, respectively. Colors that are below the detection limit are hatched on the scale bar. The concentrations represent weightings relative to the mineral end-members used in the deconvolution. Mineral groupings are listed in Table 5 [20].

Table 4: Mineral Concentrations for Representative Pixels[a] [20].

	Group/Region													
	Arabia		Amazonis		Syrtis		Acidalia		Noachis		Solis		Sinus	
Quartz					0.01	1%	0.01	2%						
K-feldspar	0.05	–	0.03	–	0.01	1	0.03	5	0.03	7%	0.01	2%	0.06	12%
Plagioclase			0.02	–	0.27	35	0.16	26	0.13	28	0.12	26	0.08	16
Amphibole					0.03	4								
Low-Ca pyroxene					0.04	5	0.06	10	0.02	4	0.02	4	0.01	2
Hi-Ca pyroxene					0.20	26	0.04	6	0.05	11	0.04	9	0.06	12
Olivine														
Sheet/high-Si glass	0.02	–	0.06	–	0.06	8	0.17	27	0.17	37	0.20	43	0.04	8
Low-Si glass													0.01	2
Oxide					0.02	3	0.04	6					0.14	29
Sulfate	0.01	–	0.02	–	0.04	5	0.07	11	0.04	9	0.04	9	0.06	12
Carbonate			0.02	–	0.09	12	0.04	6	0.02	4	0.04	9	0.03	6
RMS error, %	0.46		0.24		0.15		0.23		0.16		0.12		0.17	

[a]The first column is the actual retrieved concentration, and the second column is the normalized abundance.

The chemical formulae for each specific mineral used in the set for comparison with the TES emissivity datasets are listed in Table 5.

Table 5: End-Members Used for Deconvolution of TES Emissivity Data Sets [20].

End-Member Category	Name	Chemical formula of End-Member mineral
Quartz	Quartz	SiO_2
Potassium feldspar	Microcline	$KAlSi_3O_8$
Plagioclase	Albite	$NaAlSi_3O_8$
	Oligoclase	$(Ca,Na)(Al,Si)_4O_8$
	Andesine	$(Ca,Na)(Al,Si)_4O_8$
	Labradorite	$(Ca,Na)Al(Si,Al)_3O_8$
	Bytownite	$(Ca,Na)[Al(Al,Si)Si_2O_8]$
	Anorthite	$CaAl_2Si_2O_8$
Amphibole	Actinolite	$Ca_2(Mg_{4,5\text{-}2,5}Fe^{2+}_{0,5\text{-}2,5})Si_8O_{22}(OH)_2$
Low-Ca pyroxene	Enstatite	$MgSiO_3$
	Bronzite	$(Mg,Fe)SiO_3$
High-Ca pyroxene	Diopside	$MgCaSi_2O_6$
	Augite	$(Ca,Na)(Mg,Fe,Al,Ti)(Si,Al)_2O_6$
	Hedenbergite	$CaFeSi_2O_6$
Olivine	Forsterite	Mg_2SiO_4
	Fayalite	Fe_2SiO_4
Sheet silicate/high-Si glass	Si-K glass (Potassium silicate)	K_2SiO_3
	Biotite	$K(Mg,Fe)_3(AlSi_3O_{10})(F,OH)_2$
	Muscovite	$KAl_2(AlSi_3O_{10})(F,OH)_2$
	Chlorite	$(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2\cdot(Mg,Fe)_3(OH)_6$
	Serpentine	$(Mg,Fe)_3Si_2O_5(OH)_4$
	Nontronite	$(CaO_{0,5},Na)_{0,3}Fe_2{}^{3+}(Si,Al)_4O_{10}(OH)_2\cdot nH_2O$
	Illite	$(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[((OH)_2,(H_2O)]$
Oxide	Hematite	Fe_2O_3
Sulfate	Anhydrite	$CaSO_4$
	Gypsum	$CaSO_4\cdot 2H_2O$
Carbonate	Calcite	$CaCO_3$
	Dolomite	$CaMg(CO_3)_2$

The feldspars detected were mostly intermediate to calcic plagioclase. Even though amphibole is included in the analysis, there is little evidence for the presence of it. Also included in the dataset was basaltic glass low in Silicon and various iron-rich clay-like minerals of the smectite group.

The work of *Al-Samir, et al., 2017* has identified sulfate deposits in the Juventae Chasma basin which are listed in Table 6 [22]. Evidence for the presence of the sulphates within the Juventae Chasma basin is provided both through spectrographic detection as well as further numerical analyses concerning processes during the basin's origin history.

Table 6: Chemical formulae of minerals discussed in [22].

Phase	**Formula**
Alunite	$KAl_3(OH)_6(SO_4)_2$
Anhydrite	$CaSO_4$
Epsomite	$MgSO_4 \cdot 7H_2O$
Gibbsite	$Al(OH)_3$
Gypsum	$CaSO_4 \cdot 2H_2O$
Hematite	Fe_2O_3
Hexahydrite	$MgSO_4 \cdot 6H_2O$
K-Jarosite	$KFe_3(SO_4)_2(OH)_6$
Na-Jarosite	$NaFe_3(SO_4)_2(OH)_6$
Kieserite	$MgSO_4 \cdot H_2O$
Melanterite	$FeSO_4 \cdot 7H_2O$
Mercallite	$KHSO_4$
MHSH(Mg_1)	Mg_1OHSO_4
Mirabilite	$Na_2SO_4 \cdot 10H_2O$
Misenite	$K_8H_6(SO_4)_7$
Szomolnokite	$FeSO_4 \cdot H_2O$
Thenardite	Na_2SO_4

The elements present within the minerals listed in Table 5 and Table 6 cover many of the macro-and micronutrients needed by higher plants, green algae and cyanobacteria. Namely, the macronutrients potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S) and the micronutrient Iron (Fe) for higher plants, green algae and cyanobacteria. The macronutrient sodium (Na) and micronutrient silicon (Si) for green algae are also present.

In conclusion, the presence of these elements within the Martian soil provides a fantastic opportunity to exploit the Martian regolith for the nutritional needs of higher plants, green algae and cyanobacteria within the context of BLSSs. The extraction of potassium, calcium, magnesium, sulphur, iron, sodium and silicon from the minerals listed in Table 5 and Table 6 will be evaluated within this thesis.

4 Multi Criteria Decision Analysis

To evaluate whether it is feasible, sustainable and worthwhile to extract the elements defined in chapter 3 for the nutritional needs of higher plants, green algae and cyanobacteria used in BLSSs, it is first necessary to define the method by which the extraction processes will be evaluated. When faced with the challenge of assessing alternatives to solve a given problem, selecting the most suitable alternative is rarely a straight-forward process. Multi Criteria Decision Making (MCDM) methods are designed to compare alternatives against one another on the basis of criteria which might not be comparable at first glance. The most common example in MCDM textbooks is that of buying a mobile phone or a laptop. How does one compare the criteria such as cost and processing power against one another? MCDM methods use mathematical tools such as normalization and assigning criteria weights based on the decision makers choice and expertise to put an emphasis on certain criteria over others.

Many MCDM methods exist such as VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), Technique for Order Preference and Similarity to Ideal Solution (TOPSIS), Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) etc.. The method used for this thesis will be the Analytical Hierarchy Process (AHP). The advantages of AHP in comparison to other methods are the intuitive approach of how the importance of criteria is designated and a built-in technique to verify the method's consistency with the help of the so-called Consistency Ratio. The Consistency Ratio is an indicator of how conclusive and therefore reliable the judgements of the decision makers are that devised the values of the importance of the criteria. Furthermore, the final weightage of the criteria is not directly defined based on the decision makers subjective judgement, experience and expertise alone but is derived from a pairwise comparison of the criteria's importance against one another [23]. This approach offers an excellent opportunity for discussing each criterion's importance in regards to the overall goal and other criteria. The thought process of the decision makers is easily accessible and transparent compared to more straight-forward methods. The pairwise comparison can be done with the consensus of multiple experts to avoid individual biases and subjective opinions as much as possible. The criteria's importance within the pairwise comparison matrices discussed in chapters 4.1.1 to 4.1.3 were done in cooperation with the thesis' supervisors.

What gives the AHP analysis its name is the hierarchical structure of its criteria and sub-criteria. The inherent challenge in problems to which MCDM methods are applied is the possibility of criteria being very difficult to compare against one another. Sub-criteria and the concept of local and global weights address this issue by breaking down the criteria along different branches which can then be further split off into additional branches that bear sub-criteria. The branches group the different criteria into so called tiers. Determination of weights is done by comparing all (sub-)criteria within the same tier stemming from the same preceding criterion against one another. The first tier is comprised of the overall goal of the analysis, while the second tier encompasses criteria, the third tier the sub-criteria of the criteria in the second tier, and so on. The actual alternatives which are being analyzed are present in the last tier.

The next chapters will describe the process of how to conduct an AHP analysis step-by-step. Furthermore, the values assigned in each pairwise comparison matrix will be discussed and evaluated to illustrate the criteria by which the extraction processes for elements that can be used as nutrients for higher plants, green algae and cyanobacteria will be judged.

4.1 Analytical Hierarchy process procedure

Step 1:

Creating a hierarchical structure with the overall goal in the first tier, criteria in the second tier, sub criteria in the third and subsequent tier and the alternatives which are to be evaluated in this case extraction processes, in the final tier. See Figure 3 to Figure 7 for the hierarchical structure of the AHP analysis framework discussed in this thesis.

The extraction process alternatives will not be depicted within the figures, as they will be discussed in detail in chapter 5.

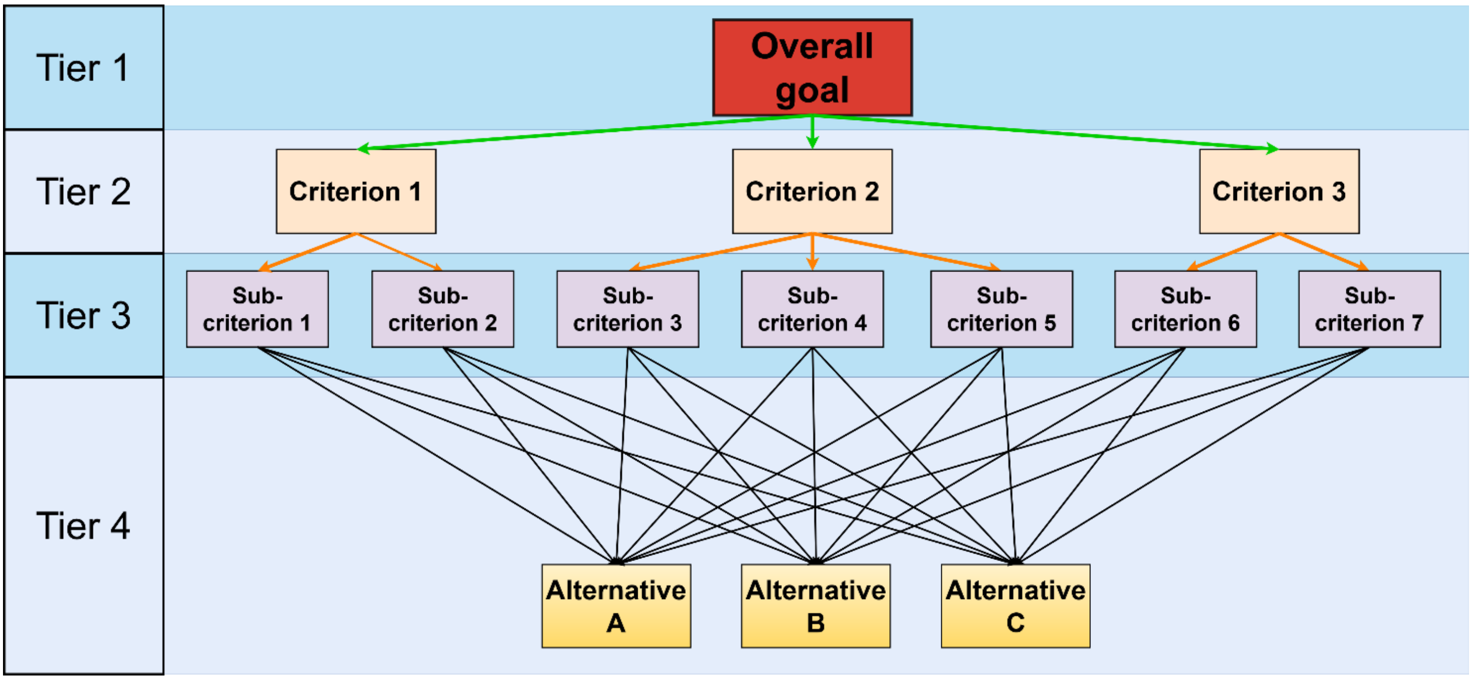

Figure 2: Exemplified hierarchy structure used for AHP analysis.

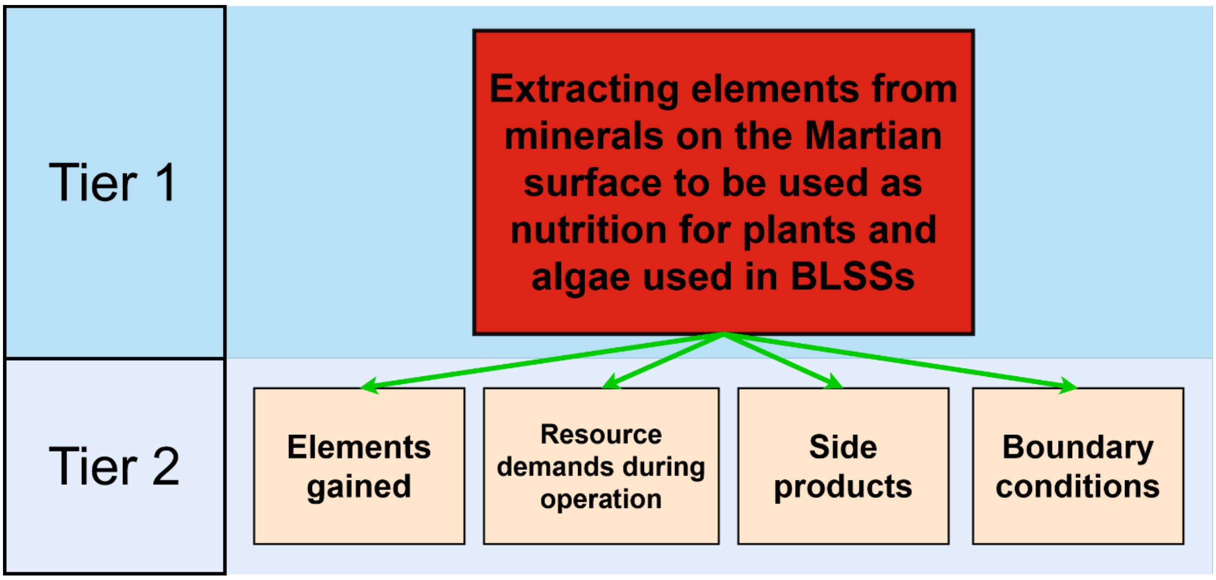

Figure 3: Tier 1 to Tier 2 of the hierarchical structure used for this thesis' AHP analysis.

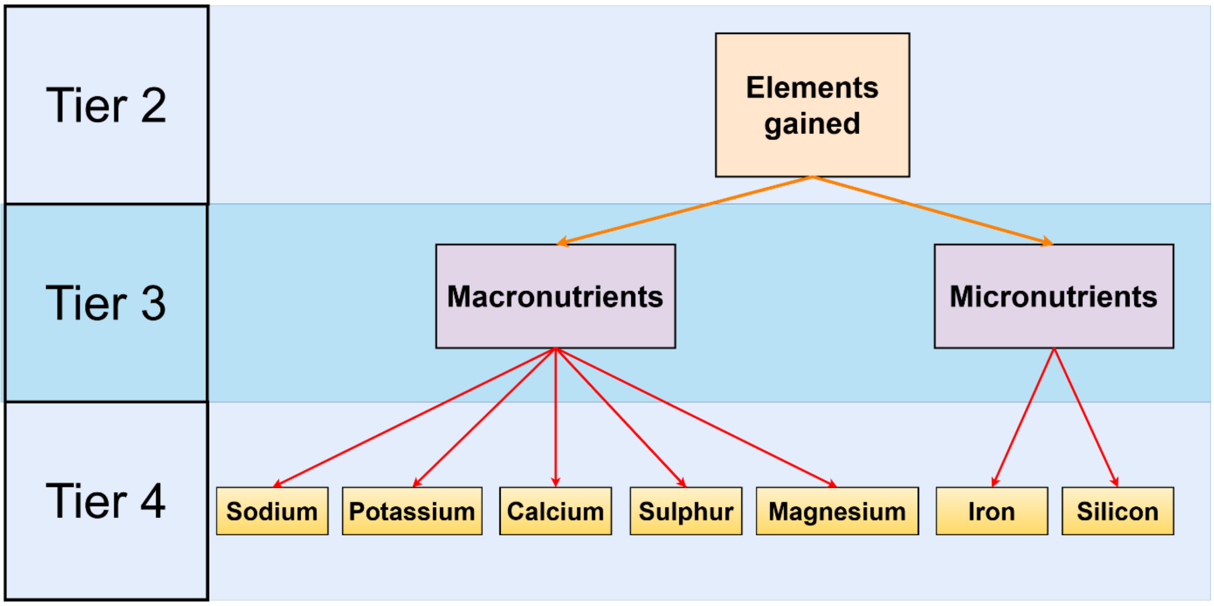

Figure 4: Tier 2 to Tier 4 of the first branch of the hierarchical structure used for this thesis' AHP analysis.

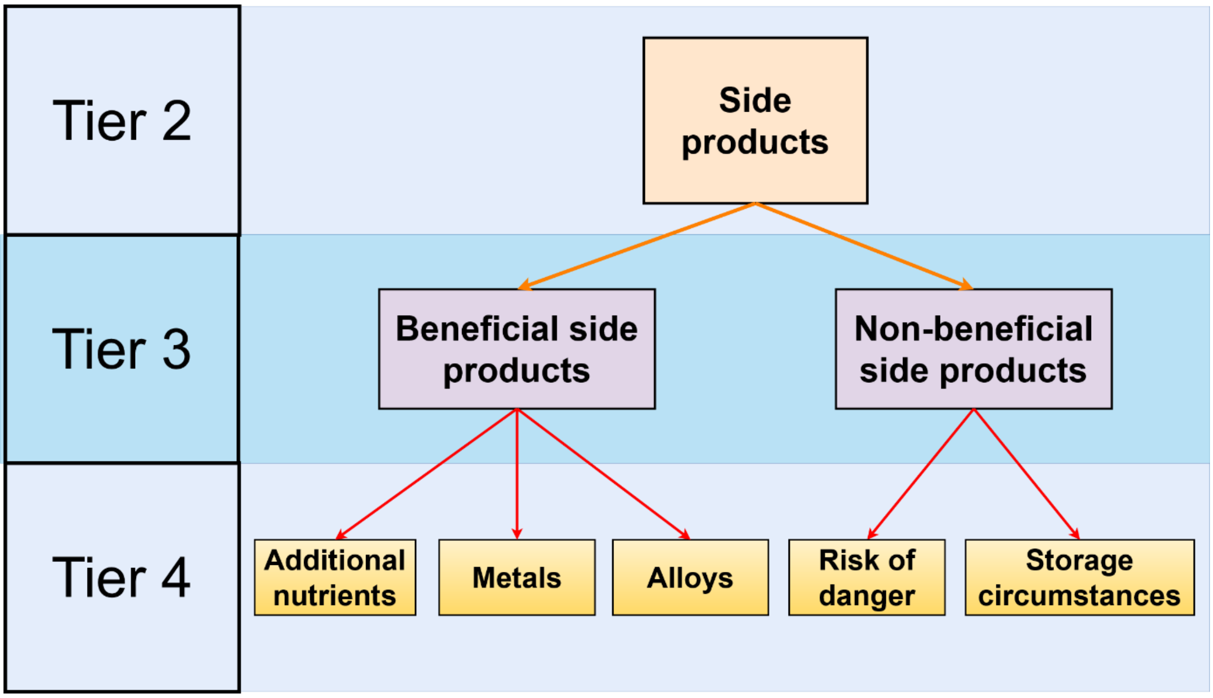

Figure 5: Tier 2 to Tier 4 of the second branch of the hierarchical structure used for this thesis' AHP analysis.

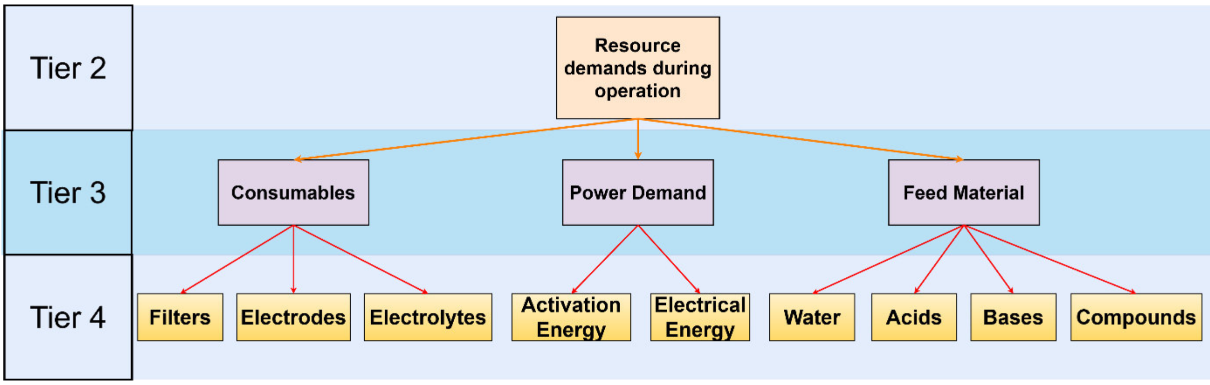

Figure 6: Tier 2 to Tier 4 of the third branch of the hierarchical structure used for this thesis' AHP analysis.

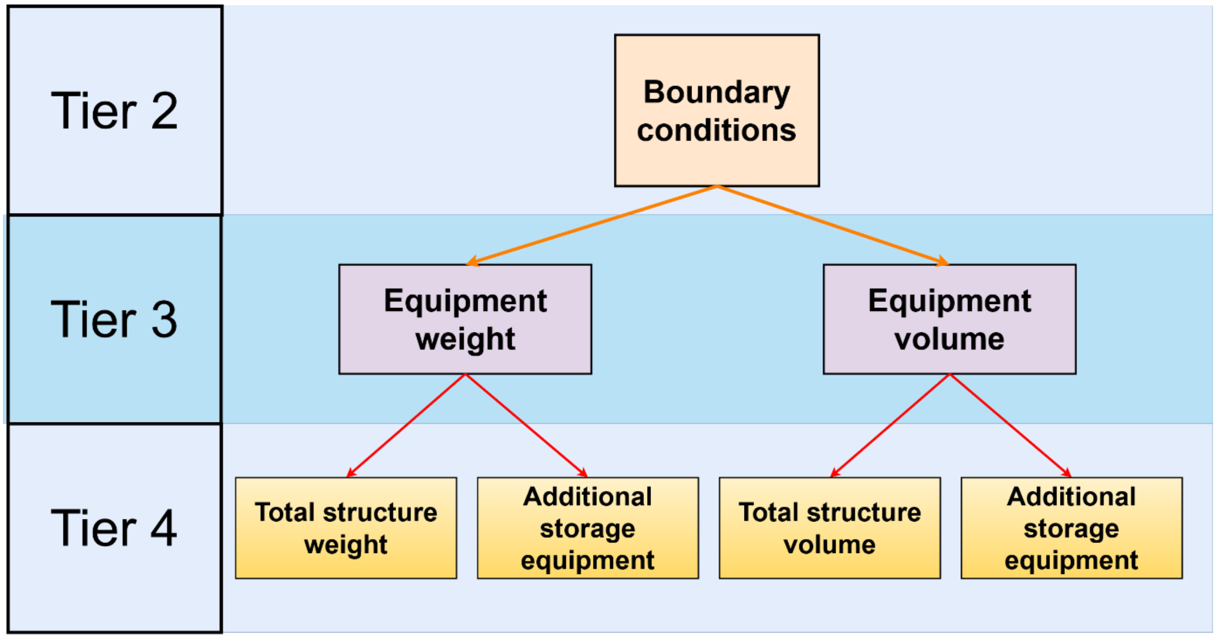

Figure 7: Tier 2 to Tier 4 of the fourth branch of the hierarchical structure used for this thesis' AHP analysis.

Step 2:

Assigning importance and calculating local weights within the so called pairwise comparison matrices for each group of (sub-)criteria. The pairwise comparison matrix indicates the importance of the criterion in the row against the criterion in the column. For example, in Table 7, sub-criterion 2 has a value of 5 in regards to sub-criterion 1. Respectively, the importance of sub-criterion 1 to sub-criterion 2 is reversed, in this case 1/5.

Table 7: Example of a pairwise comparison matrix for 3 sub-criteria.

	Sub-criterion 1	**Sub-criterion 2**	**Sub-criterion 3**
Sub-criterion 1	1	1/5	7
Sub-criterion 2	5	1	1/2
Sub-criterion 3	1/7	2	1

The value 5 in Table 7 does not mean that “sub-criterion 2 is 5 times more important than sub-criterion 1”. The definition of values used for assigning importance in pairwise comparison matrices ranges from 1 to 9 and their significance is depicted in Table 8.

Table 8: The so called "Saaty rating scale" used for pairwise comparison matrices in AHP analyses [23].

Intensity of importance	**Definition**	**Explanation**
1	Equal importance	Two factors contribute equally to the objective
3	Somewhat more important	Experience and judgement slightly favour one over the other
5	Much more important	Experience and judgement strongly favour one over the other
7	Very much more important	Experience and judgement very strongly favour one over the other. Its importance is demonstrated in practice.
9	Absolutely more important	The evidence favouring one over the other is of the highest possible validity
2, 4, 6, 8	Intermediate values	When compromise is needed

The local weights of the sub criteria of a pairwise comparison matrix are the eigenvector values of the matrix. To bypass the calculation of the eigenvector, [23] utilizes an approximation method.

The product of the elements of each row is calculated and the *n*-th root of the product taken. Let this product be called a_n where n = {1,2,…,N} and N equals the order of the pairwise comparison matrix. The local weights for each sub-criterion are then calculated with the formula

$$\frac{a_n}{\sum_{i=1}^{N} a_n} \quad (2)$$

for every n = {1,2,…,N}. Table 9 shows this procedure applied to the sub-criteria of Table 7. The value for $\sum_{i=1}^{N} a_n$ equals 4,332 in this example.

Table 9: Local weights of the sub-criteria used as an example for a pairwise comparison matrix in Table 7.

	Sub-criterion 1	**Sub-criterion 2**	**Sub-criterion 3**	a_n	**Local weights**
Sub-criterion 1	1	5	6	3,107	0,7172
Sub-criterion 2	1/5	1	3	0,8434	0,1947
Sub-criterion 3	1/6	1/3	1	0,3816	0,0881

As can be seen in Table 9, in this example the most emphasis is put on sub-criterion 1, indicated by the highest local weight of 0,7172. Sub-criterion 3 is the least important as is indicated by the lowest local weight of 0,0881.

Step 3:

After the local weights have been calculated and assigned, the consistency check of the pairwise comparison matrix is done to evaluate the validity of the pairwise comparison and therefore if the assigned importance values are trustworthy and consistent.

Let the pairwise comparison matrix be called *A* and the vector containing the local weights (which is also the eigenvector of *A*) ω. For a consistent matrix, the expression $A\omega = \lambda_{max}\omega$ with $\lambda_{max} = N$ holds true. The difference between λ_{max} and N indicates the degree of inconsistency involved in the process of assigning importance to sub-criteria in a pairwise comparison matrix.

An approximate value of λ_{max} is obtained by calculating the product of $A\omega$, dividing the entries of the resulting vector by their respective local weights/eigenvector values and then taking the average of these estimations to receive and approximate value for λ_{max}.

The transposed product of $A\omega$ for the pairwise comparison matrix A presented in Table 7 and the local weights ω calculated in Table 9 is presented in Table 10.

Table 10: Product of the pairwise comparison matrix A presented in Table 7 and the local weights ω calculated in Table 9.

2,219	**0,6024**	**0,2725**

Dividing these values by their respective local weights gives the transposed vector:

Table 11: Approximate values for λ_{max}.

3,094	**3,094**	**3,093**

Finally, the average of the different values for λ_{max}, which is called $\lambda_{max,avg}$ is calculated to receive an adequate approximation according to the formula:

$$\lambda_{max,avg} = \left|\frac{\sum_{i=1}^{N} \lambda_{max,i}}{N}\right| \quad (3)$$

With the values of $\lambda_{max,i}$ for i= {1,2,…,N} being the entries of the vector presented in Table 11 and N being the order of the pairwise comparison matrix A. In this example, $\lambda_{max,avg}$ equals 3,094. The consistency index (CI) is calculated according to the formula:

$$\left|\frac{\lambda_{max,avg} - N}{N-1}\right| \quad (4)$$

Comparing the consistency index of the pairwise comparison matrix to consistency indices of randomly generated pairwise comparison matrices of the same order, allows to validate the trustworthiness of the priorities assigned by the decision makers in the pairwise comparison matrix. This comparison is done by calculating the so-called consistency ratio (CR) with formula (5).

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \quad (5)$$

The consistency indices for randomly generated pairwise comparison matrices called the random index (RI) of the orders 1 to 15 are given in Table 12.

Table 12: Saaty's table for CR calculation [23].

Random Index (RI)	Order of the random pairwise comparison matrix
0,00	1
0,00	2
0,58	3
0,90	4
1,12	5
1,24	6
1,32	7
1,41	8
1,45	9
1,49	10
1,51	11
1,48	12
1,56	13
1,57	14
1,59	15

In this example, CI equals 0,047 resulting in a value for CR of 0,0810 which means that the judgements applied in the pairwise comparison matrix in Table 7 are trustworthy and consistent. The requirement for a consistent and trustworthy judgement within a pairwise comparison matrix is CR $> 0{,}10$ [23].

Step 4:

After the local weights of all sub-criteria along every branch are evaluated, their global weight needs to be calculated. The local weights, express the importance of a criterion in regards to the other criteria of the same tier, along the same preceding branch. The relevance of a sub-criterion of one branch to a sub-criterion of a completely different branch is expressed through the global weight of the sub-criterion.

For example, let the exemplified pairwise comparison conducted in Table 7 present the sub-criteria of a hypothetical “criterion A” within the second tier of an AHP analysis as depicted in Figure 8.

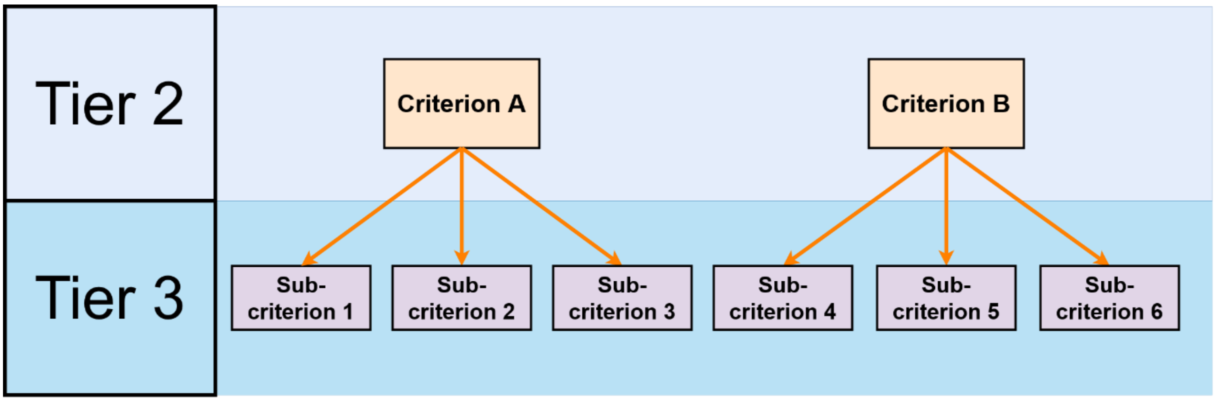

Figure 8: Example of six sub-criteria belonging to different branches within an AHP hierarchy.

When comparing sub-criteria 1 to 6 against one another, it is important to encompass the local weights of criteria A and B, devised from the pairwise comparison matrix of the second tier. Let the local weight of criterion A be called w_A and the local weight of sub-criterion 1 be called w_{A1}, the local weight of sub-criterion 2 w_{A2} and so forth. During the final comparison of all sub-criteria, the global weight of a sub-criterion is calculated by multiplying the values of local weights along a given branch.

Table 13: Illustrative example of the calculation of global weights of the sub-criteria depicted in Figure 8.

	Local weight	**Global weight**
Sub-criterion 1	w_{A1}	$w_A \cdot w_{A1}$
Sub-criterion 2	w_{A2}	$w_A \cdot w_{A2}$
Sub-criterion 3	w_{A3}	$w_A \cdot w_{A3}$
Sub-criterion 4	w_{B1}	$w_B \cdot w_{B1}$
Sub-criterion 5	w_{B2}	$w_B \cdot w_{B2}$
Sub-criterion 6	w_{B3}	$w_B \cdot w_{B3}$

In the following chapters, the importance of all criteria within their respective pairwise comparison matrices of the AHP framework presented in Figure 3 to Figure 7 is discussed.

4.1.1 Pairwise comparison matrices of the fourth tier

Table 14: Pairwise comparison matrix for the subcriteria of the criterion "Macronutrients".

	Sodium	**Potassium**	**Calcium**	**Sulphur**	**Magnesium**
Sodium	1	4	1/4	4	1/5
Potassium	1/4	1	1/5	4	1/6
Calcium	4	5	1	6	1/4
Sulphur	1/5	1/4	1/6	1	1/7
Magnesium	5	6	4	7	1

Side products that result from feed material which are brought from earth and could potentially be used as nutritional resources for higher plants, green algae and cyanobacteria will not be incorporated in this pairwise comparison matrix. Only the elements that are present in the minerals of the Martian surface will be included. This pairwise comparison matrix prioritizes exploiting the locally available mineral abundancies to their fullest potential. To encompass this, the importance of each macronutrient was characterized in regards to the Martian minerals' abundance as discussed in *Bandfield, 2002* [20]. The specific compositions of the compounds of the "Sheet Silicate and High-Si glass", "Pyroxene High Ca" and "Plagioclase" mineral groups were evaluated for particularly abundant elements. As can be seen in Figure 1, these mineral groups are the most abundant on the Martian surface and the extraction of elements which are present within this group should be prioritized. While it is true that even within the categories of macronutrients and micronutrients certain elements are required in higher amounts than other elements, as stated in chapter 2 the nutrients required by higher plants, green algae and cyanobacteria will not be classified beyond the categories of macronutrients and micronutrients. The importance distribution of the macronutrients in Table 14 is done according to the abundance of the elements' presence within the most common mineral groups ("Sheet Silicate and High-Si glass", "Pyroxene High Ca" and "Plagioclase). This approach aims at accommodating both the nutritional needs of higher plants, green algae and cyanobacteria as well as putting an emphasis on the most present mineral groups on the Martian surface, to encourage utilizing the resources available on the Martian surface to the fullest.

Magnesium is abundant in the "Sheet Silicate and High-Si glass" as well as the "Pyroxene High Ca" group and is accordingly given the most importance in this pairwise comparison matrix.

Globally, sulphur is one of the rarest elements which is why it's given the lowest priority.

Potassium is also quite rare overall. Still, numerous extraction processes with the goal of utilizing potassium as a nutrient source for terrestrial agriculture exist, as will become evident in chapter 5. Potassium is therefore ranked higher than sulphur. Calcium is particularly present in the "Pyroxene High Ca" and "Plagioclase" groups while sodium is abundant in the latter group. Calcium and sodium are therefore ranked as the second and third most important criterion respectively.

Table 15: Pairwise comparison matrix for the subcriteria of the criterion "Micronutrients".

	Iron	**Silicon**
Iron	1	4
Silicon	1/4	1

Out of the two elements present that can be classified as micronutrients for higher plants, green algae and cyanobacteria, silicon is more abundant than iron. See Table 5. However, iron can be utilized for more applications than serving as a nutrient source for the cultivation of organisms in BLSSs. Specifically, for the construction of infrastructure or as an electrical conductor. Thus, iron is prioritized slightly over silicon.

Table 16: Pairwise comparison matrix for the subcriteria of the criterion "Consumables".

	Filters	**Electrodes**	**Electrolytes**
Filters	1	1/6	1/5
Electrodes	6	1	3
Electrolytes	5	1/3	1

Among these three criteria, electrodes require the most specific processes to be produced. Electrolytes demand water, a very valuable resource during a crewed mission on the surface of Mars. Even though filters may very likely be the consumable with the shortest life cycle of these three criteria, the demand for valuable resources such as copper for electrodes and water for electrolytes places a stronger emphasis over these two criteria compared to filters.

Table 17: Pairwise comparison matrix for the subcriteria of the criterion "Power demand".

	Activation Enegery	**Electrical Energy**
Activation Energy	1	1/7
Electrical Energy	7	1

The activation energy required for a chemical reaction to occur is a value that needs to be considered in the calculation of the energy balance calculation for a given process. However, the electrical power demand on the surface of Mars is a well-known problem as well as a critical part of any life support system concept, given the environmental circumstances on the Martian surface [24]. The electrical energy criterion in this pairwise comparison matrix is therefore evidently more important.

Table 18: Pairwise comparison matrix for the sub-criteria of the criterion "Feed material".

	Water	**Acids**	**Bases**	**Compounds**
Water	1	8	8	6
Acids	1/8	1	4	1/7
Bases	1/8	1/4	1	1/7
Compounds	1/6	7	7	1

Within the framework of this thesis' AHP analysis, the "Feed material" criterion encompasses the four sub-criteria water, acids, bases, and compounds. The sub-criterion "compounds" could be further classified into "Liquid compounds", "Solid Compounds" and "Gaseous compounds". In the context of this AHP analysis, the various problems and considerations that come with feed material compounds of different phases (liquid, gaseous and solid) are covered by criteria of other pairwise comparison matrices. Should a compound be hazardous or difficult to transport and store due to factors such as toxicity, flammability or reactivity with other chemicals the "Additional storage equipment" sub criteria will encompass these complications.

The use of acids and bases outside of chemical production processes is limited. Water on the other hand is a resource required by many different aspects of a life support system as well as other segments of an extraterrestrial mission. Not only for consumption by the crew or for the cultivation of higher plants, green algae and cyanobacteria, but also for potential propellant production [17]. Acids are more dangerous than bases and require special materials for storing and handling.

Out of these sub criteria, water is absolutely the most important one due to its significance within any life support system. Compounds are given the second highest importance due to their ability to introduce new elements into existing ISRU process chains in the form of side products and, by doing so, open up more synergy possibilities.

Regardless of the amounts of acids and bases needed for a given extraction process, acids should be given stronger consideration within this pairwise comparison matrix due to their dangerous nature.

Table 19: Pairwise comparison matrix for the sub-criteria of the criterion "Beneficial side products".

	Metals	**Alloys**	**Additional nutrients**
Metals	1	1/4	1/3
Alloys	4	1	4
Additional nutrients	3	1/4	1

Metals and Alloys are both materials that can be utilized in a variety of ways to support the infrastructure of a mission on the surface of Mars. Be it for constructing equipment and infrastructure In-situ, or as feed material for further processes. Identifying synergies between byproducts of extraction processes is a major part of optimizing the utility of resources that are present on site. In this case, on the surface of Mars.

Focusing on gaining a pure metal as a side product might make research and design on the further use of the element easier due to more accessible data on material properties. However, there should not be an emphasis on exclusively focusing on pure metals as byproducts of processes rather than alloys. The possibly required extra steps, energy, and equipment necessary may not be worth it. A good example of this concept is the extraction of potassium from a feldspar mineral as presented in *Samantray et al., 2020* [25]. Potassium is being extracted for the purpose of being used as a fertilizer, therefore there is no need to further separate the potassium from the chlorine in the final product potassium chloride (KCl). Similarly, a mechanical load which a piece of equipment might need to bear could just as well be taken by an alloy rather than a pure metal. This might make research and development more difficult as the material properties of an alloy might not be readily available in literature but better serves the optimization of resource utilization in the context of an extraterrestrial mission. The necessity for more complicated research is an acceptable tradeoff to more effective usage of available resources. In conclusion, an emphasis is put on alloys as a side product over elemental metals.

Gaining additional elements that can be used as nutrients for higher plants, green algae and cyanobacteria which may have been introduced to a process through a feed material brought from earth is an obvious asset to the overall goal of this analysis. To not overemphasize bringing additional nutrients through terrestrial feed materials into the production chain, additional nutrients are deemed less critical than alloys in this pairwise comparison matrix. The local mineral abundancies should be exploited to their fullest. Simply transporting the nutrients required by higher plants, green algae and cyanobacteria from earth would defeat this purpose.

Table 20: Pairwise comparison matrix for the sub-criteria of the criterion "Non-beneficial side products".

	Risk of danger	**Storage circumstances**
Risk of danger	1	1/5
Storage circumstances	5	1

There are certain scenarios in which a side product of a process can be deemed non-beneficial. When it is indeed impossible or very difficult to neither utilize a given element or compound any further nor remove it from the proximity of an extraterrestrial habitat, it is important to emphasize what in particular makes these byproducts non-beneficial. It could be that at a given time, the side product can simply not be utilized any further for any kind of process or purpose but removing it from the habitat or mission context is also not an option because it would cost additional power and infrastructure, or a proper disposal concept has not been developed yet.

When the side product does not only need to be stored but could also have toxic effects on human health, corrosive effects on equipment or pose a threat by being flammable, special storage and containment procedures need to be put in place.

Of course, this results in stricter requirements for storage and equipment concepts and materials but could also have a detrimental effect on the crew's psychological wellbeing. Being aware of a potentially hazardous material in your vicinity while being in an environmentally closed system results in additional stress and worry.

However, the risk of danger stemming from a non-beneficial side product is merely an added negative to the already negative consequences of using up physical volume and equipment for storage. The initial circumstances surrounding the adequate storage of a non-beneficial side product is therefore seen as a more important criterion.

Table 21: Pairwise comparison matrix for the sub-criteria of the criterion "Equipment weight".

	Total structure weight	**Additional storage equipment**
Total structure weight	1	5
Additional storage equipment	1/5	1

One of the goals of In-Situ Resource Utilization is to minimize the amount of equipment, consumables and any other kind of resources that need to be transported to an extraterrestrial environment through the use of spacecraft. A very simple but crucial aspect of how to characterize the capacity that's being occupied by consumables, or a piece of equipment is of course the weight itself and its supporting infrastructure.

Spacecraft require an immense amount of fuel, energy and therefore financial resources to lift a payload out of the gravity field of the earth. The supporting structure and propulsion system of a spacecraft can only facilitate a certain physical space and maximum weight of a payload. The maximum change of velocity in the Tsiolkovsky rocket equation is dependent on the ratio of the initial total mass including propellant and final total mass excluding propellant.

$$\Delta v = v_e \cdot \ln\left(\frac{m_0}{m_f}\right) \quad (6)$$

With Δv being the maximum change of velocity of a vehicle/spacecraft (without external forces acting upon it), m_0 the initial total mass including propellant, m_f the final total mass without propellant and v_e the effective exhaust velocity.

The total structure weight, be it machinery, storage equipment or a container for consumables, therefore takes higher priority in this pairwise comparison matrix. Should additional containers be required, for example if two certain chemicals must absolutely be stored separately, there are multiple ways of addressing this issue without giving up precious payload space and weight. For example, depending on the context of a mission, additional containers or equipment can simply be send on a second spacecraft.

Table 22: Pairwise comparison matrix for the sub-criteria of the criterion "Equipment volume".

	Total structure volume	**Additional storage equipment**
Total structure volume	1	5
Additional storage equipment	1/5	1

The same reasoning used to assign the importance of the sub-criteria in Table 21 can be applied to the pairwise comparison matrix of the sub-criteria of the “Equipment volume” criterion. Additional storage equipment could be transported on a seperate spacecraft should the context of a mission allow it. The total volume of a piece of equipment or storage container which cannot be reduced or split up any more takes a higher priority in this pairwise comparison matrix.

4.1.2 Pairwise comparison matrices of the third tier

Table 23: Pairwise comparison matrix for the sub-criteria of the criterion "Elements gained".

	Macronutrients	**Micronutrients**
Macronutrients	1	7
Micronutrients	1/7	1

The distribution of importance in this pairwise comparison matrix is straightforward. As explained in chapter 2, macronutrients are required in a larger quantity than micronutrients. This applies to higher plants as well as green algae and cyanobacteria. Therefore, a much stronger emphasis needs to be put on the extraction of macronutrients over micronutrients

Table 24: Pairwise comparison matrix for the sub-criteria of the criterion "Resource demands during operation".

	Consumables	**Power demand**	**Feed material**
Consumables	1	1/7	1/5
Power demand	7	1	6
Feed material	5	1/6	1

The supply of electrical power on the Martian surface is of major importance to the infrastructure of crewed missions and continues to be a challenge. The production of electrical power through the use of nuclear reactions does not only bring complications along with it due to the radioactivity of the elements required but also generally faces a lot of skepticism and doubt by society. Relying solely on electricity generated by sunlight is difficult on the Martian surface due to day-night cycles and dust storms [24]. Life support systems need to be continuously supplied with electrical power. Therefore, “Power demand” definitely holds the highest importance within this pairwise comparison matrix.

For certain extraction processes, feed material is required to be brought along from earth and cannot be excluded. The same applies to consumables such as filters, electrodes and electrolytes. Water is required as a feed material for certain processes. As described in the reasoning of the emphasis distribution for Table 18, water is an invaluable resource during an extraterrestrial mission. This makes the “Feed material” criterion more important than the “Consumables” criterion.

Table 25: Pairwise comparison matrix for the sub-criteria of the criterion "Side products".

	Beneficial side products	**Non-beneficial side products**
Beneficial side products	1	8
Non-beneficial side products	1/8	1

When considering beneficial and non-beneficial side products of a given process, it is important to distinguish whether it is more important to strive for the beneficial criterion or to avoid the non-beneficial one. Prioritizing beneficial side products when evaluating extraction processes for elements that can be used as nutrients for higher plants, green algae and cyanobacteria opens up more synergy possibilities as more components are introduced to the production chain.

One should not avoid possibilities of utilizing the resources present on site merely because the extraction processes to do so require reagents that need be brought from earth or produce a lot of side products but see it as an opportunity to further built upon these side products and utilize previously unexposed synergies. The potential of discovering new production possibilities with beneficial side products is prioritized over avoiding non-beneficial side products.

Table 26: Pairwise comparison matrix for the sub-criteria of the criterion "Boundary conditions".

	Equipment weight	**Equipment volume**
Equipment weight	1	5
Equipment volume	1/5	1

A big volume is often directly associated with a high weight value. However, space engineering application designs strive to minimize weight wherever possible. Be it for machinery, equipment, structure, or containers. Lightweight construction often sacrifices factors such as low production costs and mechanical load capacity to utilize low-density materials and in turn reduce the weight of the final product.

For certain processes, machinery and equipment may need to be made out of a certain material to withstand loads created by heat or to avoid reacting with a specific chemical. The same applies to storage containers for consumables or feed materials. In this case, the material out of which the equipment is constructed is of critical importance and cannot be changed in favor of reducing the overall weight.

Volume does not necessarily contribute to a higher weight value and as previously mentioned, the factors that may potentially increase weight dramatically are often critical. To emphasize this, equipment weight has been given a higher importance than equipment volume.

4.1.3 Pairwise comparison matrices of the second tier

Table 27: Pairwise comparison matrix for the criteria of the Analytical Hierarchy Process' goal, "Extracting elements from minerals on the Martian surface to be used as nutrition for plants and algae used in BLSSs".

	Elements gained	**Resource demands during operation**	**Side products**	**Boundary conditions**
Elements gained	1	6	8	7
Resource demands during operation	1/6	1	7	6
Side products	1/8	1/7	1	1/5
Boundary conditions	1/7	1/6	5	1

Beyond the direct goal of this thesis to evaluate the potential use of Martian soil for nutrient supply for higher plants, green algae and cyanobacteria used in concepts for BLSSs, the subsequent indirect aim is to aid in improving sustainability of long-term human space exploration missions on the surface of Mars.

The least emphasis will be put on the "Side products" criterion. Gaining beneficial side products or minimizing non-beneficial side products is of course a nice benefit, however evaluating the fundamental needs of higher plants, green algae and cyanobacteria used in BLSSs on the surface of Mars needs to be prioritized. Therefore, the criterion "Elements gained" is given the most emphasis in this pairwise comparison matrix. The two remaining criteria "Boundary conditions" and "Resource demands during operation" encompass the difficulties of human space exploration missions such as limited resupply opportunities and payload capabilities. As the utilization of Martian soil for the nutritional demand of higher plants, green algae and cyanobacteria of BLSSs directly impacts the resources that are required for the corresponding extraction processes, the criterion "Resource demands during operation" has been assigned the second highest importance.

5 ISRU Extraction methods for elements to be used as nutrients

The concept of In-Situ Resource Utilization strives to utilize the circumstances of a given scenario to their fullest potential. The most common example of ISRU technology is the utilization of sunlight to produce electrical energy through the use of solar cells onboard a spacecraft.

Extraterrestrial ISRU applications on the surface of a planet, can be classified in three categories. Excavation, beneficiation and extraction. Excavation refers to the procurement of material, that will serve as feed material in later steps down the production line [26]. In this case, regolith from the Martian surface. Beneficiation processes prepare the excavated material for the extraction step [27]. This can be done by making sure that the feed material is as free of impurities as possible or separating the material gained from the excavation step on the basis of characteristics such as particle size. Extraction processes are applied to obtain desired resources from the locally available materials after having gone through the beneficiation step. In this case, the desired resources are elements that can be used as nutrients for higher plants, green algae and cyanobacteria used in BLSSs. This thesis focusses on extraction processes.

In the following chapters, the possibilities of extracting the elements defined in chapters 2.1 and 2.2 from the minerals presented in chapter 3 are compiled and discussed.

5.1 Indirect extraction processes

Often times, the extraction of the elements defined in chapters 2.1 and 2.2 were either an intermediate step of the respective paper's objective [28–31] or the end products of the process are not suited to provide nutrition to higher plants, green algae, and cyanobacteria. In the latter case, the process' end product was often times an oxide of the desired element [28, 32–34]. These oxides may be implemented as feed material for additional processes to extract the desired element and potentially oxygen as a side product. Some of the papers had entirely different objectives than the extraction of a certain element but used extraction methods within their argumentation, such as for the classification of minerals in the context of a geological study [35]. Other studies merely showcased possible chemical reactions aimed at extracting the desired elements [32, 36, 37].

The processes presented in this chapter serve to exhibit and demonstrate that extracting the relevant elements as discussed in chapters 2.1 and 2.2 from the minerals on the Martian surface is possible. Most of the processes only incorporated very small quantities of the reagents and minerals. Conditions and data for large-scale production processes cannot be extrapolated from small-scale studies meant to investigate fundamental procedures.

An overview of which elements from which minerals with which reagent and extraction process is extractable is given in Table 28. If the paper conducted a study on the effectiveness of multiple different reagents, all of the reagents that were studied are listed. As this list serves merely as a showcase a discussion on which reagent is the most effective within a specific study will not be held.

Table 28: Summary of possible extraction processes for elements that could be used as nutrition for higher plants, green algae and cyanobacteria from the minerals present on the Martian surface.

Resulting compound	Mineral	Reagents	Procedure	Source paper
Ca^{2+}, Mg^{2+} (Within liquid extraction solution)	Mine tailing mix of anorthite, albite, enstatite, diopside, serpentine-lizardite and clay-talc	Ammonium sulfate ($(NH_4)_2SO_4$) Water	Heat treatment and subsequent leaching	[30]
Ca^{2+} rich aqueous solution.	Wollastonite	Acetic acid (CH_3 COOH) Nitrilotriacetic acid ($C_6H_9NO_6$) Picolinic acid ($C_6H_5NO_2$) Iminodiacetic acid ($HN(CH_2CO_2H)_2$) Ethylenediaminetetraacetic acid ($C_{10}H_{16}N_2O_8$) Gluconic acid ($C_6H_{12}O_7$) Phthalic acid ($C_8H_6O_4$) Citric acid ($C_6H_8O_7$) Ascorbic acid ($C_6H_8O_6$) Glutamic acid ($C_5H_9NO_4$) Oxalic acid ($C_2H_2O_4$)	Leaching	[29]
$MgAl_2O_4$, MgO, Si	Forsterite	Aluminium (liquid)	Presentation of theoretically possible chemical reaction	[32]
MgO, CaO, SiC	Forsterite	Calcium carbide (CaC_2)	Presentation of theoretically possible chemical reaction	
MgO, Ca_2SiO_4	Forsterite	Calcium oxide (CaO)	Presentation of theoretically possible chemical reaction	
K_2O	Feldpsar (Mostly microcline, minor amount of albite and quartz)	Calcium chloride ($CaCl_2$) (heat treatment additive) Sodium chloride (NaCl) (heat	Heat treatment with additive and subsequent leaching	[28]

		treatment additive) Water (leaching solution)		
SiO_2 (in the solution)	Potash feldspar (Major phases: Microcline and albite. Minor phase: Dissociative silica)	Sodium carbonate (Na_2CO_3) (heat treatment additive) Sodium hydroxide (NaOH) (leaching solution)	Heat treatment with additive and subsequent leaching	[33]
Na_2O, K_2O	Albite, anorthosite (Major phases: anorthite, andesine and labradorite. Minor phases: High-Ca pyroxene, ilmenite, magnetite, and olivine)	Lithium hydroxide monohydrate ($LiOH \cdot H_2O$)	Leaching in a pressurized and heated vessel	[34]
Ca, Mg, Na, K (each in cationic form)	Olivine (mix of forsterite and fayalite), enstatite, diopside, augite, actinolite, microcline, anorthoclase (mix of albite and orthoclase), albite, oligoclase, calcite and dolomite	Ammonium acetate (NH_4OAc) Sodium acetate (NaOAc) Water	Leaching	[35]
$CaO.(SiO_2)_3$, Fe	Fayalite	Calcium Carbide (CaC_2)	Presentation of theoretically possible chemical reaction	[36]
Si, Ca, Mg, Fe, Na (within the solution)	Basalt containing: Quartz, olivine, sanidine, amphibole, hematite, labradorite 55, albite, anorthite, augite [38]	Hydrochloric acid (HCl) with or without the addition of calcium chloride (CaCl)	Physicochemical simulation of leaching procedure	[37]
Fe^{2+} (from szomolnokite), Na^{+}, Fe^{3+} (from na-jarosite)	Szomolnokite, na-Jarosite	Water (used for szomolnokite), Aqua regia (HNO_3+3 HCl) and water (used for na-jarosite)	Leaching	[31]

A notable example is present in the case of the “Alternative ÅA Route”, which aims at storing carbon dioxide (CO_2 in an effort to combat terrestrial climate change [30]. Calcium and Magnesium cations are extracted as an intermediate step; however, the end result of the process are various magnesium and calcium carbonates. The specific form of the carbonates is dependent on the source mineral. As the Martian Atmosphere is rich in CO_2, this process could be well applied should magnesium and calcium carbonates be required resources within a mission scenario on the Martian surface.

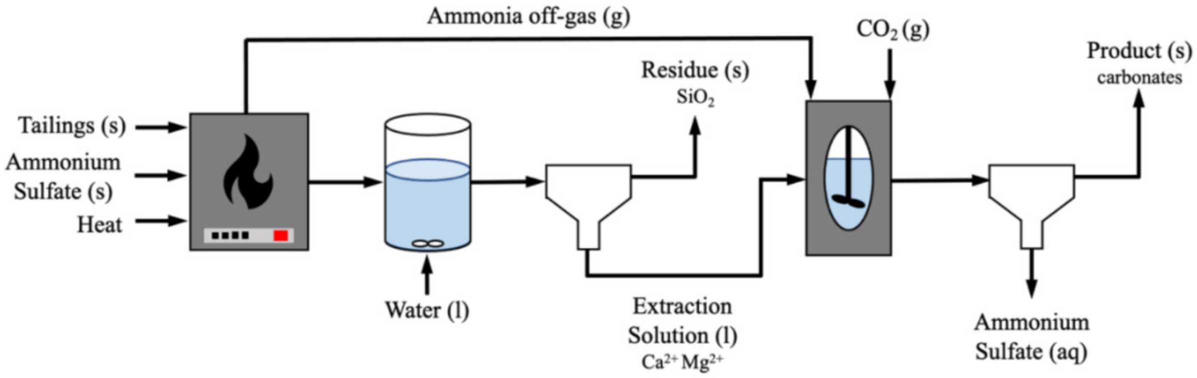

Figure 9: Process Flow Diagram of Alternative ÅA Route [30].

The process studied by *Jena et al., 2019* react microcline in two separate instances with sodium chloride and calcium chloride respectively to bring potassium into a soluble form, which is potassium chloride (KCl) [28]. Potassium chloride can be used as a fertilizer to provide potassium to higher plants in soil cultivation [39]. The extraction of compounds rather than elements can be beneficial when pursuing the goal of providing nutrition to higher plants, green algae and cyanobacteria as discussed within the importance distribution of the pairwise comparison matrix present in Table 19. This is why extraction processes that did not primarily focus on the extraction of the elements discussed in chapters 2.1 and 2.2 in their cationic form were included in this chapter.

In the processes presented in Table 28, the minerals were often treated using acids, water or other additives to extract the relevant elements. Introducing reagents such as acids that enable the extraction of relevant compounds to the production chain opens up the possibility for additional synergies. The reagents need to be brought from earth which at first glance might seem counter intuitive as one of the objectives of applying ISRU extractions on the surface of Mars is minimizing the dependence on resupply missions. However, when the resulting compounds of a process offer additional opportunities to benefit the needs of a mission scenario, a more complex production chain with additional resources might ultimately be more beneficial and sustainable. The processes described in [28, 32–34, 36] have oxides as the resulting compounds. Should feasible processes for the extraction of oxygen from the respective compounds exist, combining the two extraction steps could justify supplying the reagent as a terrestrial resource. Further research and analyses should take these opportunities into account when defining their objectives and criteria.

Heat treatment with or without additives can be a step involved in the extraction processes. This is often, but not exclusively, done to react a mineral into a more soluble form to then leach the desired elements. The apparatuses used in the processes were most often commercial laboratory equipment. While data on these devices exists, it is without question that machinery designed for small scale laboratory studies can neither be feasibly transported to the surface of Mars nor would their inclusion in a production chain benefit large scale production processes and will therefore not be discussed in detail.

5.2 Direct use of minerals as fertilizers

In order to provide nutritional resources to higher plants, the elements that can be used as macro-and micronutrients do not necessarily need to be extracted. Certain minerals present on the Martian surface can act as fertilizers in a variety of other ways.

A representative overview of the possibilities of providing nutrition to higher plants used in BLSSs by other means than the extraction of specific elements from the minerals present on the Martian surface is given in this chapter.

Epsomite has been used in studies as a magnesium source for apple trees, applied both as soil dressing as well as foliar spray [40–42].

Kieserite fertilizer is commercially available as either granulate or powder [43] and is applicable to a wide variety of soil but is unsuitable as foliar fertilizer or in fertigation systems [44].

A greenhouse study on the effectiveness of dolomite treated with microbes compared to kieserite fertilizer as a potential source of magnesium for cocoa plants and palm trees proposed high potential for the application of treating minerals with microbes to provide nutrition to these higher plants [45]. The same study mentions the possibility of using microbes to treat silicia and feldspar to solubilize silicon and potassium respectively.

Verdete rock consisting mainly of glauconite, microcline and quartz was studied as a potential source of potassium for eucalyptus, cropped maize and grass in a typic hapludox soil [39]. The verdete rock proved unsuitable as a potassium source for the maize and eucalyptus plants. However, thermal treatment with calcium chloride ($CaCl_2 \cdot H_2O$) and acidification with an acid industrial effluent respectively showed promise that the treated verdete rock could be used as a potassium fertilizer. This process may be applicable to the microcline and quartz present on the Martian surface.

In conclusion, possibilities for providing nutrition for higher plants on the Martian surface through other means than the extraction of specific elements exist in the form of producing fertilizers by treating minerals with microbes or chemicals reagents. Additional research is required in order to determine whether or not these possibilities are applicable to the precise mineralogical compounds present on the Martian surface.

The prospect of treating minerals with microbes to produce fertilizers will not be considered further in this thesis. The process does not classify as an extraction process and the handling of microbes requires additional considerations not considered in the AHP framework discussed in chapters 4.1 to 4.1.3.

The possibility of using epsomite and kieserite as a magnesium source for higher plants, should be accounted for by future ISRU excavation and beneficiation processes when considering the nutritional requirements of higher plants used in BLSSs.

5.3 Extraction processes

The processes that target the extraction of elements that can be used as nutrients for higher plants, green algae and cyanobacteria from the minerals present on the Martian surface which hold the most potential and synergy possibilities for BLSSs are presented in this chapter.

The investigation by *Orosco et al., 2019* aimed at developing a simple and low-cost process to extract potassium from microcline [46]. Calcite ($CaCO_3$) and microcline ($KAlSi_3O_8$) are mixed together and reacted with chlorine gas to produce anorthite ($CaAl_2Si_2O_8$), potassium chloride (KCl), Silica (SiO_2) as well as gaseous carbon dioxide (CO_2) and oxygen.

$$CaCO_3 + 2KAlSi_3O_8 + Cl_2(g) \rightarrow CaAl_2Si_2O_8 + 2KCl + 4SiO_2 + CO_2(g) + 0{,}5O_2(g) \quad (7)$$

The effect of heating during the reaction was investigated and the atmosphere within the furnace was a 50% chlorine and 50% nitrogen gas mixture. Optimal extraction of potassium chloride was achieved between 700 and 900 °C.

Applying this reaction for the extraction of potassium chloride would be an excellent opportunity to gain a potassium fertilizer for higher plants. Calcite as well as anorthite are both present on the Martian surface. As previously discussed, potassium chloride is a commonly used fertilizer for higher plants. Two of the side products of the reaction, anorthite and silica, are already present in mineral form on the Martian surface. These side products could be integrated in processes targeted at extracting elements such as silicon, oxygen and calcium and would not represent new components within existing production chains.

A similar reaction was investigated by *Samantray et al., 2020* [25]. A feldspar mainly consisting of microcline, orthoclase and quartz was reacted with calcite obtained from eggshells and hydrochloric acid (HCl), heat treated and leached with water. Potassium perchlorate ($KClO_4$) was precipitated with the help of sodium perchlorate ($NaClO_4$) and was thermally decomposed to receive crystalline potassium chloride (KCl). The process is illustrated in Figure 10.

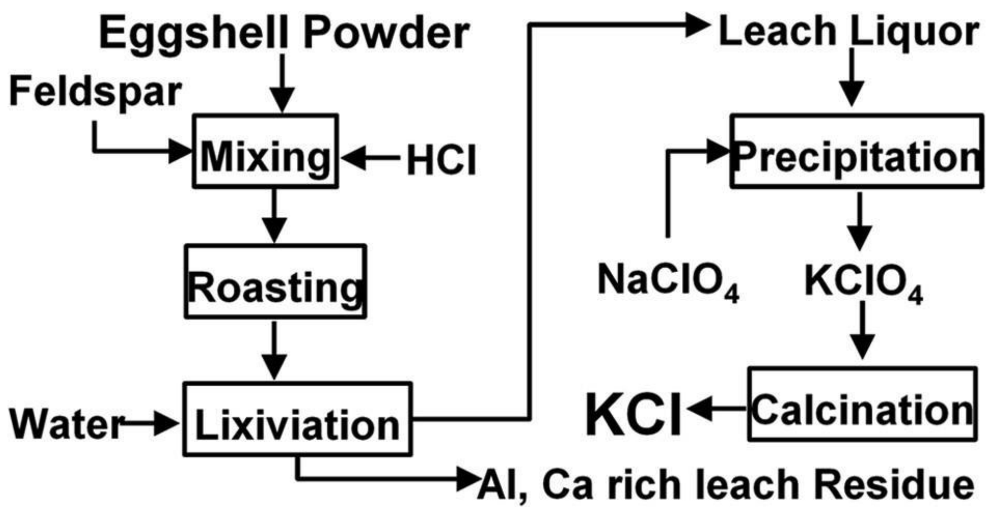

Figure 10: Flowchart for the extraction of potassium chloride from feldspar [25].

During the initial mixing, hydrogen chloride and calcite react to form calcium chloride ($CaCl_2$), which is the reagent necessary to extract potassium from the feldspar.

$$CaCO_3 + 2HCl \rightarrow CaCl_2 + CO_2\uparrow + H_2O \quad (8)$$

The carbon dioxide resulting from reaction 3 was reacted with a saturated aqueous solution of calcium hydroxide, commonly called lime solution ($Ca(OH)_2$) to gain additional calcite and water.

$$Ca(OH)_2 + CO_2\uparrow \rightarrow CaCO_3 + H_2O \quad (9)$$

This step requires lime solution as an additional resource. It is not feasible to transport lime solution to the Martian surface solely for the purpose of gaining more calcite, as it is already present as a mineral. The reaction that occurs during roasting is theorized to be:

$$2KAlSi_3O_8 + 2CaCl_2 + 0{,}5O_2 \rightarrow 2KCl + CaAl_2Si_2O_8 + 3SiO_2 + CaSiO_3 + Cl_2 \quad (10)$$

X-ray diffraction analysis has identified the aluminium and calcium rich leach residue to be composed of anorthite, quartz and wollastonite. During the thermal decomposition of potassium perchlorate in a furnace, oxygen was emitted.

$$KClO_4 \rightarrow KCl + 2O_2 \quad (11)$$

The leach liquor obtained after the lixiviation step was reported to contain considerable amounts of sodium and calcium, which were not extracted in the subsequent steps. Further research on the extraction of sodium and calcium from the leach liquor could make this process even more attractive for the application on the Martian surface than it already is. Microcline, quartz and calcite are already present on the Martian surface, but hydrochloric acid and sodium perchlorate would need to be transported to Mars. Additionally, water is required for the extraction process. However, the side products of this process are very attractive and could make contributing the valuable resource water worthwhile. Anorthite, quartz and wollastonite are already present as minerals and would not represent new components introduced to existing production chains. Additionally, the thermal decomposition step of potassium perchlorate releases oxygen which could be captured and further utilized.

Similarly to many of the processes presented in chapter 5.1, the extraction process described by *Duarte et al., 2022* uses oxalic acid ($C_2H_2O_4$) to extract potassium from verdete rock consisting mainly of potassium feldspar, muscovite, glauconite and quartz [47]. The reason why this process is discussed here and not in chapter 5.1, is because the potassium extraction is the main goal of the process and not an intermediate step or a side product.

Biotite is able to react with strontium nitrate ($Sr(NO_3)_2$) and hydrochloric acid (HCl) to replace potassium cations (K^+) with strontium cations (Sr^{2+}), thereby extracting potassium from biotite [48]. When the reaction takes place for a sufficiently long enough time (10 hours), the leached biotite transforms into vermiculite-type hydrated Sr-mica, which is suitable as material to produce electrodes such as button batteries and therefore a valuable side product of the potassium extraction.

A unique synergy in the context of a crewed space exploration mission exists in the possibility of mixing potassium silicate solution with carbamide (urea)($CO(NH_2)_2$) to produce a Si-K-N gel that can be used as a fertilizer [49]. The potassium silicate solution used in the study was obtained by heating silica (SiO_2) present within geothermal sludge with potassium hydroxide (KOH). After diluting the solution with demineralized water, carbamide was added and CO_2 was let into the reactor glass. The Si-K-N gel formed after aging for 24h and drying in an oven at 100 °C for another 24h. The procedure is displayed as a flowchart in Figure 11.

While a large amount of carbamide was used within this study (50g/75g per 1L potassium silicate solution), the presence of silica on the Martian surface in the form of quartz and the availability of carbamide from human waste products during a crewed space exploration mission is an exceptional synergy that should be considered when including the crew as a component within a BLSS.

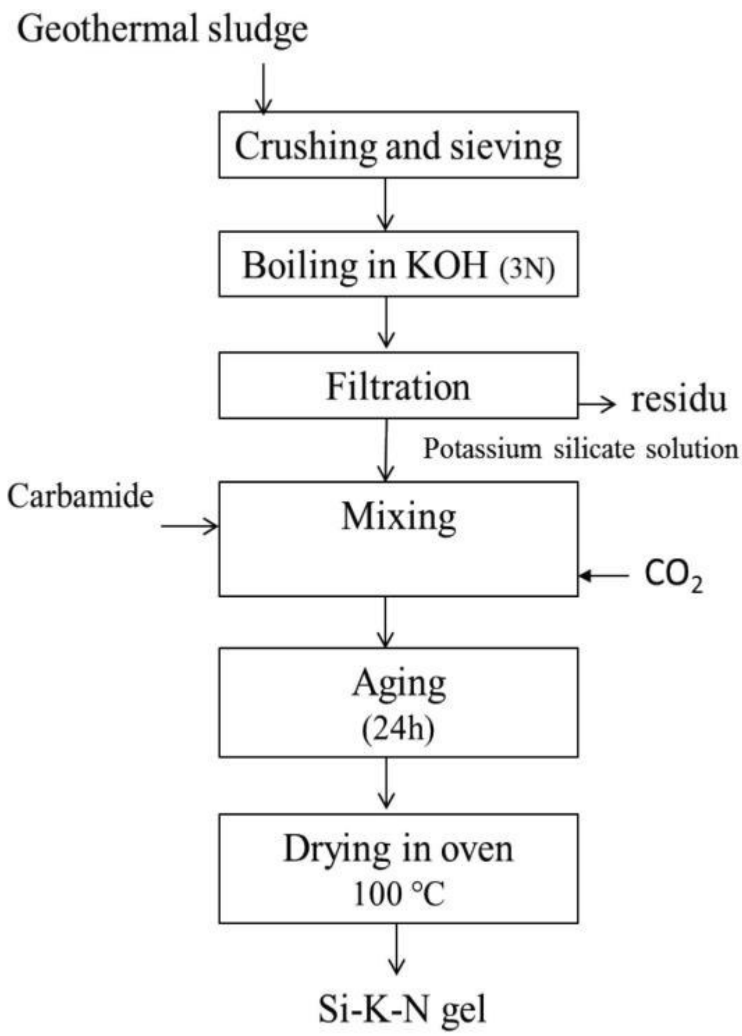

Figure 11: Diagram procedure of Si-K-N gel [49].

Potassium hydroxide was also used in an investigation on developing a closed-loop, green, gradient leaching recovery process for potassium from alunite tailings consisting mostly of potassium alunite, kaolinite and quartz [50]. The “green” refers to the minimization of energy and resource consumption needed for the process as well as the toxicity of the process’ by-products while “gradient leaching” means prioritizing the extraction of potassium and aluminium over the extraction of silicon. The removal of silicon from the leaching solution is difficult. Also, the extraction of potassium and aluminium is hindered when large amounts of silicon is released into the solution. The process uses a stainless-steel heatable batch reactor equipped with a magnetic stirrer to react the alunite tailings with potassium hydroxide and water at a specific temperature. The filters used for the filtration process were not specified.

Optimal conditions for the extraction of potassium and aluminium have a remarkably low reaction time and required temperature of 41,6 minutes and 81,8 °C.

The residue of the leaching process by potassium hydroxide solution is high in quartz and kaolinite which can then be fed to processes targeting the extraction of silicon.

As the design of this process pursues the development of a closed loop system, the expensive potassium hydroxide solution is recirculated as much as possible by evaporating and concentrating the mother liquor of the crystallization process depicted in Figure 12. If this process were to be integrated into a production chain on the surface of Mars, the further usage of the water vapor created during the evaporation of the leaching filtrate should be taken into account as a possible opportunity to recover water.

The application of the resulting compounds K_2SO_4 and $Al(OH)_3$ has not been discussed within the design of the process. The applicability as a fertilizer or further extraction processes to recover potassium and sulphur from these compounds need to be taken into account by further additional research.

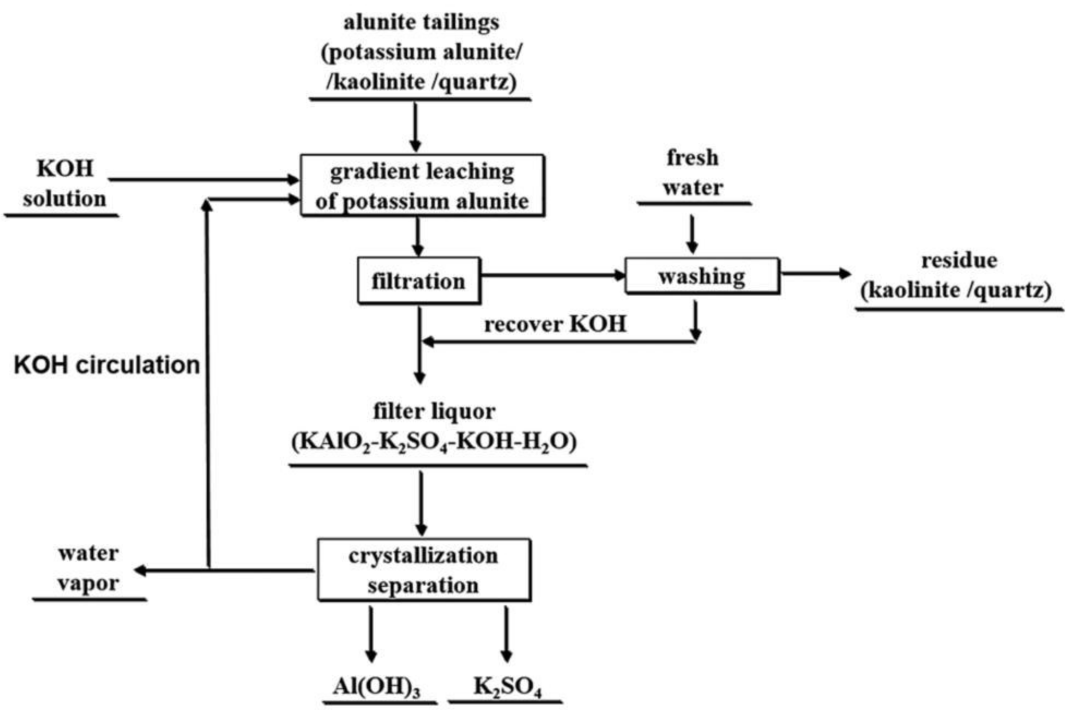

Figure 12: Flow sheet for potassium and aluminum recovery from alunite tailings using the green gradient leaching process [50].

A furnace made of steel designed to extract silicon from quartz to be utilized as semiconductor material for the construction of solar cells is described in the work of *Amin et al., 2013* [51]. The design and construction of the furnace laid out to produce 300g of metallurgical grade silicon per 1 kg of raw mineral quartz by melting the quartz at around 2000 °C is laid out in detail. The furnace can be operated both with an electrical fire system as well as a burner using either natural gas or liquid petroleum gas.

The inner chamber of the furnace is a cylinder with a circumference of 240 mm and a height of 360 mm. Graphite crucibles were used to store the quartz test samples during the melting process. Furthermore, ceramic wool served as a heat insulator to minimize heat dissipation to the surrounding atmosphere. To operate the furnace electrically, a 125 kVA three phase transformer is required, and the average graphite electrode consumption was stated to be 0,0467 cm/min.

The paper itself states, that these dimensions are small scale and were partly chosen to avoid the costs of using large scale electrical arc furnaces used in terrestrial steel mills.

The possibility of gaining silicon from quartz by liquification, as achieved by the furnace described in the work of *Amin et al., 2013* should be considered in the future development of ovens and furnaces designed for operation on Mars.

The final extraction process which will be presented in this chapter is the Frasch mining technique [52]. It is essentially a continuously operated sulphur well. Three concentric aluminium pipes with a diameter of 20,32 cm, 10,16 cm and 0,635 – 2,54 cm each are situated in the ground, stabilized by a cement casing, to extract sulphur in its liquid form from anhydrite and gypsum.

Water is pumped down the biggest pipe at a temperature of about 165,5 °C with a pressure of 8,618 – 17,24 bar. These values are given for application on earth and the required pressure might be different on the Martian surface. The sulphur is melted at its melting point of 139,4 °C and is pumped up the middle pipe. This process can take several days. Once liquid sulphur has successfully reached the top of the pipe, air is pumped through the smallest pipe at about 34,47 bar to discontinue part of the water flow and uphold the extraction of the sulphur.

One ton of sulphur requires 14158 – 25285 litres of compressed air and 5678 – 26498 litres of water. One well is able to cover an area of about 2023 m^2. These quantity ratios are immense, and the procedure is required to be operated continuously. If compressed air from the Martian atmosphere were to be used for this process, it needs be investigated whether the composition of the Martian atmosphere could react with the sulphur and hinder the extraction process.

The depth of the pipes and the applicability of the process is of course highly dependent on the local geology and how deep the gypsum and anhydrite deposits are located underground. Another drawback is that no recovery method for this type of installation exists. This process was used on earth in the early 20th century and the installations were simply abandoned after all of the sulphur was extracted. As the sulphur is extracted, the gypsum and anhydrite become more porous and cavernous which can enable movement of the mineral layers above. Subsidence can damage the pipes and is mostly unpredictable without detailed assessment of the geological composition at the extraction site. In addition to potential damage caused by subsidence, the cavities in the gypsum and anhydrite layer can enable the hot water to escape underground, in turn increasing the water required to continue the extraction process. Also, the hot water could potentially alter the surrounding subterranean composition by reacting with minerals in the vicinity of the gypsum and anhydrite deposits.

If the water used for extracting the sulphur could be recycled and a sustainable deinstallation process developed, this extraction process might be applicable on the Martian surface, depending on the subterranean geology at the extraction site.

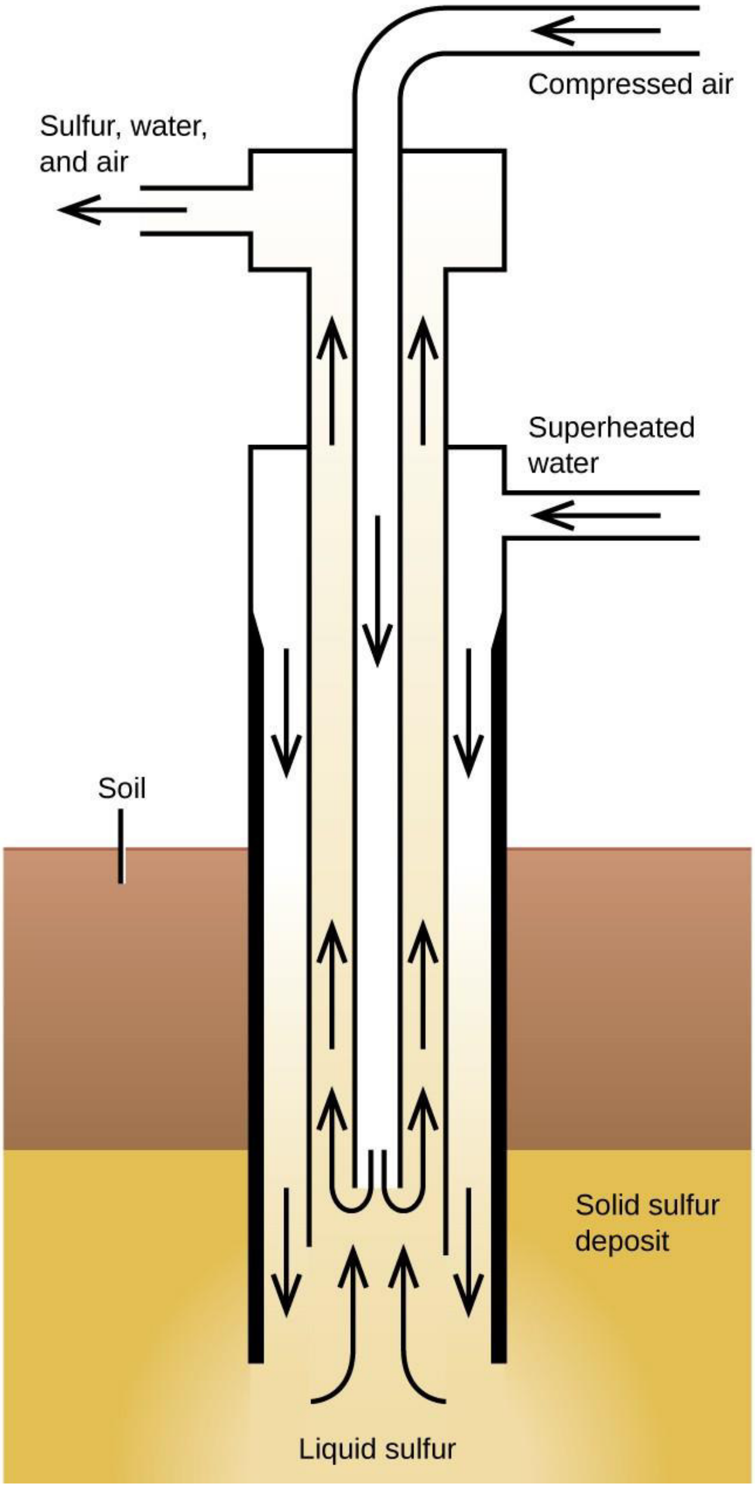

Figure 13: Schematic depiction of the Frasch mining technique [53].

6 Conclusion and Outlook

Overall, the research and evaluation of extraction processes that could be applied to extract elements that can be used as nutrients for higher plants, green algae and cyanobacteria from minerals present on the Martian surface proved quite difficult. Frequently, the extraction processes of interest were an intermediate step of a study or experiment that had a different overall objective than the extraction itself. Concepts that specifically target the extraction of certain elements do exist but were more uncommon.

The extraction step is most often done by reacting the mineral in question with a leaching solution or another kind of reagent. Heat treatment in ovens or furnaces can be involved during the reaction. The duration of reaction times varied from mere minutes to multiple hours and the most efficient duration for extraction is dependent on the specific minerals and reagents in question. The timespan required by an extraction process is an important factor for application on the Martian surface as the supply of electrical power continues to be a challenge. However, conclusions on the power consumption of an extraction process cannot be made as long as data on the power consumption of the used equipment is not defined or available. The machinery used for small scale laboratory experiments cannot be feasibly transported to Mars. Available specifications on this equipment are therefore irrelevant to calculating the required power consumption. Machinery and equipment practical for application on the Martian surface would first need to be selected or designed.

A common theme among the evaluated processes were their small scale. Generally, studies were conducted using samples and reagents of very small quantities. Many of the discussed studies merely set out to prove that an extraction concept is possible and therefore did not require large quantities of minerals and reagents. Confirming and demonstrating proof of concepts and designing large-scale production processes are two different challenges and data from small-scale studies cannot universally be upscaled to larger dimensions without more in-depth research.

In addition to unsuitable quantities, processes were often conducted under conditions most optimal for taking reliable measurements which lessens the informative value of an extraction process' data in regards to large-scale production chains. Minerals were frequently dried in ovens for multiple hours prior to extraction procedures to ensure that a sample is as clean as possible. Similarly, leach residues were often washed with copious amounts of water and dried in ovens for long durations before techniques such as X-ray diffraction were applied to collect measurements. Reactions that took place in furnaces, oftentimes did so within a controlled atmosphere.

While it is important to ensure that reliable data is taken for feasibility studies, the same amount of detail and precaution cannot be implemented within a production chain under such limiting conditions as on the Martian surface. To efficiently extract elements, drying and washing to ensure most optimal and clean materials might not be necessary to the extent done in a detailed feasibility study. This is a factor that needs to be taken into consideration when investigating large-scale production processes for the extraction of elements that can be used as nutrients for higher plants, green algae, and cyanobacteria used in BLSSs. Other factors include a minimization of required resources, process duration, and power demand. Recycling of byproducts and reagents needs to be implemented as much as possible.

Utilizing minerals as fertilizers without the need to first extract specific elements is a possibility that continues to be of interest for terrestrial applications and holds a lot of promise for application on the Martian surface. Epsomite and kieserite are minerals that can be used as fertilizers for higher plants in soil cultivation. Studies conducted on very specific mineral compositions such as verdete rock prove that mineral compositions can serve as a nutrient source for higher plants in soil cultivation. Research on using the specific mineral compositions present on the Martian surface for supplying nutrients to higher plants used in BLSSs is a prospect that should be pursued. Evaluation of the possibility of applying minerals as nutrient sources in other cultivation systems such as aeroponic and hydroponic systems should be evaluated to increase their application opportunities.

Kieserite and epsomite served as a magnesium source for higher plants in soil cultivation. It should be assessed whether or not these minerals could also serve as a magnesium source for green algae and cyanobacteria.

The presented processes are either lacking in available data or extrapolation of information relevant to the conditions of a BLSS on the Martian surface is not applicable. Analysis and evaluation according to the proposed Analytical Hierarchy process framework is not feasible. Too many values would be missing or would need to be hypothesized. The value and significance of results obtained in this way are insignificant to ambiguous at best. The distribution of importance to the criteria of the AHP framework's pairwise comparison matrices serves as a descriptive and concrete assessment by which the processes targeted at extracting elements that could be used as nutrients for higher plants, green algae and cyanobacteria of BLSSs were evaluated. Due to the inapplicability of the AHP analysis framework the pairwise comparison matrices' consistency checks were not performed.

In conclusion, the utilization of the minerals present on the Martian surface for the purpose of providing nutrition to higher plants, green algae and cyanobacteria is possible in multiple ways. The chance that mineral compositions of the Martian regolith can be used as fertilizer in soil culture with little to no necessary treatment or beneficiation is high and the utilization in alternative cultivation methods such as hydroponics and aeroponics systems should be investigated. Methods targeted at extracting specific elements from the available minerals to then use them as nutrients are most often done by reacting the mineral with a reagent. The reagent is in most cases and acid and the desired elements are obtained by a leaching process. Transporting resources such as acids onboard a spacecraft to the Martian surface is a downside to the feasibility of a process. The hazardous nature of acids and occupation of valuable payload space needs to be carefully weighed against the potential benefit of introducing acids as new components to production chains. The limiting conditions of a BLSS on the Martian surface are rarely accounted for in the available processes. The design of future processes and concepts needs to prioritize factors such as high quantities per production cycle, recirculation of side products, integration of side products to other processes that may use these side products as feed material and minimization of electrical power consumption.

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