Feasibility of cereal crop cultivation on Mars: constraints, regolith limitations, and emerging mitigation strategies

[1,2]Ioan G. Oroian, [3]Arpita Tripathi

[1] Department of Environmental Engineering and Protection, Faculty of Agriculture, University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca, Romania; [2] Balkan Environmental Association (BENA), Thessaloniki, Greece; [3] Faculty of Education, Teerthanker Mahaveer University, Moradabad, India. Corresponding author: A. Tripathi, arpitatripathi0391@gmail.com

Abstract. The prospect of cultivating cereal crops on Mars represents a critical component of long-term extraterrestrial colonization and bioregenerative life support systems. This review synthesizes current evidence on the feasibility of cereal production under Mars-like conditions, focusing on key abiotic constraints including nutrient-deficient regolith, perchlorate toxicity, high salinity, water scarcity, and atmospheric composition dominated by CO_2. Studies using Martian regolith simulants (e.g., JSC-Mars-1A, MMS-1, MGS-1) consistently demonstrate that unamended substrates are incapable of supporting plant growth. In contrast, chemical and biological amendments, such as incorporating organic matter, adjusting pH, and introducing plant growth-promoting microorganisms, significantly improve outcomes. Perchlorate contamination remains a major unresolved barrier due to its persistence and phytotoxicity. Water treatment technologies, including desalination via cyanobacteria and plasma-activated water, show promise in enhancing plant performance. Although certain cereals, such as rye and wheat, have demonstrated partial growth success in amended simulants, no study has yet achieved full life-cycle cereal production under integrated Mars-like environmental conditions. The review highlights critical knowledge gaps, particularly regarding germination under low-oxygen, high-CO_2 atmospheres and the combined effects of multiple stressors, and outlines future research directions necessary for sustainable Martian agriculture.

Keywords: Mars agriculture, cereal crops, regolith simulants, perchlorate toxicity, salinity stress, bioregenerative life support, plant growth-promoting bacteria, water treatment, extraterrestrial farming, soil amendment.

Introduction. Growing cereal crops on Mars will require overcoming multiple interacting stressors: nutrient-poor regolith, perchlorate toxicity, high salinity, water scarcity, elevated CO_2, and oxidative stress (Petrescu-Mag, 2009; Botha et al., 1018; Duri et al., 2022; Casu et al., 2026). Current evidence from Martian regolith simulant studies suggests that cereal growth is feasible with substantial substrate amelioration, but no study has yet demonstrated full life-cycle cereal production under combined Mars-like conditions.

Aim of the Study. The aim of this mini-review is to critically evaluate the current state of knowledge regarding the potential for cereal crop cultivation on Mars, with a particular emphasis on the limitations imposed by Martian regolith and environmental conditions. The study seeks to integrate findings from experimental research using regolith simulants to identify the primary physicochemical and biological constraints affecting plant growth, assess the effectiveness of various soil and water amendment strategies, and determine the feasibility of sustaining cereal production under Mars-like conditions. Additionally, the review aims to highlight existing research gaps and propose directions for future investigations necessary to enable reliable and scalable extraterrestrial agriculture.

Martian Regolith Simulants and Their Limitations. Martian regolith simulants, including JSC-Mars-1A, MMS-1 (Mojave Mars Simulant), and MGS-1 (Mars Global Simulant), are the primary substrates used to assess plant growth potential on Mars, though their mineralogical fidelity to actual Martian soil remains debatable. Five new simulants incorporating phyllosilicate clays and carbonates have been developed to better reflect agriculturally relevant Mars surface materials, enabling more realistic fertility and toxicity assessments (Fackrell et al., 2021). None of the three most widely used simulants (JSC-Mars-1A, MMS, MGS-1) can support plant growth without nutrient supplementation, and the highly alkaline MGS-1 (pH > 9.0) fails to sustain growth even with added nutrients. Acidification of MGS-1 nearly doubled plant longevity, indicating that pH correction is a prerequisite for certain simulants (Eichler et al., 2021). Martian regolith is also coarse-grained with a mineral profile that differs significantly from terrestrial arable soil, resulting in poor seed germination and stunted development (Sasi et al., 2025). The field calls for standardized methods and benchmarks for simulant development and experimental reporting so that results across laboratories can be compared meaningfully (Fackrell et al., 2024) (Table 1).

Table 1

Comparison of three widely used Martian regolith simulants and their capacity to support plant growth

Simulant	*Key properties*	*Plant growth without amendment*	*Primary limitation*
JSC-Mars-1A	Volcanic ash-derived	Not supported	Nutrient deficiency (Eichler et al., 2021)
MMS-1	Mojave basaltic	Not supported	Nutrient deficiency, high pH (Eichler et al., 2021; Fackrell, 2021)
MGS-1	Global composition, pH > 9.0	Not supported even with nutrients	Alkalinity, perchlorate (Eichler et al., 2021).

Perchlorate Toxicity and Saline–Oxidative Stress. Perchlorate (ClO_4^-) is globally enriched in Martian regolith at concentrations commonly toxic to plants, presenting a fundamental obstacle to agriculture (Oze et al., 2021). The addition of calcium perchlorate to simulants at Mars-relevant concentrations renders every tested simulant incapable of supporting plant growth, regardless of nutrient supplementation (Eichler et al., 2021). In Martian regolith simulant specifically, perchlorate prevented germination across all plant treatments, while in potting soil plants germinated at 1 wt% perchlorate but showed restricted growth and decreased biomass. Perchlorate also increases metal and phosphorus release from the regolith, potentially modifying metal availability to such an extent that the substrate remains phytotoxic even after perchlorate removal. Soil column flow-through experiments were unable to completely remove perchlorate despite its high solubility, suggesting that simple leaching is insufficient and that biological or volatilization-based remediation strategies will be needed (Oze et al., 2021).

High soil salinity, a related but distinct stressor, reduces seed germination, growth, yield, and quality in cereal crops by creating osmotic stress that impairs water uptake and triggers downstream oxidative damage through reactive oxygen species (ROS) accumulation. Among cereals, barley and sorghum adapt best to salinity, wheat and maize are moderately adapted, and rice is salt-sensitive with significant yield reductions under saline conditions. Cereal tolerance mechanisms include effluxing or vacuolar compartmentalization of Na^+ and activation of antioxidant defense systems to detoxify ROS (Alkharabsheh et al., 2021). These findings are directly relevant to Mars agriculture because Martian briny water and regolith salts impose analogous osmotic and oxidative challenges (Kasiviswanathan et al., 2022).

Water Scarcity and CO_2 Atmosphere Constraints. Water on Mars is potentially abundant in polar regions or shaded crater microenvironments, but would need to be located near agricultural stations and extracted from ice or metal oxides (Macdonald et al., 2020). The low nutrient content of Martian soil and high salinity of briny water render both resources unfit for direct use in crop production, necessitating desalination and nutrientenrichment strategies. The marine cyanobacterium *Synechococcus* sp. PCC 7002 effectively desalinates briny water simulant, and filtration through basalt-type volcanic rocks further enhances desalination, producing water suitable for irrigation (Kasiviswanathan et al., 2022). Water chemistry optimization also offers gains: irrigation with plasma-activated water (PAW) enriched in reactive oxygen and nitrogen species, combined with mineral-enriched water from locally available feldspar, increased germination by up to ~567% and biomass by ~412% in *Brassica oleracea* microgreens grown on simulated Martian regolith (Sasi et al., 2025).

The Martian atmosphere is composed of 95.9% CO_2, which is ideal for photosynthesis but inhibits seed germination because most crop plants require oxygen for germination, and high CO_2 concentrations suppress it. Germination in *Brassica* species is eliminated below 2% O_2 and severely limited below 5% O_2, underscoring the oxygen bottleneck in a CO_2-dominated atmosphere. A polymer-based oxygen delivery system using foamed, lightly cross-linked polyacrylate supports germination and growth of cress (*Lepidium sativum*) in Martian regolith simulant under a 100% CO_2 atmosphere at 101 kPa, achieving germination rates and plant mass nearly identical to plants grown in air. This polymer is lightweight, added in low amounts, and also protects root structures and anchors plants in the coarse regolith. No reports in the literature document successful germination or growth of cereal crops in Mars regolith simulant under a pure or nearly pure CO_2 atmosphere, representing a critical gap (Macdonald et al., 2020).

Candidate Cereal Crops and Amendment Strategies. Rye (*Secale cereale*) is the cereal most consistently tested on Martian regolith simulants, having been grown successfully alongside nine other crop species on MMS-1 mixed with organic matter, producing viable seeds with germination rates comparable to Earth soil controls (Wamelink et al., 2019). Wheat (*Triticum aestivum*) was grown on Mars and Moon simulants in early experiments, flowering and performing particularly well on Mars regolith simulant compared to Moon simulant and even to nutrient-poor Earth control soil (Wamelink et al., 2014). A dedicated wheat study on Martian simulant substrates with vermicompost amendment found that vermicompost positively affected wheat on soil but had negligible effect on plants grown on the Martian simulant substrate, and that wheat survival depended on the presence of plant growth-promoting rhizobacteria (PGPR) capable of providing additional nitrogen (Przemieniecki et al., 2024). Maize (*Zea mays*) survival under simulated Martian conditions was assessed by combining simulated Martian gravity (0.38 g), hypomagnetic field (~40 nT), and MGS-1 regolith toxicity; MGS-1 chemical imbalance emerged as the dominant stressor, overriding biophysical cues, with the combination of simulated Martian gravity and MGS-1 posing the greatest threat through systemic metabolic depletion and disrupted root development (Servetto et al., 2026) (Table 2).

Table 2

Cereal crops tested on Martian regolith simulants and their growth outcomes

Crop	*Simulant*	*Amendment*	*Key outcome*
Rye (*Secale cereale*)	MMS-1 + organic matter	Harvest residues	Viable seeds produced; germination comparable to Earth soil (Wamelink et al., 2019)
Wheat (*Triticum aestivum*)	Mars simulant	Vermicompost	Negligible improvement; survival depends on PGPR (Przemieniecki et al., 2024)
Maize (*Zea mays*)	MGS-1 (30%)	None	Regolith chemistry is dominant stressor over gravity or magnetism (Servetto et al., 2026).

Organic matter amendment is consistently the most effective strategy for converting nutrient-poor, alkaline regolith into a functional plant growth medium. Mixing MMS-1 with composted organic waste at a 70:30 ratio (simulant:compost) sustained lettuce growth and improved photosynthetic activity, nutritional value, and water use efficiency, with the 30:70 ratio being optimal but less sustainable given compost's scarcity in space (Duri et al., 2020). Monogastric manure, an analogue of crew excreta and crop residues, added to MMS-1 at 70:30 stimulated microbial biomass, enzymatic activity, and nutrient bioavailability, producing the best agronomic performance among tested ratios (Caporale et al., 2022a). Peat amendment of MMS-1 at 15% and 30% volumes mitigated the simulant's alkalinity (pH 8.86) by lowering pH to neutral or subacid values, enabling successful soybean germination and growth (Caporale et al., 2022b). Alfalfa grown as a biofertilizer in nutrient-limited basaltic regolith simulant sustained subsequent growth of turnip, radish, and lettuce, demonstrating a biological amendment pathway that requires no Earth-supplied organics (Kasiviswanathan et al., 2022). However, the high pH and salinity of manure amendments can raise soluble salt content and sodium levels in the exchange complex, and can increase toxic soluble aluminium and heavy elements, particularly in strongly alkaline lunar simulants, a caveat that applies to Martian substrates as well (Caporale et al., 2022b).

Intercropping systems tested on MMS-1 Mars regolith simulant showed that rhizobia nodulation was absent in the regolith, negating nitrogen fixation and giving an overall yield disadvantage compared to monocropping (RYT = 0.93), while in sand with favorable soil conditions intercropping significantly outperformed monocropping (RYT = 1.32). Adverse regolith conditions, high pH, elevated compactness, and nutrient deficiencies presumably restricted rhizobia survival and nodulation, suggesting that simple regolith improvements to enhance nodulation conditions could unlock intercropping's potential for Martian agriculture (Gonçalves et al., 2024). Seed inoculation with plant growth-promoting bacteria tolerant to metal-rich, nutrient-poor conditions improved germination rates and preserved photosynthetic function in watermelon grown on Martian regolith simulant, representing a strategy directly transferable to cereal crops (Sokić et al., 2026). Selecting a higher grain grade of the regolith at the onset of Martian agriculture could reduce soil compactness and improve drainage, salinity conditions, gas diffusion, and nutrient availability, a low-cost intervention with cascading benefits (Gonçalves et al., 2024).

Conclusions. Current evidence indicates that cereal crop cultivation on Mars is theoretically feasible but remains experimentally unachieved under fully integrated Martian conditions. The primary limiting factors are the chemical and physical properties of regolith, particularly nutrient deficiency, high alkalinity, and perchlorate toxicity, which collectively inhibit germination and plant development. While amendment strategies such as organic matter addition, microbial inoculation, and pH correction substantially improve plant performance, they do not fully mitigate all constraints, especially under combined stress scenarios. Water scarcity and salinity further complicate cultivation, although emerging technologies such as biological desalination and plasma-activated water offer promising solutions. The CO_2-rich, oxygen-poor Martian atmosphere represents a critical bottleneck for seed germination, with only preliminary technological interventions demonstrating partial success in non-cereal species. Importantly, no study has yet demonstrated complete cereal life-cycle closure - from germination to viable seed production - under realistic Martian environmental simulations. Future research must prioritize integrated system-level experiments that combine regolith chemistry, atmospheric composition, water management, and biological enhancement strategies. Achieving sustainable cereal production on Mars will depend on multidisciplinary approaches that bridge plant physiology, soil science, microbiology, and space engineering.

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Authors:
Ioan Gheorghe Oroian (IGO), Department of Environmental Engineering and Protection, Faculty of Agriculture, University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca, 3-5 Calea Mănăştur Street, 400372 Cluj-Napoca, Romania, e-mail: ioan.g.oroian@gmail.com
Arpita Tripathi (AT), Faculty of Education, Teerthanker Mahaveer University, Moradabad, 244001, Uttar Pradesh, India, e-mail: arpitatripathi0391@gmail.com

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