Characterisation of Martian soil simulant MMS-1 in mixture with green compost for future sustainable space agriculture

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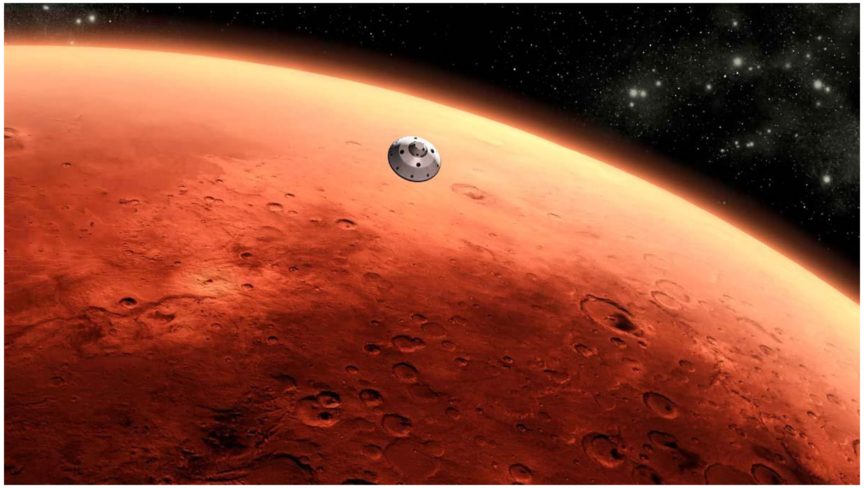
Introduction



The international space explorations foresee missions of ever increasing duration.

The configuration of a biologically active and fertile substrate consisting mainly of Martian soil/regolith to facilitate the growth of edible plants during long-term manned missions to Mars constitutes one of the main challenges in spatial research.

Regolith amendment with compost derived from recycled crew effluent and crop waste generated by bioregenerative life support systems constitutes a substrate that may contribute to upgrade crew autonomy and long-term survival in space.

In this context, the present work aimed to:

i) **study the geochemical and mineralogical composition** of MMS-1 Mars simulant;

ii) **study the physicochemical and hydraulic properties of growing substrates** obtained by mixing **simulant and green compost** at varying rates (0:100, 30:70, 70:30, 100:0; v:v);

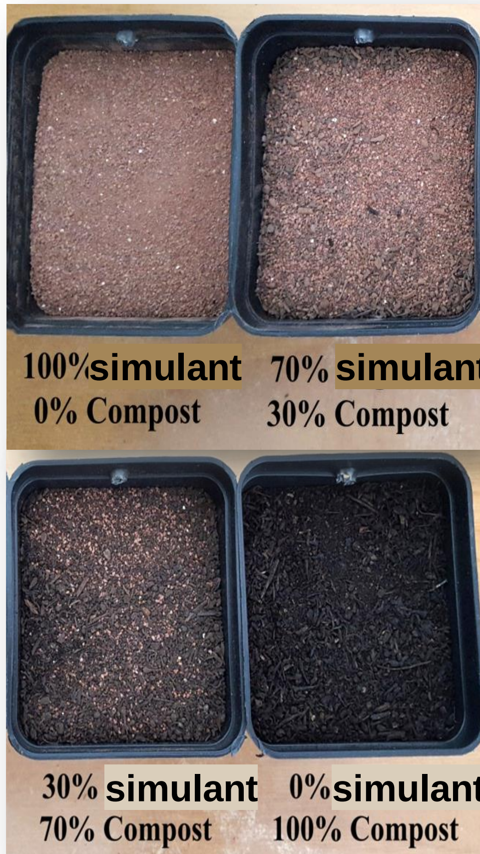
iii) **evaluate the potential use of MMS-1 as growing medium of two lettuce cultivars**;

iv) assess how compost addition may impact on sustainability of space agriculture exploiting local resources.

Experimental Design

4 substrate mixtures

- 0:100 (Simulant:Compost)
- 30:70 (Simulant:Compost)
- 70:30 (Simulant:Compost)
- 100:0 (Simulant:Compost)



2 cultivars of lettuces

X

- **Green Salanova®**
- **Red Salanova®**

Treatments were arranged in a randomized complete block design with three replicates

MMS1 - Simulant

Physico-chemical properties

Substrate properties	
Coarse fraction (>250 µm - g kg^{-1})	650
Medium-coarse fraction (250-20 µm - g kg^{-1})	260
Medium-fine fraction (20-2 µm - g kg^{-1})	65
Fine fraction (<2 µm - g kg^{-1})	25
pH in milliQ water	8.86
pH in 1M KCl	7.67
Organic C (g kg^{-1} DW)	0.24
Total N (g kg^{-1} DW)	0.09
C/N ratio	2.7
Total carbonates (g kg^{-1} DW)	27.1
Cation exchange capacity (cmol(+) kg^{-1})	7.94
Exchangeable Ca (mg kg^{-1} DW)	1034
Exchangeable K (mg kg^{-1} DW)	248
Exchangeable Mg (mg kg^{-1} DW)	106
Exchangeable Na (mg kg^{-1} DW)	292

The PSD revealed abundance of coarse sand particles (65 %) and very low amount of clay (2.5%).

pH was strongly alkaline and the difference of 1 unit lower when measured in KCl is probably due to the reduced hydrolysis of base-saturated colloids

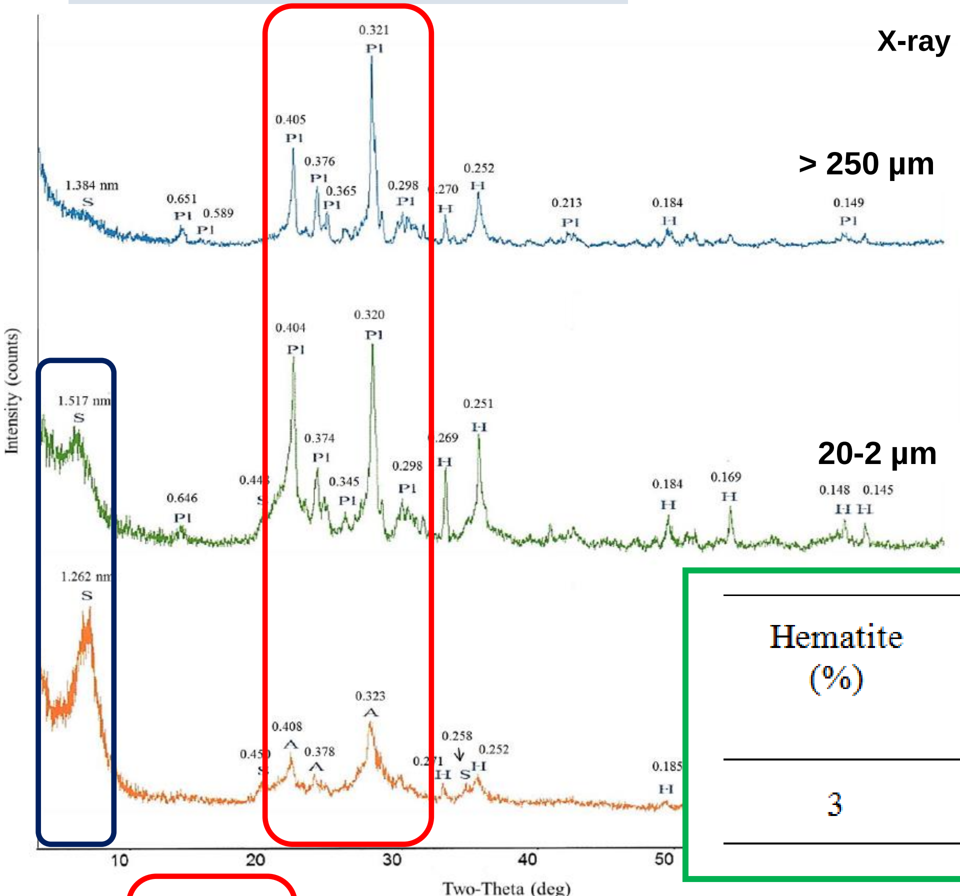
Contents in organic C and total N were negligible (their sum is ~0.03 % of the simulant), probably arising only from pioneer biofilms colonising simulant mineral surfaces.

The total carbonates content was moderate (<3 %) and rather low the CEC, with an exchangeable complex saturated by Ca (65 %), and then by Na (16 %), Mg (11 %) and K (8 %). The abundance of exchangeable Na was at expense of exchangeable Mg and K. There is a risk of Mg deficiency.

MMS1 - Simulant

Mineralogical composition

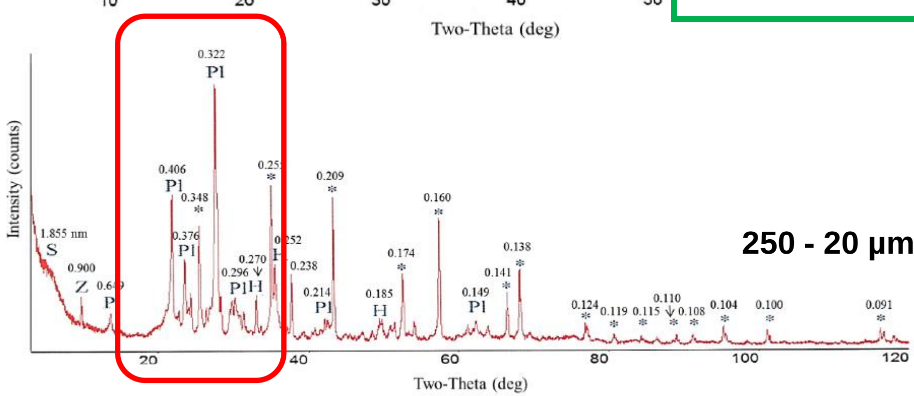
X-ray Powder Diffraction (XRPD)



Four particle-size fractions were analyzed

- plagioclases (mainly anorthite) were in all fractions,
- smectite minerals (Na-saturated montmorillonite) in the clay and silt fractions.

Hematite (%)	Plagioclase (Anorthite) (%)	Smectite (%)	Zeolite (Clinoptilolite) (%)	Amorphous Residual (%)
3	57	<1	12	28



The quantitative analysis of the fine sand (20-250 µm) evidenced that plagioclases were the most abundant minerals, followed by amorphous materials (glass) and zeolites (clinoptilolite).

MMS1 - Simulant

Chemical composition

Element oxide	Content (%)
SiO_2	57.3 ± 1.3
Al_2O_3	12.9 ± 0.1
Fe_2O_3	9.1 ± 1.0
CaO	4.9 ± 0.9
K_2O	2.1 ± 0.4
MgO	4.1 ± 0.3
MnO	0.1 ± 0.04
Na_2O	4.2 ± 0.8
P_2O_5	0.2 ± 0.06
TiO_2	1.1 ± 0.2
Loss of ignition	4.0 ± 0.2

Trace element	Content (mg kg^{-1})
Ba	566 ± 16
Cu	31 ± 4
Ni	116 ± 14
Rb	45 ± 2
Sr	283 ± 2
Zn	52 ± 3
Zr	292 ± 2

The MMS-1 simulant mostly consisted of SiO_2 (57.3 % of the total), Al_2O_3 (12.9 %) and Fe_2O_3 (9.1 %), but also contains significant amounts of other element oxides such as CaO, K_2O, MgO, MnO, Na_2O and P_2O_5 (0.1-4.9 %), essential for plant growth and physiology.

Green compost

Chemical composition

C (%)	H (%)	N (%)	S (%)	H/C	C/N
29.3 ± 3.0	3.07 ± 0.34	2.31 ± 0.15	0.12 ± 0.03	1.3 ± 0.1	14.8 ± 0.6

Measured by elemental analyser and H/C and C/N ratios as atomic ratios (n=3)

Major element	Content (g kg^{-1})
Al	4.7 ± 0.3
Ca	12.5 ± 3.6
Fe	4.7 ± 0.5
K	17.2 ± 1.7
Mg	3.9 ± 1.1
Na	3.5 ± 0.1
P	2.6 ± 0.2

Trace element	Content (mg kg^{-1})
As	2.9 ± 0.6
Cd	0.2 ± 0.1
Co	2.3 ± 0.3
Cr	7.8 ± 1.1
Cu	97 ± 5
Ni	9.0 ± 0.6
Pb	24.0 ± 1.2
V	6.5 ± 0.4
Zn	91.0 ± 10.3

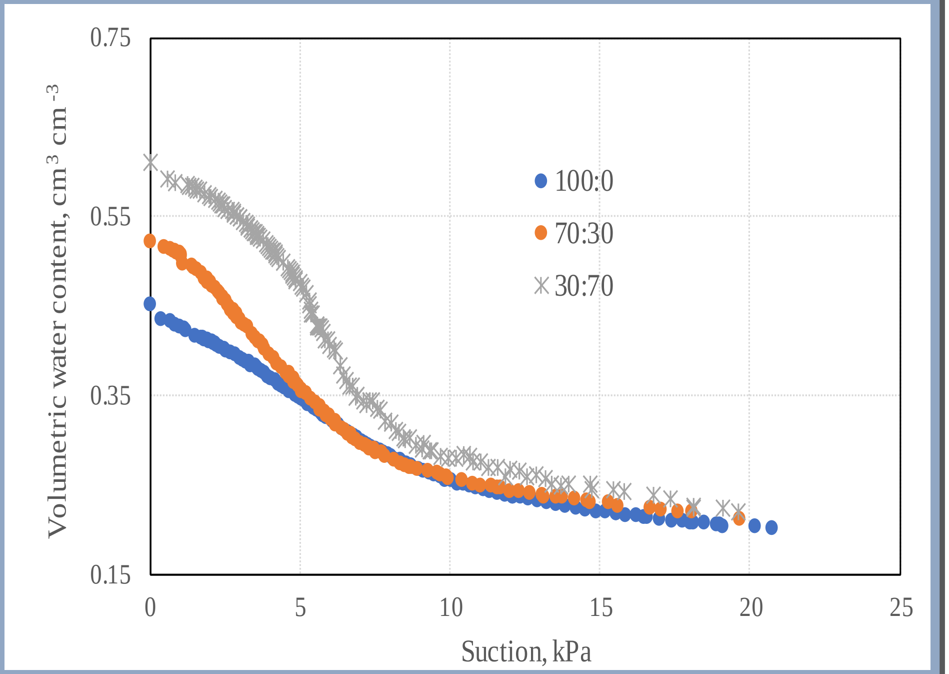
Main chemical properties of different mixtures (simulant:compost) measured *before* the growing cycle of green and red Salanova lettuces.

100% compost

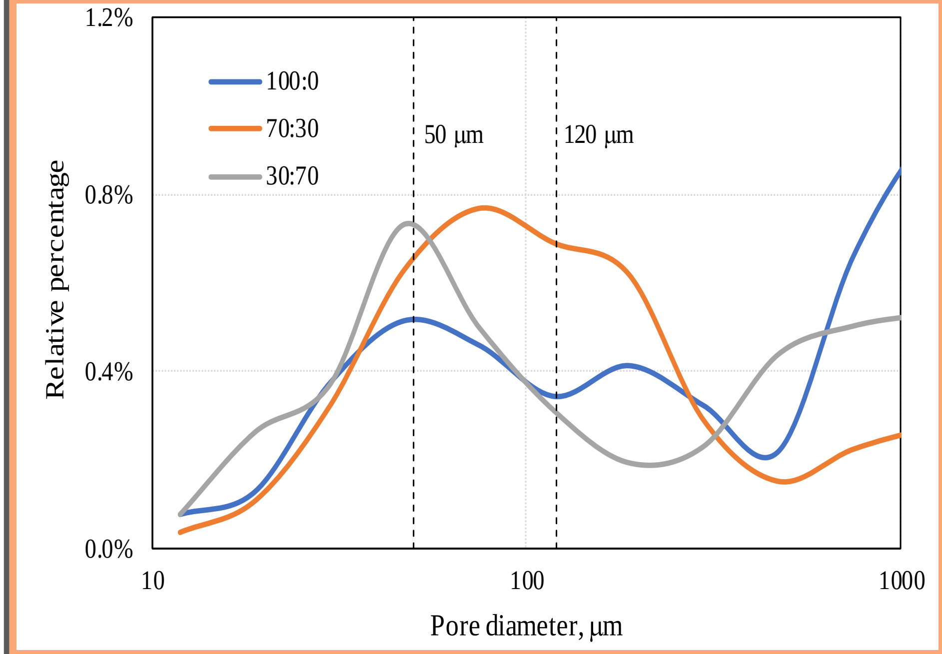
100% simulant

Substrate property	Start point			
	0:100	30:70	70:30	100:0
Bulk density ($g\ cm^{-3}$)	0.58 d	0.73 c	0.93 b	1.08 a
Organic matter (% w/w)	50.47 a	25.93 b	8.74 c	0.04 d
pH in milliQ water	8.25 c	8.29 b	8.28 b	8.86 a
Electrical conductivity ($dS\ m^{-1}$)	3.47 a	1.80 b	0.58 c	0.28 d
Water-soluble Ca ($mg\ kg^{-1}$ DW)	1242 a	848 b	465 c	212 d
Water-soluble K ($mg\ kg^{-1}$ DW)	10149 a	7019 b	1967 c	21.4 d
Water-soluble Mg ($mg\ kg^{-1}$ DW)	380 a	256 b	131 c	49.2 d
Water-soluble Na ($mg\ kg^{-1}$ DW)	204	275	294	216
Water-soluble Cl ($mg\ kg^{-1}$ DW)	1782 a	1061 b	310 c	8.0 d
Water-soluble NO_3 ($mg\ kg^{-1}$ DW)	741 a	439 b	130 c	11.7 d
Water-soluble PO_4 ($mg\ kg^{-1}$ DW)	405 a	238 b	61.4 c	0.9 d
Water-soluble SO_4 ($mg\ kg^{-1}$ DW)	263 a	158 b	61.5 c	9.1 d

Hydrological properties of MMS-1/compost mixtures



Experimental water retention curves of different mixtures



Pore-size distribution of different mixtures

Agronomic performance of green and red lettuce on MMS-1/compost mixtures

- Both lettuce cultivars were able to grow on all mixtures for 19 days under fertigation.
- *Red Salanova* lettuce produced a statistically-greater ($p<0.001$) dry biomass, leaf area and number than *Green Salanova*.
- Leaf area and plant dry biomass were higher on 30:70 simulant/compost mixture.
- The shoot/root ratio of plants decreased as simulant in growth substrate increased.
- Lettuces grown on the 100% simulant produced the lowest biomass among the growing substrates.
- Lack of biological fertility and possible salt stress negatively impacted on plants grown in non-amended simulant.

In conclusion…

From the Hollywood movie "The Martian", 2015

This study demonstrates as a staple crop such as lettuce, source of vitamin C, phenolic compounds and fibres for space crews, can be grown in MMS-1 Mars regolith simulant if suitably amended by compost and fertilised.

On the other hand, the moderate reduction of all growth parameters when the simulant rate increases in the mixture suggests suitable nutrient supply to plants from modified Hoagland solution and the release of some essential elements, which guarantee low but not negligible lettuce production.

Overall, in terms of water and nutrient transport processes, all selected substrates would be eligible to be used as growth media in BLSS. However, the substantial improvement in hydraulic properties and water-plant relations in the 70:30 simulant:compost mixture indicates that the latter is the best option combining satisfactory plant growth performance and sustainable use of compost, a limited resource in BLSS.

More details in the following paper…

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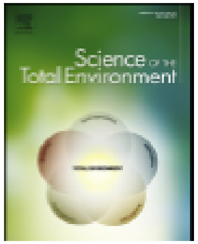

Geo-mineralogical characterisation of Mars simulant MMS-1 and appraisal of substrate physico-chemical properties and crop performance obtained with variable green compost amendment rates

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