Environmental Science and Ecotechnology 19 (2024) 100344

Contents lists available at ScienceDirect

Environmental Science and Ecotechnology

journal homepage: www.journals.elsevier.com/environmental-science-and-ecotechnology/

Discussion

Space aquatic chemistry: A roadmap for drinking water treatment in microgravity

Baiwen Ma [a, b], Yaohui Bai [a], Chengzhi Hu [a, *], Beizhen Xie [c], Junya Zhang [d, e], Mathias Ulbricht [b], Libing Zheng [b, d]

[a] *Key Laboratory of Drinking Water Science and Technology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, 100085, China*
[b] *Lehrstuhl für Technische Chemie II, Universität Duisburg-Essen, Essen, 45117, Germany*
[c] *Institute of Environmental Biology and Life Support Technology, School of Biological Science and Medical Engineering, Beihang University, Beijing, 100191, China*
[d] *Department of Water Pollution Control, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, 100085, China*
[e] *Department of Isotope Biogeochemistry, Helmholtz Centre for Environmental Research - UFZ, Leipzig, 04318, Germany*

ARTICLE INFO

Article history:
Received 3 October 2023
Accepted 8 November 2023

Keywords:
Microgravity
Drinking water treatment
Water quality
Challenges
Strategies

ABSTRACT

Rapid advancement in aerospace technology has successfully enabled long-term life and economic activities in space, particularly in Low Earth Orbit (LEO), extending up to 2000 km from the mean sea level. However, the sustainance of the LEO Economy and its Environmental Control and Life Support System (ECLSS) still relies on a regular cargo supply of essential commodities (e.g., water, food) from Earth, for which there still is a lack of adequate and sustainable technologies. One key challenge in this context is developing water treatment technologies and standards that can perform effectively under microgravity conditions. Solving this technical challenge will be a milestone in providing a scientific basis and the necessary support mechanisms for establishing permanent bases in outer space and beyond. To identify clues towards solving this challenge, we looked back at relevant scientific research exploring novel technologies and standards for deep space exploration, also considering feedback for enhancing these technologies on land. Synthesizing our findings, we share our outlook for the future of drinking water treatment in microgravity. We also bring up a new concept for space aquatic chemistry, considering the closed environment of engineered systems operating in microgravity.

Manned spaceflights have been around for more than 60 years. From what was once merely science fiction, human activity in space is now “common”. Several countries are operating ambitious space programs, and space stations, such as the International Space Station (ISS) and the China Space Station, are now well established. However, microgravity remains an insurmountable challenge in furthering our operations in space. Microgravitational conditions make functioning several regular processes difficult, such as food and water production. Ensuring continuous freshwater availability is essential to ensure sustained space operations and other capabilities and reduce costs of space exploration, earth monitoring, and Low Earth Orbit (LEO) Economy functioning. A critical step is to reduce the reliance on regular supply and instead develop water treatment technologies that enable the treatment and reuse of wastewater under microgravitational conditions. The development of such water treatment technologies will enormously benefit long-term space inhabitation. In addition, the unique phenomena encountered in space (e.g., buoyancy disappearance) [1] may also promote a better understanding of the mechanisms underlying the effective design of water treatment technologies and ultimately benefit the operation of such technologies on Earth.

1. Considerations of design

Two water management systems have been successfully applied in space station. (1) Independent treatment of water streams, e.g., wastewater such as urine and condensate water. It is particularly practiced in the Russian space station [2]. (2) Simultaneous treatment of wastewater. This method is applied in the US Segment of

* Corresponding author.
E-mail address: czhu@rcees.ac.cn (C. Hu).

https://doi.org/10.1016/j.ese.2023.100344

ISS [3]. However, other aspects must be considered in order to improve the operation of current water treatment methods:

(1) Wastewater generated in space comes from complex sources. The three main wastewater types in space stations are identified as condensate water, waste hygiene water, and urine. The treatment of such water from such diverse sources would benefit from advancing the development of a circular water treatment theory for limited environments.
(2) Wastewater generated in space, particularly human urine, has an altered chemical composition. Urine in space has a much higher Ca^{2+} concentration than Earth's due to differences in human metabolism in space [4]. Such urine has a very high corrosive potential due to the formation of calcium carbonate deposits on contact surfaces. The risk of such corrosion needs to be considered in designing appropriate treatment systems incorporating alleviation strategies capable of withstanding scaling.
(3) Low water recovery leads to low efficiency in freshwater recovery. Urine is approximately 95% water. However, current water treatment technologies in space recover only a maximum of 85% of this water [4]. Future water treatment technologies should aim to improve recovery.
(4) New technologies development needs to tap into energy resources available in space. Currently, operating water purification methods are mainly focused on physical (e.g., membrane filtration) and chemical (e.g., oxidation) technologies. Membrane technology has been promising in space due to its excellent water quality and easy modularization [5]. However, the operation of such technologies places a significant burden on earth-to-space supply chains. In this context, future water purification technologies need to tap into resources — such as solar energy — abundant in outer space to remove the dependency on expensive energy supplies from earth to conduct essential processes.

2. Quality considerations for drinking water in space

Necessarily, the quality standards for drinking water in space stations are much more stringent than those on Earth. For instance, the acceptable microbes limit is 50 colony forming units (CFU) mL^{-1} in-flight [6], while that is twice as much at 100 CFU mL^{-1} on Earth (e.g., China, GB 5749—2022). In the efforts of the National Aeronautics and Space Administration (NASA) to gradually streamline the water standards on the ISS, microbes remain the focus because of the potentially huge health and safety threats [6–8]. Due to the altered conditions in space, microorganisms may further enhance their “toxic” effects [7,8]. Thus, more attention should be paid to the potentially increased risks and control methods to establish suitable microbiological standards. One possible strategy is to develop novel sensors coupled with online daily monitoring methods. For example, it has been confirmed that identifying bacterial populations using 16S rDNA nanopore sequencing could be conducted entirely in flight [9], illustrating the potential application of this technology in routine online monitoring conducted on ISS. In addition to microbial quality, water smells caused by disinfection by-products can negatively impact astronauts' mental and physical health. Therefore, the water quality standards should consider factors beyond microbiological safety in designing and improving space water technologies.

3. Simulation experiments applying microgravity

Simulation experiments are limited due to the few options available and the difficulty of creating long-term (e.g., hours) microgravity conditions in terrestrial systems. Short-term systems such as drop towers (~5 s), parabolic flight (<30 s), and even sounding rockets (~13 min) have been developed to overcome this challenge [7]. However, not only are the operation costs of such systems very high, but the experimental conditions are also rather strict [1]. To further optimize the processes and their potential, the rotating wall vessel (RWV) and the random positioning machine (RPM), respectively, were successfully designed for simulating microgravity [7]. A previous study has demonstrated a linear relationship between the extent of certain phenomena (e.g., oxygen bubble size during water electrolysis) and the degree of gravity. Therefore, some mechanisms of interfacial phenomena under microgravity can also be inferred through investigating behaviors under high gravity outer conditions [1], which is easily achieved by rotation systems on Earth.

4. Lessons from space to earth on water research

Terrestrial and space water treatment technologies are closely interconnected, and even many experiments conducted in space are controlled on Earth to understand better the mechanisms involved [7]. Theories and technologies established on Earth provide the bases for those utilized in space. In addition, space is considered the “final frontier” as it provides a unique scientific platform to test and optimize the technology. To date, science and the economy have significantly benefited from space research on agriculture and biology towards increasing production and treating diseases better on Earth [10]. Similarly, the discovery of related phenomena in microgravity may further enhance the development of water treatment theories and methods on Earth. In space, surface tension and capillary force determine fluid flow; due to the lack of buoyancy, the output of related experiments may further improve the fundamental understanding of water treatment mechanisms (e.g., coagulation) and pollutants removal relationships under different process conditions (e.g., varied gravity) on Earth. Figure 1 shows the relationships regarding water treatment process between the terrestrial and space boundary conditions.

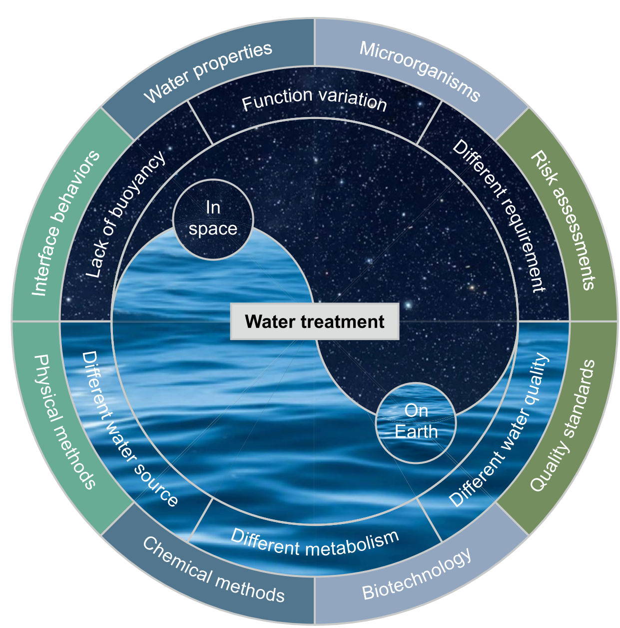

Fig. 1. Potential relationships between terrestrial and space boundary conditions that are relevant for drinking water treatment.

5. Foundations and future of aquatic chemistry for space

The research on space water treatment has just begun, and there are yet many unknowns to be explored and explained. For water treatment in space, the aquatic chemistry theory proposed by W. Stumm in 1970 lays a solid scientific and conceptual foundation [11]. The key processes are as follows: acid-base equilibrium, redox equilibrium, coagulation-flocculation equilibrium, adsorption-desorption equilibrium, and dissolution-precipitation equilibrium. Owing to the unique phenomena in space, these equilibria can be somewhat influenced. The extent of changes is expected to be more significant for equilibria involving two phases (i.e., a solid and a liquid for coagulation, flocculation or precipitation) instead of those involving one aqueous phase, such as an acid-base equilibrium.

Further, different water treatment characteristics may be easily observed in space compared to the terrestrial processes. For instance, in a space station, potable water supply is tightly coupled with wastewater treatment in a limited space within the closed system. In addition, much attention should be paid to the permeate re-mineralization after membrane filtration because of the long-term cycle [12]. Therefore, recognizing the current limitations, a new concept for space aquatic chemistry should be proposed, aiming to further develop the water treatment theory as a basis for efficient and sustainable technologies ensuring astronauts' health and the establishment of stable space economies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the Funds for National Natural Science Foundation of China (Grant No. 52070183, 52322001), the International Cooperation and Exchange of the National Natural Science Foundation of China (51820105011), and the Program of the Youth Innovation Promotion Association of the Chinese Academy of Sciences. Dr. Baiwen Ma is grateful for the financial support from Alexander von Humboldt Foundation.

References

[1] B.A. Lomax, G.H. Just, P.J. McHugh, P.K. Broadley, G.C. Hutchings, P.A. Burke, M.J. Roy, K.L. Smith, M.D. Symes, Predicting the efficiency of oxygen-evolving electrolysis on the Moon and Mars, Nat. Commun. 13 (2022) 583.
[2] L. Bobe, N. Samsonov, L. Gavrilov, V. Novikov, M. Tomashpolskiy, P. Andreychuk, N. Protasov, Y. Synjak, V. Skuratov, Regenerative water supply for an interplanetary space station: the experience gained on the space stations "Salut", "Mir", ISS and development prospects, Acta Astronaut 6 (2007) 8–15.
[3] L. Carter, C. Brown, N. Orozco, Status of ISS water management and recovery, in: 43rd International Conference on Environmental Systems, Vail, Colorado, USA, 2013.
[4] F. Volpin, U. Badeti, C. Wang, J.X. Jiang, J. Vogel, S. Freguia, D. Fam, J. Cho, S. Phuntsho, H.K. Shon, Urine treatment on the international space station: current practice and novel approaches, Membranes 10 (2020) 327.
[5] P. Bernardo, A. Lulianelli, F. Macedonio, E. Drioli, Membrane technologies for space engineering, J. Membr. Sci. 626 (2021) 119177.
[6] D.L. Pierson, D.J. Botkin, R.J. Bruce, V.A. Castro, M.J. Smith, C.M. Oubre, C.M. Ott, Microbial Monitoring of the International Space Station, NASA Technical Report Server (NTRS), 2013. JSC-CN-28760[R].
[7] G. Senatore, F. Mastroleo, N. Leys, G. Mauriello, Effect of microgravity & space radiation on microbes, Future Microbiol. 13 (2018) 831–847.
[8] L.Y. Liu, G.J. Xie, D.F. Xing, B.F. Liu, J. Ding, N.Q. Ren, Biological conversion of methane to polyhydroxyalkanoates: current advances, challenges, and perspectives, Environ. Sci. Ecotechnol. 2 (2020) 100029.
[9] A.S. Burton, S.E. Stahl, K.K. John, M. Jain, S. Juul, D.J. Turner, E.D. Harrington, D. Stoddart, B. Paten, M. Akeson, S.L. Castro-Wallace, Off earth identification of bacterial populations using 16S rDNA nanopore sequencing, Genes 11 (2020) 76.
[10] J.L. Becker, G.R. Souza, Using space-based investigations to inform cancer research on Earth, Nat. Rev. Cancer 13 (2013) 315–327.
[11] W. Stumm, J.J. Morgan, Aquatic Chemistry, Wiley-Interscience, 1970.
[12] Y.Y. Zhao, T.Z. Tong, X.M. Wang, S.H. Lin, E.M. Reid, Y.S. Chen, Differentiating solutes with precise nanofiltration for next generation environmental separations: a review, Environ. Sci. Technol. 55 (2021) 1359–1376.